Proceedings of the International Symposium held at Punjab Agricultural University, Ludhiana, India, 22-25 November 2006

Volume I: Invited Papers

Balanced Fertilization for Sustaining Crop Productivity

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International Potash Institute
Horgen, Switzerland
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Foreword

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 food crops responsive to fertilizer nutrients. However, the agriculture growth rate has not kept pace with the population growth rate. With more than 200 million tons of food-production, India is not able to meet the domestic demand and had to import it for self-sustenance. Though the consumption of fertilizers in India increased steadily over the years, but their use efficiency remained low and now there are reports of declining response to applied nutrients. This raises serious concerns about the sustainability of the production system.

The decline in the crop responses to applied fertilizer nutrients, *inter alia,* could be ascribed to emerging nutrient deficiencies on account of intensification of agriculture and inadequate or imbalanced application of fertilizers and manures. It has become increasingly recognized around the world that N, P and K fertilizers alone are not always sufficient to provide balanced nutrition for optimal crop yields and quality and application of secondary and micronutrient elements has to be made.

Even though India stands 3rd in the world in terms of gross fertilizer consumption, yet the consumption levels in the different agro-ecological regions are highly skewed. Only 102 districts out of total 500 districts, contribute to 50% of national fertilizer consumption. There is a wide gap in total fertilizer use and nutrient consumption ratio in different regions/states in India. Out of the four regions, consumption per unit of gross cropped area is the highest in south followed by north and east; and the lowest in west zone. North-zone, considered to be the food grain bowl of India, has the highest consumption of N but lowest consumption of potassium. Comparing Punjab in the north and Tamil Nadu in the south, the $N:P_2O_5:K_2O$ consumption ratio is much wider in Punjab (42.6:11.9:1.0) as compared to Tamil Nadu (2.6:1.0:1.0). This indicates that the highest fertilizer consuming state has the greatest imbalanced use of nutrients. The main reason of the variation in fertilizer consumption ratios in north and south is due to the nature of soils and cropping pattern. In north, the soils are alluvial with illite as predominant K containing mineral as compared to red and lateritic soils with kaolinite or swell-shrink soils with smectite as predominant minerals in south. Cereals are predominantly grown in the north region, whereas in the south in addition to cereals plantation crops are cultivated. Therefore, one has to take a wholesome view of the soil, plant and climatic factors for obtaining sustainable productivity and high fertilizer use efficiency. This is as much true of cereal crops as for horticultural and plantation crops. With people becoming increasingly conscious about quality of food-products (such as cereals, fruits, vegetables, spices etc), the task of achieving sustainable production without degrading the environment becomes all the more challenging. Obviously, the attainment of this goal warrants serious attention of the scientific community to deliberate and chart its future research agenda.

I am pleased to know that an International Symposium on Balanced Fertilization for Sustaining Crop Productivity was held at the Punjab Agricultural University, Ludhiana, India during 22 to 25 November, 2006. During the symposium, eminent scientists from India and other countries deliberated various aspects of soil, plant and nutrient management in relation to balanced fertilization and sustainable crop production. I compliment Dr. D.K. Benbi, Dr. M.S. Brar and Dr. S.K. Bansal for their conscientious and commendable efforts for editing the invited contributions and bringing them out in the form of a book. This volume contains valuable information and will be of immense use to the scientists, teachers, extension workers, students and the policy makers associated with agriculture and the environment.

Dated: 27 December, 2006

K.S. Aulakh
Vice Chancellor
Punjab Agricultural University
Ludhiana (Pb.), India

Foreword

The International Potash Institute (IPI) has a long track record of promoting optimized crop production through improved nutrient management in the Indian sub-continent. This work has predominantly been through hundreds of on-farm demonstrations and field trials, and large numbers of meetings with farmers, extension officers and researchers. Through these events IPI has been able to explore, demonstrate and disseminate knowledge on potassium's role in improving both the quality and quantity of yields.

India's increasing population, and change in demand for food crops, has resulted in tremendous challenges for the agriculture sector. The challenges can be met thanks to the richness of agro-climatic conditions and the special blend of crops grown on many types of soils, and thanks to the strong agricultural research in the country. These enable a wide range of solutions and ways to improve food production, and at the same time maintain sustainability for future generations.

In the past many of India's soils contained high levels of exchangeable K, but after years of production and increasing yields, the removal of nutrients, especially of potassium, became alarming. This process has been accelerated by typically low levels of organic matter application, which is often used as fuel. In addition, the production of fruits and vegetables, which have higher demand for potassium, has increased significantly. The outcome is a reduction in soil potassium and consequently soil fertility, which is reflected in increasing stagnation of cereal production. Thus, there is a need to adopt better diagnostic tools and to improve the farmers' agricultural knowledge in order to achieve improved productivity.

'Potassium in Indian Agriculture' was the theme of the previous International symposium jointly organized by IPI and the Potash Research Institute of India (PRII) in 2001. Now, five years on, we are pleased and honored to conduct a joint IPI-Punjab Agriculture University (PAU) International symposium with the theme 'Balanced Fertilization for Sustaining Crop Productivity'. The papers appearing in these proceedings reflect the efforts and achievements made in India, and elsewhere in the world, to achieve higher, sustainable agricultural productivity through balanced fertilization.

H. Magen

Dated: 27 December, 2006

Hillel Magen
Director
International Potash Institute
Horgen, Switzerland

Preface

Balanced fertilization is the key to sustainable crop production and maintenance of soil health. It has both economic and environmental implications. An imbalanced fertilizer use results in low fertilizer use efficiency leading to less economic returns and greater threat to the environment. It is imperative that fertilizers are used in a judicious manner based on crop demand and nutrient supply from the soil. Nutrient requirement depends on the type of crop grown, harvest levels and the environmental conditions. Therefore, one needs to devise practices suitable to different crops, cropping systems, plantations and environmental conditions. Keeping this in view, papers were invited from leading scientists to share their experiences during an International Symposium on Balanced Fertilization for Sustaining Crop Productivity held at the Punjab Agricultural University, Ludhiana, India during November 22 to 25, 2006. This volume embodies all the papers, which discussed different aspects of balanced fertilization in relation to soil, crop and sustainability of the production system.

Nitrogen application has made a substantial contribution to the tripling of global food production over the last five decades. But its use efficiency in agriculture is generally low and ranges between 20-50%. Imbalanced application of other essential nutrients is one of the reasons for low fertilizer use efficiency. Since there is a synergistic interaction of N with P, K, S and several micronutrients, it is imperative that fertilization practices include the application of not only N but also other deficient nutrients. This will result in not only improved nutrient use efficiency but also ensure sustainable productivity. Therefore, it is important to introspect the sustainability issues vis-a-vis fertilization practices (Samra), role of soil organic matter (Lal), and dynamics and mineralogy of potassium in soils (Pal *et al.*; Mukhopadhyay and Brar). Integrated nutrient management, which advocates the combined and optimum use of all available nutrients is the key component of soil health enhancement. Generally, animal manures and organic residues positively interact with applied fertilizer nutrients for enhanced productivity and nutrient use efficiency (Bonfil *et al.*; Zhang *et al.*). Potassium has diverse roles in soil-plant system but its application is often neglected, may be because crop responses to its application are not as glaring as for nitrogen. But the results from several countries confirm its need for use in field, vegetable and fruit crops. Scientists from China (Chen and Zhou), India (B-Singh and Y-Singh; Mishra *et al.*) and Bangladesh (Mazid Miah *et al.*) present their experiences with respect to role of potassium in balanced fertilization of rice and rice based cropping systems. Whereas experiences from Germany, Pakistan and Iran on role of potassium in balanced nutrition and sustainable crop production are presented by Römheld; Akhtar and Saleem; and Malakouti, respectively. The EU legislation and nutrient balances for selected

European countries are also discussed (Olfs). Several papers discuss nutrient management strategies for different field (Blaise; Yadav; Yadav *et al.*; Golakiya *et al.*), vegetables (Prabhakar and Hebbar), fruits (Singh *et al.*; Srivastava; Kumar *et al.*), spices and plantation crops (Karthikeyan). Genetic manipulation is a modern technique that could be exploited to breed crops with high nutrient utilization efficiency (Khanna-Chopra and Srivalli). It is not only the amount but also the mode and method of application which influences nutrient use efficiency. Application of fertilizers along with irrigation water (fertigation) can enhance nutrient use efficiency (Heilig and Imas). Balanced application of nutrients help plants in overcoming/tolerating biotic and abiotic stresses and thus ensure sustainable productivity (Cakmak; Datnoff *et al.*; Setter *et al.*). Finally, the role of industry and extension services in promoting balanced fertilization is discussed (Magen and Imas; Gupta; Gill and Gill). We hope the information contained in this volume will be useful to all those concerned with nutrient management and sustainable crop production.

We are thankful to the authors of individual chapters for the time and diligence without which this volume would not have been possible. We are also thankful to Dr. S.S. Mukhopadhyay and Mr. Amandeep Singh for their help in publication of these proceedings.

Editors

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Inaugural Address

G.S. Kalkat

Chairman, Punjab State Farmers' Commission,
Mohali (Punjab)

The spectacular progress made in agriculture sector since the inception of new farm technologies in the mid-sixties, has changed the agricultural scenario of the country from a stage of begging bowl to the stage of self-reliance in food production. 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 food crops responsive to fertilizer nutrients. The increase in food grain production during 1951 and 1965 before the green revolution period was 21.5 million tons as compared to 27.2 million tons in a span of five years during 1965 to 1970. This was in spite of the fact that the net area under the plough increased by 17.4 per cent during 1951 to 1965 as compared to only 4.7 per cent during 1965-1970. The large increase in food grain production during the last four decades has resulted from the increase in gross cropped area and productivity with increased use of fertilizer inputs, expansion of irrigation facilities mostly through private tubewells, and adoption of new technology coupled with mechanization of farm operations.

Punjab with 1.53 per cent of the geographical area of the country produces about 20 per cent wheat, 11 per cent rice and 13 per cent cotton, and the state is contributing 60 per cent of wheat and 40 per cent of rice to the national buffer stock of food grains. Rice-wheat is the most common cropping system covering about 60% of the cultivated area in the state. Both the crops are exhaustive feeders with nutrient removal of 500 kg ha^{-1} as N-P-K in one cropping cycle that produces 5.2 t ha^{-1} of paddy and 4.0 t ha^{-1} of wheat against recommended application of 120 kg N to rice, and 120 kg N, 60 kg P_2O_5 and 30 kg K_2O ha^{-1} to wheat totaling 330 kg N-P_2O_5-K_2O ha^{-1}. A negative balance of nutrients has thus been commonly obtained in rice-wheat system and deficiencies of secondary and micronutrients are emerging. Field scale zinc deficiency was first noticed in 1969-70, within 4-5 years of the introduction of high yielding varieties of wheat in Punjab. In 1975-76, iron deficiency in the state appeared in rice, when it was adopted by the farmers on coarse-textured soils. Deficiency of manganese became prevalent during 1979-80 on wheat grown sequentially with rice, particularly on sandy soils. Thus to sustain crop yields, balanced nutrition not only with NPK but also with micronutrients is required.

Soil health and productivity are the keys to sustainability of agriculture in India. Helping farmers to enhance their knowledge about soils and best management practices are vital. Even though India stands 3rd in the world in terms of gross fertilizer consumption, which was 20.62 million ton in 2005-06, average rate of nutrient application is less than 100 kg ha^{-1}, as the consumption levels in the different agro-ecological regions are highly skewed. Only 102 districts out of the total 500 districts, contribute to 50% of national fertilizer consumption. Large areas are still receiving very small rates of fertilizer application. There is a wide gap in total fertilizer use and nutrient consumption ratio in different regions/states in India. Out of the four regions in the north, south, west and east, consumption per unit of gross cropped area is the highest in south followed by north and east; and the lowest in west zone. The main reason of the variation in fertilizer consumption ratios in north and south is due to the nature of soils and cropping pattern. In north, soils are alluvial with illite as predominant K containing mineral as compared to red and lateritic soils with kaolinite or swell-shrink soils with smectite as predominant minerals in south. Cereals are predominantly grown in the north region, whereas in the south, in addition to cereals, plantation crops are cultivated. The procurement price of food grains is not fixed on the basis of quality. Therefore, the farmers of the north of India are not quality conscious. On the other hand in the south of India, cash crops like tea, coffee, pepper, cardamom and similar crops are priced according to the quality of the produce. The farmers are well aware that quality of crop depends upon the balanced nutrition and therefore, they go for balanced fertilizer application.

Water is another essential input for sustainable crop production. Due to large scale cultivation of paddy, the demand for water for irrigation purposes has risen causing a serious imbalance in the availability and actual consumption of water. The deficit is met by over exploiting ground water resources through tubewell pumping. Ground water exploitation has reached an alarming proportion with 100 out of 141 blocks in the state are categorized as dark blocks. In central Punjab, the area having water table below 30 feet depth has increased from 3% in 1973 to 95% in 2005. Water table is falling in 90% of the area in the state. On an average, in the central districts, water table has been falling at the rate of 54 cm/year. However, there was a fall of 75 cm during 2004-05. It is predicted that by 2023, the water table depth in 66% area of the central zone will be between 70-160 feet. In Punjab, there are a total of 1.15 million tubewells, out of which 0.9 million tubewells are electricity driven. Due to rapidly falling water table, the energy requirement for tubewells has increased by 20% in the Punjab during the last five years (2001-05). The centrifugal pumps are being replaced by submersible pumps, tubewells pits are deepened and electric motors are replaced involving additional cost of Rs. 2300 crore till the year 2005. In addition, Punjab State Electricity Board (PSEB) had to purchase electricity from other states worth Rs 5500 crores during the years 2002-05. By the year 2010, about 0.16 million more tubewells with an additional cost of Rs.1100 crore would have to be replaced.

With the fall of water table, the farmers have already started tapping the deep saline waters as fresh water layers have been depleted in the south-west districts. Furthermore, the ground water in 40% of the area in the state in the southwest part is saline that is marginal/unfit for irrigation. Application of such irrigation water will result in the formation of saline alkali soil (*kallar*). Therefore, there is a need to enhance water use efficiency. Management options to enhance water use efficiency include partially diversifying from high water-requiring crops to low water-requiring crops and employing field-scale water-saving technologies.

Due to continuous disposal of untreated effluents by the industries into sewage system and irrigation of fields with effluent containing sewage there is accumulation of heavy and pollutant elements in soils and plants, which may attain an alarming level due to their possible entry into the food chain. Large accumulation of toxins in edible parts of some vegetables is a matter of serious concern. There is a possibility of practicing remedial measures to reduce the entry of pollutant heavy metals into plants being grown on contaminated soils. Furthermore, as a consequence of dumping animal wastes and following wrong practices for storing these wastes, nitrate content is continuously increasing in shallow ground waters drawn through hand pumps for drinking purposes in the vicinity of many villages.

Future strategies for increasing agricultural productivity will have to focus on using available nutrient and water resources efficiently. Integrated nutrient management together with effective crop, soil, water and land management will be critical for sustaining agriculture over the long term. Integrated nutrient management. is a strategy that incorporates both organic and inorganic plant nutrients to attain higher crop productivity, prevent soil degradation, and therefore help meet future food supply needs.

I am aware that scientists are seized of these issues and are already in the process of reorienting their research agenda. In the present scenario, it is very timely that Punjab Agricultural University is hosting this symposium in collaboration with International Potash Institute (IPI). I am sure the deliberations during the symposium will bring out fruitful recommendations for posterity and help in solving the problems of modern agriculture.

Presidential Remarks

K.S. Aulakh

Vice-Chancellor, P.A.U., Ludhiana

It is an auspicious moment for the university and for me to be a partner of the International Symposium on Balanced Fertilization for Sustaining Crop Productivity. This is the first ever international symposium sponsored by the International Potash Institute held at any university in the world, and we esteem this relationship.

In the 1960s, the farmers of Punjab transformed the food-deficit nation into a food-surplus country. With 3 percent of the net cultivated area of the country, the state contributes 70 percent of wheat, and 50 percent of rice to the nations' food-grain reserve. It is a leading state in the production of cotton, milk, honey, mushroom, poultry, and forage. These unparallel strides were possible, because of availability of high yielding varieties, and assess to irrigation and knowledge, and more importantly, use of fertilizer. Punjab Agricultural University chartered the rally of food-grain production of the country. In the urgency of feeding the nation; the soils of Punjab have been depleted of nutrient store, and that could be one of the reasons of yield plateau of food crops that has been experienced in this decade. The scenario of nutrient depletion from soils is perhaps the same all over the world.

Almost all field and greenhouse experiments infer significant contribution of balanced fertilization to yield formation, but at most of the places, the experimenters have failed to persuade farmers to repeat the fete in their fields. There is a need to introspect on this issue. To my mind, experimenters must look beyond yield, and take into consideration food and nutrition securities together, and reorient their priorities towards the need of the millions of small and marginal farmers of the developing nations.

The unchecked depletion of macro-, micro-, and rare earth elements from soils calls for a writ. The non-application of balanced fertilizers makes this scenario more complex. For example, when only one nutrient (say nitrogen) is applied, it accelerates depletion of many more nutrients. We must take a holistic view to agricultural production with balanced fertilization as an inseparable part of it, and view them in the context of ecology. To do it, we are required to develop sound scientific hypotheses for future agricultural production that are dialectically connected to the interests of livelihood of small and marginal farmers.

With the globalization and abolition of trade barriers, agricultural scenario has undergone qualitative changes. Now, farmers have opportunities to sell their produce anywhere they like, *albeit* the cost and the quality of produce are globally competitive. Research in agriculture must also become globally competitive, share global knowledge pool, and focus on the intellectual property generation.

Colleagues and friends, I am humbled with the rapid pace of development in agricultural sciences, especially in soil science. The discipline advocates both short term and long-term objectives. For example, we now know that clay minerals on the earth were originated when huge amounts of organic matter, estimated to be more than 90 percent, was laminated over them, causing oxygen surplus in the atmosphere and triggering hierarchical evolution of plants and animals. With global rise of carbon dioxide and other green house gases, pollution from nitrogen and phosphorus fertilizations, accumulation of carcinogenic substances in soils, environmental toxicity from pesticide, and similar ecological concerns, I am compelled to insist that balanced fertilization programmes must involve use of nutrient elements to reduce pesticide load, ameliorate accumulation of toxins in edible parts in plant products, precisely use every drop of water, and must look to newer cheap sources of plant nutrients. A huge amount of our trapped solar energy goes waste, when farmers produce crops, but could only sell a fragment of their usable produce, and burn (or waste) the remaining plant parts. This means around 95 percent of fertilizer that contribute to produce non-useable plant parts are wasted. Perhaps, balanced fertilization programme can have greater emphasis on recycling of these plant parts. Balanced fertilization programme must look beyond a few chemical fertilizers, and must explore a combination of chemical, biological, and biochemical means of plant nutrients. We will not be pardoned by our children and grand children, if we only insist on greater nutrient uptake and ignore depleted state of our soils. We must recognize that blossoms bloom at the expense of soil-resident nutrients and every harvest depletes them, and when produce from farm or forest fields moves to consumer zones, there is pedosphere-debt of nutrients, which is detrimental to life support system. The primary objective of balanced fertilization need to be 'restoring' of nutrient elements to soil, in place of 'response' to plants; and nutrient dividend in plants/trees in relation to produce-quality and nutrition-security in place of mere nutrient uptake. To my mind, it must aim to return all nutrients that are being debited from the soil, and scientific communities must address these issues with a thorough probing on transport and transformation processes in soil-plant continuum. I am sure, all of you will use this opportunity of meeting global minds to propel your research to a modem egalitarian height, and would thrive to bring happiness to the minds of farmers, who are your true masters.

Declining Factor Productivity and Sustainability of Crop Production

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Abstract

Trend growth rate in agriculture peaked to 4.7% during 1980-90 and decelerated after that to 1.1% (average of 2002-2005). Total factor productivity of West Bengal, Haryana, Bihar and Uttar Pradesh declined during 1990 to 1996 and remained almost stagnant in Punjab. Response ratio of fertilizers came down from 10.5 of 1960s to 5.3 of 1990s and growth process is not sustainable. Balanced use of fertilizers and integrated nutrient management based on soil and water analysis is called upon. Liming of acid soils, reclaiming of wastelands, conserving soil, diversification of crops, farming system and tillage should be prioritized for public and private investments. Integrated development of poor quality waters, surface and ground resources, water logging, domestic and industrial affluent are some of the options to manage irrigation water scarcity. Participatory watershed management for converging rain water conservation on the production of crops, horticulture, agro-forestry, livestock and micro-enterprising is essential for sustainable livelihoods in rainfed regions. Extension of technologies, infrastructure investments in research and development for addressing emerging challenges are important for reversing growth deceleration.

Keywords: Food-grain production, nutrient management, water management, response ratio

Agriculture is a back bone of Indian economy since 70% of population is residing in rural area, 58% are directly employed in agriculture and contribute 22% to Gross Domestic Product (GDP). As shown in Fig 1 the agricultural growth trend peaked in 1980s and has declined since then (Ahluwalia, 2004-05). Wheat productivity of 4696 kg ha^{-1} in Punjab reached maximum in the coldest season of 1999-00 and declined thereafter (Fig 2). The total food grain production peaked to 213.46 mt in 2003-04 and is stuck up around this figure.

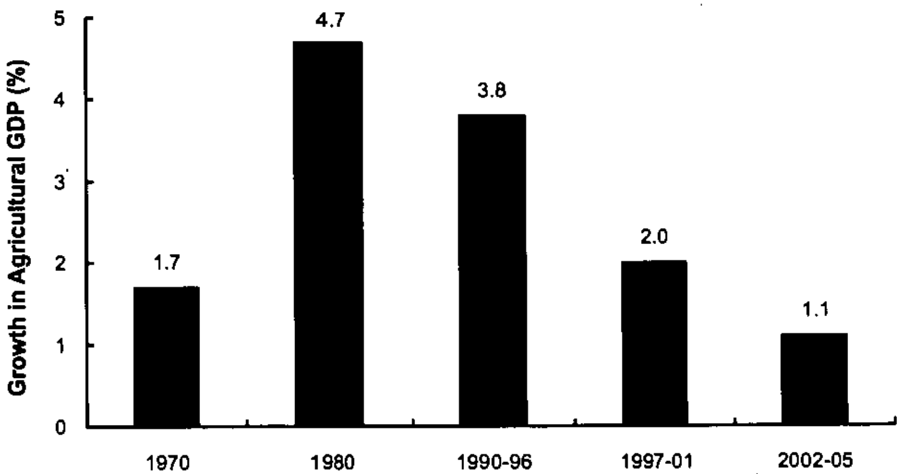

Fig 1. Growth trend in Indian agriculture

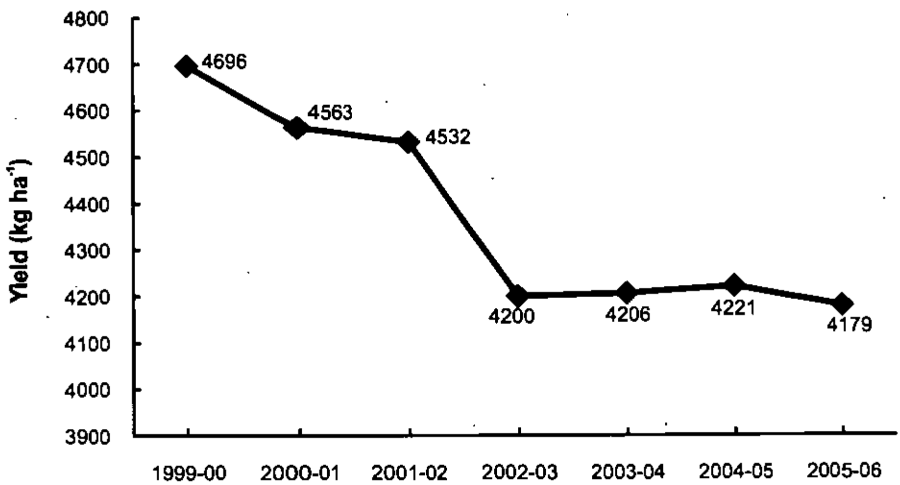

Fig 2. Decline in productivity of wheat in Punjab after 1999-2000

Declining Factor Productivity

Total Factor Productivity (TFP) being a ratio of total out put index to total input index was analyzed by Kumar *et al.*, 2004. Total input index was constructed with ten variables of land, fertilizers N, P and K, FYM, irrigation, human labour, bullock energy, machinery and plant protection. Variables on research, extension, education, infrastructure and health of natural resources were also included in the analysis. Total factor productivity growth in various states of Indo-Gangetic plains which was in forefront of experiencing the first green revolution is given in Table 1.

Table 1. Total factor productivity growth (percent per annum) in crop production of some states

State	1981-82 to 1989-90	1990-91 to 1996-97
West Bengal	5.13	1.25
Haryana	3.22	0.10
Bihar	1.47	0.24
Uttar Pradesh	1.40	0.54
Punjab	1.24	1.20

Source: Kumar *et al.* (2004)

During 1980 to 1990 West Bengal and Haryana witnessed highest growth rate, it was low in Bihar & U.P. and Punjab had already reached stagnation (Kumar *et al.*, 2004). However, TFP declined sharply in the subsequent 7 years in U.P., West Bengal, Haryana and Bihar whereas Punjab continued to stagnate. Excessive exploitation of groundwater, poor soil health, imbalanced use of inputs, weather or environmental changes, inadequate extension services and insufficient technological inputs were important reasons of decline in TFP and cost competitiveness. Various factors affecting factor productivity and their management are discussed in the subsequent sections.

Fertilizer consumption and productivity

Over the last 35 years, 50-55% improvement in crop productivity could be attributed to fertilizer inputs. Consumption of fertilizers in India increased steadily over the years, but their use efficiency remained low (30-50% for N, 20-25% for P and 2-5% for Zn, Fe and Cu). Achieving greater fertilizer use efficiency (FUE) is important as inefficient use of fertilizers represents substantial economic loss and an environmental degradation. At present level of fertilizer consumption and assuming use efficiency of 50% for N and 20% for P, a 1% increase in the efficiency of N and P use would save 0.22 million tonnes of N and 0.2 million tonnes of P, which together translate to a monetary gain of Rs. 6250 million annually. But FUE in terms of incremental crop grain yield response is on decline. A simple regression analysis was made between food grain production and fertilizer consumption for each 10 year period starting from 1950-51 and the relationships are given in Table 2. Increase in the intercept value of these equations over decades suggests gains of overall technological advances other than fertilizers. In the initial decade of 1950-51 to 1959-60, when chemical fertilizer had just arrived on the scene, the partial factor productivity of fertilizer (PFPF) was 94.6 kg grain kg^{-1} fertilizer which declined to 10.52 kg grain kg^{-1} fertilizer during 1960-61 to 1960-70. This deceleration continued further and in the terminal decade of the last century it was reduced to only 5.36 kg grain kg^{-1} fertilizer. Data on production and productivity growth rate (% per annum) given in Table 3 show that except for pulses, the production growth rates during 2000-01 to 2002-03 for all the crops are negative. As regards the productivity during this period, it is negative for all the crops except wheat.

Table 2. Relationships between food grain production and fertilizer consumption in India

Decade	Y = a+bX	R^2
1950-51 to 59-60	Y = 52205+94.59X	0.64
1960-61 to 69-70	Y = 74934+10.52X	0.50
1970-71 to 79-80	Y = 88933+6.64X	0.40
1980-81 to 89-90	Y = 88902+6.99X	0.86
1990-91 to 99-00	Y = 112135+5.36X	0.72

Where Y is food grain production in '000 tonnes, X is the fertilizer consumption in '000 tonnes,

Source: Rajendra Prasad (2006)

Table 3. Production and productivity growth rate (% per annum) of major crops in India

Crop	Production			Productivity		
	1980-81 to 1989-90	1990-91 to 1999-2000	2000-01 to 2002-03	1980-81 to 1989-90	1990-91 to 1999-2000	2000-01 to 2002-03
Rice	3.62	1.90	-5.60	3.19	1.27	-0.72
Wheat	3.57	3.81	-0.28	3.10	2.11	0.73
Pulses	1.52	0.61	0.99	1.61	0.96	-1.84
All Food grains	2.85	1.94	-3.73	2.74	1.52	-0.69
Oilseeds	5.20	2.13	-5.30	2.43	1.25	-3.83
Non-food grain	3.77	2.78	-2.21	2.31	1.04	-1.02

Source: Rajendra Prasad (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 emerging new nutrient deficiencies on account of intensification of agriculture and inadequate or imbalanced application of fertilizers and manures. Therefore, this paper basically reviews the crop responses to applied major and micro nutrients as a function of years and tries to find the possible soil and water related constraints so that the management could reverse the decline of the growth in productivity. A wholesome approach has to be followed for achieving balanced nutrition of crops, deploying chemical fertilizers, bio-fertilizers and a range of organic sources of nutrients.

Crop responses to nutrients under different application regimes

The long term effect of chemical fertilizers and manures applied individually and in combination on yield of crops and soil health is being studied at 11 major agro-climatic regions of India under the All India Coordinated Research Project on Long-term Fertilizer Experiments (ICAR) since 1970-71. The response ratios to applied nutrients were computed for rice (Barrackpore), wheat (Barrackpore, Ludhiana, Pantnagar and Palampur), maize (Ludhiana and Bangalore) and finger millet (Bangalore) and are presented in Fig 3. The application of N alone caused reduction in response ratio from initial 12.5 to 5 over 30 years primarily due to deficiency of P and K. The response ratio increased with the application of P along with N, but its reduction with time was again conspicuous in the absence of K application. The ratio got stabilized at a higher level only with the balanced application of NPK. With the addition of higher amounts of chemical fertilizers @ 150% recommended NPK response ratio rather declined since micronutrients became limiting.

The response ratios appreciated with a rising trend only when chemical fertilizers were supplemented with multi-nutrient source of organic manure. The average response ratios of N, NP, NPK and NPK+FYM were 8.1, 10.1, 12.8 and 15.2, respectively (Fig 4). The continued additions of chemical fertilizers at higher rate without organic manures induced deficiencies of other secondary and micro nutrients, thereby, lowering the response ratios. The deficiency of S and drop in the response ratios became evident in maize (Fig 5), wheat (Fig 6) at Palampur and in rice at Barrackpore (Fig 7) centers when S was omitted from the fertilization schedule. Likewise, the omission of Zn from the fertilization schedule led to lowering of average response ratios of crops at different locations (Fig 8).

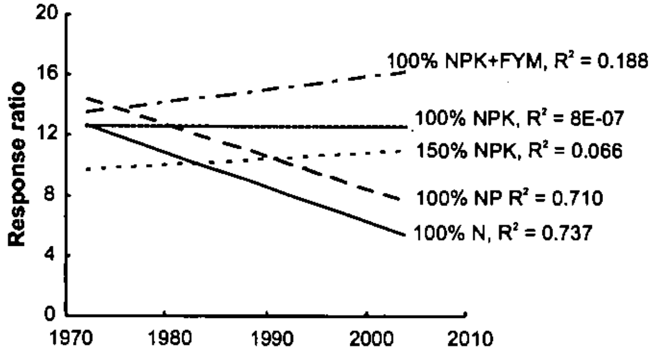

Fig 3. Nutrient response ratios (kg grain kg^{-1} nutrient) in cereals (LTFE data averaged over 1972-2003 and several locations of rice, wheat, maize and finger millet)

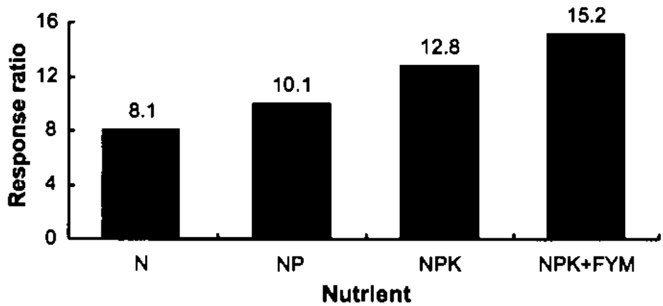

Fig 4. Response ratios (kg grain kg^{-1} nutrient) of nutrients (LTFE data, 1972-2003) averaged over several locations and cereal crops

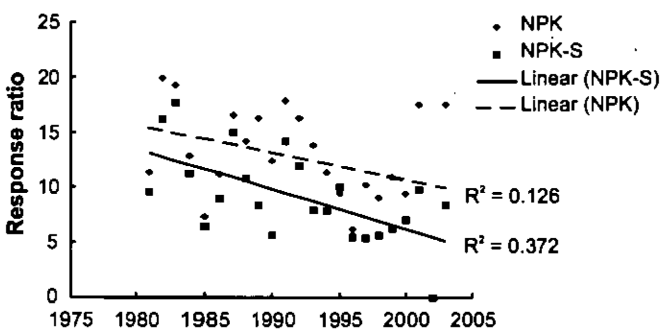

Fig 5. Response ratios (kg grain kg^{-1} nutrient) of sulphur in maize at Palampur (Data averaged over 1980-2003 under LTFE)

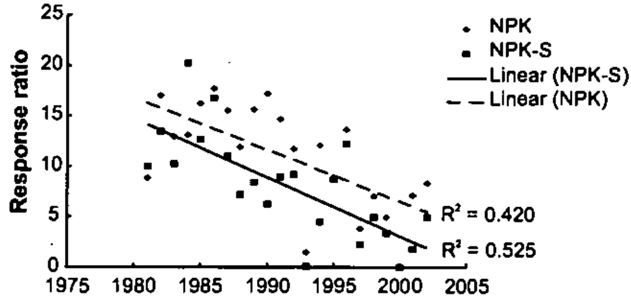

Fig 6. Response ratios (kg grain kg^{-1} nutrient) of sulphur in wheat at Palampur (Data averaged over 1980-2003 under LTFE)

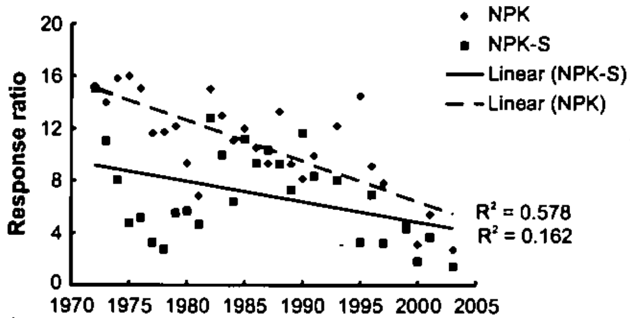

Fig 7. Response ratios (kg grain kg^{-1} nutrient) of sulphur in rice at Barrackpore (LTFE data)

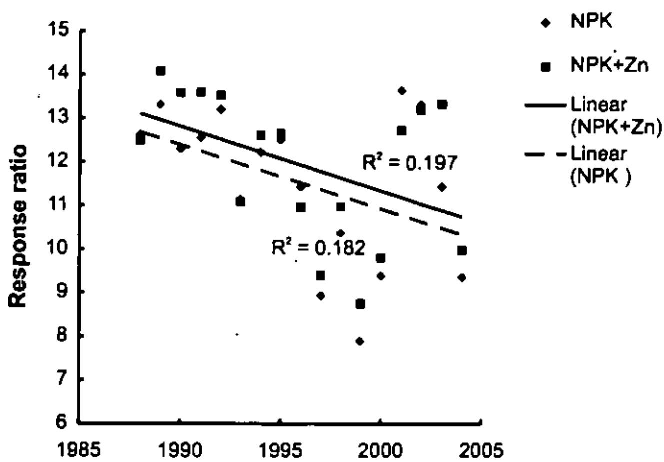

Fig 8. Response ratios (kg grain kg^{-1} nutrient) of Zn in cereals (LTFE data)

Water management

Among several inputs, water, energy and their nexus is very important for sustaining productivity of the country. Massive public investments provide 25% of surface irrigation whereas private investments into ground water exploitation contributed 75% of total irrigation. The indiscriminate use of resources has, however, given rise to both declining and rising water tables in different parts of the country, putting a question mark on the sustainability of agriculture.

Declining water table

The technological developments, private investments in ground water extraction and preference of crops requiring more water have led to phenomenal increase in the ground water utilization. Presently ground water is used to irrigate almost 75% of total irrigated land in the country. However, over-exploitation of the resource is forcing fall in the ground water table in many regions of Haryana, Punjab, Tamilnadu, Rajasthan, Union territories of Chandigarh, Delhi and Lakshdweep. The water table has fallen in about 80% area of Punjab constituting largely central districts of Amritsar, Kapurthala, Jalandhar, Ludhiana, Nawansheher, Sangrur and Patiala. The drop from 5-10 m in 1973 to below 15 m in 2002 in a sizeable area (25%) of central Punjab is really of big concern. The region occupies a prominent position in the production of 67 and 56% of total rice and wheat, respectively, of the state. Due to fall in the ground water, the cost of pumping water has increased manifold. The existing 0.4 million centrifugal pumps would require replacement with the submersible ones at a whopping cost of Rs. 30 billion. Besides this, the energy requirement will also be doubled. Greater increase in summer rice in West Bengal is also causing heavy withdrawals of ground water forcing its decline, especially in medium land-toposequence. Besides more energy requirements, the change-over is aggravating the problem of arsenic toxicity especially in West Bengal. The intrusion of saline sea water into the inland aquifers due to more exploitation of ground water is also threatening the agricultural productivity of coastal areas.

Rising water table

In almost all the irrigation commands, the water table has a rising trend by 0.1-1.2 m $year^{-1}$. The benefits of the major and medium irrigation works were, therefore, spectacular for the first 10-20 years, but these diminished with the occurrence of water logging and secondary salinity. It has been estimated that 4.5 m ha area in irrigation commands has been affected by water logging, thus, lowering the productivity of the lands.

Degraded lands

About 8.5 m ha area is affected by alkalinity and salinity alone in the country. The affected lands suffer due to toxicities of salts, nutritional disorders, poor drainability and low productivity. Also about 25 million hectares of cultivated lands with pH less than 5.5 are highly acidic. The productivity of acid soils is also very low (about 1 t ha^{-1}) due to deficiencies as well as toxicities of certain nutrients. Besides chemically deteriorated lands, a fairly large area (about 25 m ha) is also physically deteriorated (ravines, sand dunes, eroded) constituting open degraded forest/waste lands. These lands generally constituting common property resources are ill maintained and are contributing very little to the GDP.

Sustaining Crop Production

From numerous experiments, it is evident that imbalanced application of nutrients do not produce a sustainable production system. This was analyzed by the Sustainability Yield Index (SYI) in different cropping systems of LTFE (Table 4). Higher SYI indicates better sustainability of the system. Highest SYI was obtained in 100% NPK+FYM followed by 100% NPK+lime in acid soil, 100% NPK, 100% NPK (without S), 100% NP, 100% N and control. Application of lime in acid soils also improved SYI considerably particularly in soybean-wheat system at Ranchi. The results indicate that the application of organic manures, vermicompost, phosphocompost, green manure, crop residues, lime and micronutrients need to be practiced in different cropping systems as per the requirement and availability in order to ensure a sustainable system. Integrated use of organic manures and inorganic fertilizers is, however, most desirable for maintaining stability in production through correction of marginal deficiencies of secondary and micronutrients. Organic manures besides supplying nutrients to the current crop often leave some residual effect for succeeding crop in the system. The use efficiency of applied fertilizers also increased when applied with organic manures. Further, incorporation of organic sources along with NPK fertilizers is effective in alleviating the adverse effects of acidity or alkalinity in the soil besides improving the physical conditions and biological activities of soil. For instance, organic carbon, microbial biomass carbon and microbial count increased (Table 5) with the application of recommended NPK+ FYM compared to NPK alone in a long term experiment on Typic Hapludalf at Palampur. The addition of FYM along with NPK also increased the mean weight diameter, water retention and infiltration in the same experiment (Acharya *et al.*, 1988).

Table 4. Sustainable Yield Index (SYI) for various treatments at different long term experiments in India

Location	Crop	Control	100 % N	100 % NP	100 % NPK	100 % NPK +FYM	100 % NPK +Lime*	100 % NPK-S
Barrackpore	Rice	0.17	0.37	0.44	0.45	0.51	-	0.38
	Wheat	0.14	0.41	0.48	0.52	0.54	-	0.51
Coimbatore	Fingermillet	0.05	0.12	0.48	0.47	0.55	-	0.48
	Maize	0.05	0.07	0.40	0.43	0.50	-	0.41
Bangalore	Fingermillet	0.06	0.07	0.09	0.53	0.62	0.53	0.55
	Maize	0.00	0.00	0.00	0.41	0.55	0.51	0.34
Ranchi	Soybean	0.14	0.02	0.21	0.47	0.62	0.61	0.08
	Wheat	0.05	0.02	0.21	0.31	0.37	0.35	0.16
Jabalpur	Soybean	0.18	0.20	0.38	0.44	0.47	-	0.40
	Wheat	0.13	0.13	0.49	0.53	0.57	-	0.51
Mean		0.01	0.14	0.32	0.46	0.53	0.50	0.38

Source: Wanjari *et al.* (2004), * Acid soils

$$SYI = \frac{(Y-SD)}{Y\ max}$$

Where, Y = Average yield over the years for a particular treatment
SD = Standard Deviation for the treatment
Y max = Maximum yield obtained in any of the treatment in any of the year

Table 5. Long term effect of fertilizer and organic manure on some chemical and biological attributes of soil quality

Treatment	Organic carbon ($g\ kg^{-1}$)		Microbial biomass-C ($mg\ kg^{-1}$)	Microbial count (CFU x $10^6\ g^{-1}$ soil)	
	1972 (Initial)	2000		Bacteria	Fungi
Control	7.9	7.8	257	5.6	0.3
100% N	7.9	8.4	190	3.7	0.3
100% NP	7.9	7.4	205	5.4	6.6
100% NPK	7.9	8.9	316	34.0	5.0
100% NPK (-S)	7.9	9.0	207	34.0	4.1
100% NPK+FYM @ 10 t ha^{-1}	7.9	13.3	410	71.0	62.0

Source: Sharma *et al.* (2002), CFU=Colony forming unit

Balanced fertilizer use

Macronutrients

The fertilizer use is still imbalanced in most parts of the country affecting the sustainability of crop production. The imbalanced fertilizer use in terms of NPK is evidenced by their wider consumption ratios of 27.8:7.3:1 and 40.3:12.3:1 against desirable ratio of 4:2:1 in agriculturally advanced states of Punjab and Haryana, respectively. The withdrawal of subsidy on phosphatic and potassic fertilizers led to their less consumption. The introduction of Concession Scheme by the states to restore their consumption did not meet with the desired results. It is quite evident that all the three major plant nutrients are essential for a high and sustainable production system. Plant species differ in their abilities to utilize native, applied and the residual P. Therefore, it is important to recommend a dose of fertilizer P for a cropping system rather than a single crop. There was little residual effect on wheat of the P applied to preceding rice crop and accordingly in rice-wheat sequence, fertilizer P needs to be applied to wheat only taking advantage of the residual effect on rice (Singhania and Goswami, 1974). It was reasoned that (i) wheat removes higher amount of fertilizer P than rice, (ii) wheat cannot utilize the residual P in the Fe-P, and (iii) rice utilizes residual-P in the form of Fe-P and Al-P due to puddling and anaerobic conditions. A study conducted at Ludhiana showed that application of P only to wheat reduced P accumulation with negative P balance in soil, although rice yields were not affected by directly applied P (Yadvinder Singh *et al.*, 2002). The results suggested that application of 32 kg P to wheat and 15 kg P to rice was optimal and these rates will maintain positive balance in soil P.

From the literature it appears that the preferential application of fertilizer to crop in a cropping system mainly depends upon the (i) nutrient requirement of individual crops (ii) the extent of response of crops to a particular fertilizer nutrient and (iii) the capacity of crops to utilize the residual fraction of soil nutrients. Based on the hypothesis several experiments have been conducted to develop strategies of preferential application of fertilizer nutrient to crops in a cropping system for attaining maximum fertilizer use efficiency through higher crop responses (Table 6).

Secondary and micronutrients in balanced nutrition

Continuous intensive cropping with imbalanced and inadequate fertilizer use has depleted the soils of secondary and micronutrients also. Sulphur deficiency is fast emerging as an important limiting factor in rice-wheat cropping system. Increased use of concentrated fertilizers and replacement of S bearing ammonium sulphate and single superphosphate by urea and diammonium phosphate, respectively has caused S deficiency. Sulphur deficiency has been frequently observed in wheat in coarse textured soils of Punjab, which can be corrected with the use of single superphosphate or gypsum as a source of P and S (Nayyar *et al.*, 2000). After N, Zn is perhaps the most important nutrient limiting yields in rice-wheat cropping system. Zinc deficiency has been recognized as a widespread nutritional disorder in rice on sodic and calcareous soils having high pH, low organic matter, high available P or Si, high Mg:Ca ratio and low available Zn (Nayyar *et al.*, 2000). Rice is relatively more sensitive to Zn deficiency than wheat. Soil application of Zn to rice can also meet the requirement of following wheat crop. Studies carried out at Ludhiana indicate that an application of 11.2 kg Zn ha^{-1} is sufficient for 1-2 years of rice-wheat rotation (Modgal *et al.*, 1995). At Pantnagar, there was a general declining trend in rice productivity, but the minimum loss was in case of 100% NPK + Zn and maximum in 100% NPK-S (Nambiar, 1994). This indicates the hidden deficiency of both S and Zn in the soil. Incorporation of 15 t FYM ha^{-1} yr^{-1} along with NPK also decreased the productivity, despite maintenance of organic matter content at the initial level. The deficiency of S and Zn was only partially mitigated by FYM application. Rice suffers from Fe deficiency on coarse-textured soils because of low Fe content and the difficulty of maintaining standing water (Nayyar *et al.*, 2000). Similarly, the deficiency of Mn is increasingly appearing on wheat when it is grown after rice on light-textured soils. It is essential to make need-based application of these nutrients for obtaining higher yields of both the crops in the system.

Table 6. Preferential application of fertilizer nutrients to crops in a cropping system

Cropping sequence	Strategy
Rice-wheat, Pearlmillet-wheat, Soybean-wheat	Apply phosphorus to winter *(rabi)* wheat and skip P application to summer *(kharif)* crops
Maize-wheat, Sorghum-wheat	Prefer P application to wheat
Gram-rice	Apply super phosphate to gram and harness the residual effect on rice
Sorghum-castor	Apply P at recommended dose to sorghum and castor crop may be given a reduced dose
Potato based cropping system	P should be applied to potatoes in a crop rotation
Groundnut-wheat	Apply recommended dose of P to wheat and skip application to groundnut
Rice-wheat	Use of potassium may be preferred in the rice crop
Jute-paddy-wheat	Apply K to paddy and wheat and harness the residual effect on jute
Jute-paddy-potato	Apply K to potato and paddy and grow jute on residual effect

Source: Acharya *et al.* (2003)

With the intensification of agriculture with high-yielding crop varieties, the deficiency of micronutrients particularly of zinc became a serious constraint limiting crop production in several parts of the country. To delineate the extent of micronutrient deficient areas, more than 0.25 million soil samples were analyzed which indicated 49, 32, 12, 5, and 4% deficiency of zinc, boron, iron, manganese and copper (Table 7) (Singh, 2001a) . In recent years, deficiency of boron has emerged in red, lateritic and highly calcareous soils. About 41% soils of India are deficient in sulphur (Singh, 2001b). In order to establish magnitude of crop response to Zn, a large number of experiments on cultivators' fields were conducted (Table 8) which revealed significant response (208-254 kg ha^{-1}) in rice, wheat, maize and barley (Singh, 1999). Overall response to zinc fertilization was highly significant and beneficial (Singh, 1999; Singh, 2001c).

Table 7. Extent of micronutrient deficiencies in soils of India (Based on 0.25 million samples

State	Per cent deficient samples				
	Zn	Cu	Fe	Mn	B*
Andhra Pradesh	46.8	<1.0	2.8	1.0	52.9
Assam	34.0	<1.0	2.0	20.0	
Bihar	54.0	3.0	6.0	2.0	37.0
Gujarat	23.9	4.0	8.0	4.0	2.0
Haryana	60.5	2.0	20.0	4.0	0.0
Himachal Pradesh	42.0	0.0	27.0	5.0	
Jammu & Kashmir	12.0				
Karnataka	72.8	5.0	35.0	17.0	32.0
Kerala	34.0	3.0	<1.0	0.0	
Madhya Pradesh	44.2	<1.0	7.3	0.0	21.8
Maharashtra	83.0	0.0	24.0	0.0	
Meghalaya	57.0	2.0	0.0	23.0	
Orissa	52.5	<1.0	0.0	0.0	23.3
Pondichery	8.0	4.0	2.0	3.0	
Punjab	46.1	1.1	14.0	2.3	23.4
Rajasthan	21.0				
Tamil Nadu	58.6	6.0	17.0	6.0	21.0
Uttar Pradesh	45.7	1.0	6.0	3.0	24.0
West Bengal	36.0	0.0	0.0	3.0	68.0
All India	48.8	3.0	11.9	4.4	31.8

Source: Singh (2001b), * Based on 50,000 samples

Table 8. Mean response to zinc application over NPK in experiments on cultivator fields

Crop	No. of Experiments	Grain yield in NPK, kg ha^{-1}	Mean grain response over NPK			B : C Ratio
			% increase	kg grain ha^{-1}	kg grain kg^{-1} Zn	
Rice	1252	3483	6.3	219	39.9	3.0 : 1
Wheat	5172	2353	8.8	208	37.8	2.8 : 1
Maize	601	2987	7.6	226	41.1	3.1 : 1
Barley	209	2734	9.3	254	46.2	3.5 : 1
Over all	7234	2612	8.3	213	38.7	2.9 : 1

Source: Singh (2001c)

Cereals showed greater response to zinc fertilization than pulses and oilseed crops. Out of 2211, 2525 and 231 field experiments conducted on rice, wheat and maize, 73, 57, 52% cases showed grain yield response of more than 200 kg ha^{-1} (Singh *et al.*, 1979; Singh 1991). Data in Table 9 clearly showed that in the initial phase of Green revolution the percentage of experiments showing response to less than 200 kg ha^{-1} was more but subsequently in nineties, maximum number of experiments showed response between 200-500 kg ha^{-1}. This is because of continuous depletion of zinc content in soils due to intensive cropping. Not only cereals, but also oilseeds and pulses grown on marginal lands responded to zinc fertilization. Application of Zn significantly increased the yield and the magnitude of response varied from 28 to 135 kg seed per kg of zinc applied (Table 10) (Singh, 2002). Pulses, cotton and sugarcane also significantly responded to zinc application. With the awareness of zinc deficiency and its impact on crop yields, the farmers have now been using zinc in several parts of country. As a result of this, zinc deficiency is declining while deficiencies of multi micronutrients like iron, manganese are emerging fast which are lowering yields. Manganese and boron deficiencies have been found in Indo-Gangatic alluvial plains. Copper deficiency is not a major problem in Indian crops and soils. However, about 33% soil samples analysed from various parts of country indicated deficiency of boron (Table 11). Its deficiency is wide spread particularly in red and lateritic, acidic coarse textured alluvial and highly calcareous soils of Bihar (Sakal *et al.*, 1996; Sakal *et al.*, 1997; Singh, 2000). Studies revealed that zinc deficiency can be corrected either by soil or foliar application or cultivation of micronutrient tolerant crops or cultivars. Application of 5.5 to 11.2 kg zinc ha^{-1} was generally found sufficient to correct zinc deficiency. Zinc also leaves residual effect on succeeding crops. So frequency of application needs to be optimized. Repeated application of zinc is essential in third or fourth crop depending upon the rate of zinc application (Table 12) (Nayyar *et al.*, 1999).

Table 9. Percentage of cases in different categories of response to zinc over years in farmer fields

Years	No. of trials	Percent distribution of experiments in different response range, kg ha^{-1}			
		< 200	200-500	500-1000	>1000
1975-76	250	44	41	15	0
1978-80	413	46	30	17	7
1981-84	489	22	40	30	8
1984-85	277	16	43	35	6
1985-86	103	21	44	27	8
1986-90	222	13	65	14	8

Source: Singh (1991)

Table 10. Response of oilseeds and pulses to zinc fertilization over NPK in front line demonstrations

Crop	No. of field Experiments	Seed yield, kg ha^{-1}		Response over NPK	
		NPK	NPK+Zn	kg grain kg^{-1} Zn added	Percent
Soybean	24	1109	1248	27.8	12.5
Groundnut	30	1509	1713	40.8	13.5
Gobhi-sarson	9	1595	1842	49.4	15.7
Linseed	2	1064	1316	30.4	13.8
Mustard	6	1352	1832	96.0	37.6
Raya	8	1499	2177	135.8	48.2
Sunflower	2	1610	2230	124.0	41.6
Cotton	27	1151	1370	44.0	14.5
All oil seeds	108	1322	1578	50.1	18.2

Source: Singh (2002)

Table 11. Crop response to boron fertilization in field trials conducted on different soils

Crop	No. of trials	kg grain kg^{-1} boron added	Per cent response over NPK
Rice	107	384	16.6
Wheat	35	468	15.1
Maize	5	684	32.5
Chickpea	7	420	44.1
Lentil	4	298	18.6
Groundnut	11	144	9.9
Sesame	5	108	23.9
Mustard	15	320	32.8
Sunflower	3	660	35.2
Cotton	2	312	11.6
Average	194	380	24.0

Source: Singh (2006)

Table 12. Mean response of rice-wheat sequence to different levels and frequency of zinc application in a loamy sand soil of Punjab

Rate of application (kg Zn ha^{-1})	Mean response (kg ha^{-1})*				
	Frequency of zinc application				
	All six rice crops	Alternate rice crop	I & IV rice crops	Initial rice crop	Mean
2.8	662	527	432	310	483
5.6	1015	900	873	645	858
11.2	1225	1115	1148	840	1085
Mean	970	850	820	600	

*Mean of six cropping cycles

**Mean yield in NPK 7366 kg ha^{-1} per rice-wheat cycle

Source: Nayyar *et al.* (1999)

Integrated use of organic manures either alone or in combination with zinc enhances the micronutrient status of soil and helps in correction of micronutrient deficiencies (Singh, 1994). In the absence of FYM soybean responded upto 12 kg ha^{-1} of Zn and when FYM was applied there was hardly any response to Zn beyond 3 kg ha^{-1} (Table 13). Studies revealed that when farm yard manure is added regularly, the deficiency of micronutrient is taken care off automatically, otherwise 10-12 kg Zn ha^{-1} needs to be applied to sustain the higher yield of various crops. When manure application is limited to 4-8 t ha^{-1}, application of zinc dose may be reduced to 3-6 kg Zn ha^{-1} thereby saving the input by 50-75% without reduction in yield (Singh, 1994).

Table 13. Soybean yield as influenced by integrated use of FYM and Zn application in a medium swell shrink soil

FYM added (t ha^{-1})	Seed yield (kg ha^{-1} over NPK)				
	Rate of Zn added (kg ha^{-1})				
	0	3	6	12	Mean
0	1348	1411	1482	1678	1480
4	1554	1643	1821	1946	1741
8	1625	1875	1999	2080	1895
16	1893	2216	2161	2188	2114
Mean	1605	1786	1866	1973	-

L.S.D. (P 0.05): FYM = 98, Zn = 77, Zn x FYM = 155

Source: Singh (1994)

Manganese deficiency is rapidly spreading in coarse textured alkaline soils having low organic matter content. Soil application of 20-50 kg Mn ha^{-1} is the optimum, but is highly uneconomical as compared to 2-3 foliar sprays of 0.5-1.0% manganese sulphate solution at weekly intervals (Nayyar *et al.*, 1990). The response of wheat and other crops to foliar sprays ranges from 200-3000 kg ha^{-1} over NPK. Most often manganese application decided entire failure or success of crop production in about 0.15 million hectares area (Singh, 2000). Data in Table 14 showed that tolerant cultivars need less number of foliar sprays of manganese as compared to susceptible cultivars of wheat (Nayyar *et al.*, 1999; Singh and Saha, 1995).

Table 14. Relative tolerance of wheat cultivars to foliar sprays of manganese sulphate

Cultivars	Susceptible/ Tolerant	Grain yield (t ha^{-1})				
		No. of sprays				
		0	1	2	3	Mean
PBW 34	Susceptible	1.28	1.96	2.39	3.15	2.19
HDS 2285	Susceptible	1.87	2.95	3.61	4.30	3.43
Mean	Susceptible	1.58	2.46 (57)	3.00 (90)	3.73 (136)	2.81
WL 2265	Tolerant	4.12	4.29	4.75	4.79	4.49
HD 2329	Tolerant	4.15	4.78	4.98	5.11	4.73
Mean	Tolerant	4.14	4.54 (10)	4.87 (18)	4.95 (20)	4.56

Figures in parentheses represent per cent increase over control
Source: Nayyar *et al.* (1999); Singh and Saha (1995)

With continuous use of high-analysis fertilizers free from sulphur, the deficiency of sulphur has been widely observed. Its deficiency is becoming a major constraint for sustaining optimum yields of oilseed, pulse crops, onion and garlic (Singh 2001b). The crops grown in many areas are showing significant response ranging from 9-19 kg grain kg^{-1} of sulphur applied in case of oilseeds and 4-10 kg grain kg^{-1} of sulphur applied to pulse crops in various agroecological zones of India (Table 15). Balanced fertilization includes wide range of nutrient application strategies from N+Zn in newly-reclaimed alkali (sodic) soils to N+P+K+S+Zn in coarse-textured alluvial soils of the wheat belt.

Integrated nutrient management

There exist several opportunities for promoting integrated nutrient management through a number of technological interventions:

Use of organic manures

In rice-wheat system, the yield potential of crops can be realized by organic manuring with locally available organic materials by supplementing fertilizer N up to 50% of the total requirement without affecting the system productivity (Sharma and Mitra, 1990). The grain yield of rice with FYM or water hyacinth compost at 10 t ha^{-1} (50% moisture basis) was equivalent to that with 30 kg N ha^{-1} of urea fertilizer. The yield of wheat grown solely on residual soil fertility was low and direct N fertilizer was essential for achieving high productivity. In a long-term study at Ludhiana, the highest yield of rice was obtained with 75%

NPK + 25% N replaced by FYM, which was comparable with 100% NPK or where 50% N was replaced by green manure (GM). Replacement of 50% N with FYM for rice consistently produced the highest wheat yield, which was significantly higher than with 100% inorganic N, indicating a positive residual effect of FYM. Thus, integrated use of manures and fertilizers proved to be as efficient as 100% NPK in the productivity of rice-wheat cropping system, suggesting that 50% N can easily be replaced by FYM or GM without yield reduction. The effect of poultry manure (PM) and urea was investigated in rice-wheat cropping system when applied at equal N rates or in 1:1 ratio (Bijay Singh *et al.*, 1997). Poultry manure was inferior to urea fertilizer in the first year, but by third year, it produced significantly more yield than the same rate of N as urea. Further, the poultry manure sustained the grain yield of rice, while the yield decreased with urea. A residual effect of poultry manure applied to rice to supply 120-180 kg N ha^{-1} was observed in the following wheat, which was equivalent to 40 kg N ha^{-1} plus some P.

Table 15. Response of oilseeds and pulses to sulphur fertilization over NPK in front line demonstrations

Crop	No. of trials	Seed yield, kg ha^{-1}		Response over NPK	
		NPK	NPK+S	Kg grain kg^{-1} S	Percent
Oil seeds					
Groundnut	6	1425	1783	9.0	9.9
Gobhi-sarson	2	1443	1980	13.5	13.4
Mustard	6	1487	2158	16.8	21.6
Raya	11	1435	1983	13.7	13.7
Soybean	2	1230	1950	18.0	18.0
All oil seeds	27	1430	1975	13.6	14.9
Pulses					
Chickpea	21	1623	2017	9.9	26.7
Green gram	11	809	976	4.2	21.7
Lentil	10	1342	1576	5.9	17.5
Black gram	8	816	975	4.0	19.5
Pigeon pea	9	1209	1464	6.4	21.2
All pulses	59	1251	1522	6.8	22.9
Total	86	1307	1664	8.94	20.4

Source: Singh (2001b)

Green manuring

Green manuring with leguminous crops is desired not only for enhancing the yield of rice-wheat cropping system but also for improving the fertility status of the soil. A 6-8 week old crop of sunnhemp or dhaincha during summer accumulates about 3-4 t ha^{-1} dry matter and 100-120 N ha^{-1}, which when incorporated *in situ*, supplements up to 50% of the total N requirement of rice, besides leaving some residual effect on succeeding crop of wheat. A number of experiments have shown the beneficial effect of green manure crops through increased yield of succeeding crops and saving of N fertilizer in rice ranging from 60-120 kg N ha^{-1} (Yadvinder Singh *et al.*, 1991). It is beneficial to apply P fertilizer to the green manure crop for enhancing dry matter production and N accumulation, consequently leading to greater saving of N fertilizer in rice (Sharma and Mitra, 1988). Application of P to rice can be skipped altogether if it is preceded by a phosphate treated green manure. In the calcareous soils of Bihar, green manuring with dhaincha and sunnhemp was equally effective in improving the productivity of rice-wheat system (Prasad *et al.*, 1995). Further, the requirement of Zn of both the crops could completely be met through the green manuring. Long-term experiments at 6 locations in the Indo-Gangetic plains revealed that grain yield of rice and wheat decreased under control and sub-optimal fertilizer inputs. Whereas recommended NPK fertilizer increased yield of rice but did not prevent decline in yield of wheat. Partial substitution of inorganic fertilizer with green leaf manure of *Sesbania sesban* brought further improvement in the yield of rice and the residual effect of green manure reversed the declining trend in wheat yield. The sustainability yield index was also greater in plots receiving 100% NPK or green manure+NPK, indicating that rice-wheat system is more stable under these treatments. The yield performance of rice and wheat was evaluated under integrated nutrient management practices on farmers' fields in a high-productivity zone (Jalandhar) and low-productivity zone (Ghazipur) (Yadav, 2001). At Jalandhar, green manuring was the superior practice for enhancing grain yields of the system compared with other nutrient management practices in 3 out of 5 years. On the other hand, in the low-productivity zone of Ghazipur, fertilizer NPK alone increased the yields of rice-wheat system compared with other nutrient management practices.

In rice-wheat system, a lean period of 70-90 days (April to June) is generally available which can profitably be utilized for growing a catch crop of summer pulse. Inclusion of a legume crop either for grain or fodder during summer can help in restoring the soil fertility, resulting in higher yield of the rice-wheat system. Growing of green gram, black gram or cowpea and incorporating the residues into the soil after harvesting the grains/pods is suggested for not only increasing the system productivity but also for saving of a portion of inorganic fertilizer (John *et al.*, 1989, Kundu and Pillai, 1992). Incorporation of green gram residues after picking of pods before transplanting rice economized 40-60 kg N ha^{-1} in rice. Green gram straw incorporation can substitute up to 50% NPK needs of rice, amounting to 60 kg N, 30 kg P_2O_5 and 15 kg K_2O in rice-wheat system, without any adverse effect on total productivity. In a study at New Delhi, incorporation of green gram residue increased the yield of rice by similar magnitude as Sesbania green manure, although the amount of biomass and N added were higher under the latter than for former (Table 16 (Sharma *et al.*, 1995). The residual effect of all summer legumes on succeeding wheat followed the order: green gram residue incorporated > sesbania green manure > green gram residue removed > fallow. An additional advantage of 0.9 t ha^{-1} of seed yield of green gram, besides beneficial effect of productivity of rice-wheat cropping system was obtained. Thus, the practice of incorporation of green gram and cowpea stover after picking the pods was as good as or even better than green manuring. Further, it also helps in mobilizing the available N, P, K and micronutrients like Zn, Fe and Mn from soil.

Table 16. Effect of summer legumes on performance of rice-what cropping system at New Delhi (mean of 2 years)

Treatment	Summer legumes		Direct effect on rice yield (t ha^{-1})	Residual effect on wheat yield (t ha^{-1})
	Biomass added (t ha^{-1})	N added (kg ha^{-1})		
Fallow	-	-	4.50	3.25
Sasbania green manure	4.0	73.3	5.05	3.70
*Greengram (residue removed)	-	-	4.65	3.50
*Greengram (residue incorporated)	2.7	63.5	5.00	3.80

*A grain yield of 0.9 t ha^{-1} was harvested from greengram

Source: Sharma *et al.* (1995)

Biofertilizers

Crops in dryland areas suffer due to moisture stress and low native soil nutrient status. Use of integrated nutrient management practices involving application of chemical fertilizers along with organics and biofertilizers is important to impart sustainability to production. Experiments in the All India Network Project on Biofertilizers in loamy sand soils with very poor organic matter content, at Bawal in Haryana showed that inoculation of bacterial biofertilizers like Azospirillum and Pseudomonas on pearlmillet, wheat and mustard gave 10-22% increase in grain yield when applied along with 75% recommended doses of nitrogen and saved 25% N dose. Fifty field demonstrations in farmers' fields in six districts of Haryana showed that pearlmillet yields were improved and there was an increase of 15% in net income (Rs. 800 ha^{-1}) earned by farmers through simple inoculation (Table 17). A number of field experiments with different rice varieties grown in Alfisols and Vertisols in Tamilnadu have consistently proved over the last five years that by applying AZOPHOS, a mixed Biofertilizer comprising of Azospirillum and Phosphate solubilising bacteria (PSB) through dipping of the rice seedlings in a slurry of the inoculum at transplanatation, about 25% recommended dose of N and P can be saved, i.e., yields at 75% NP with inoculum are at par with 100% recommended dose of NP (Table 18). This was additionally proved by also using leaf colour charts in which not only a saving of 15 kg N ha^{-1} but significantly higher yield was obtained with Azophos inoculation. (Table 19). In a long term experiment started seven years ago on inoculation of *Bradyrhizobium japonicum* in soybean and Azotobacter inoculation in wheat in Vertisols of M.P., additional grain yields of about 200 kg in soybean and 300 kg in wheat have been recorded due to inoculation (Table 20) over and above the recommended dose of NPK. In terms of total additional nutrient uptake in crops and accretion in soil due to BNF it was found that this amounted to nearly 90 kg N ha^{-1} yr^{-1} (Table 20). Combined inoculation of Rhizobium and a PGPR (plant growth promoting rhizobacteria) Pseudomonas saved 25% N and P in groundnut in Alfisols of Tamilnadu by improving nodulation (Table 21) and nitrogen fixation. In acid soils, micronutrients availability is reduced and since molybdenum and cobalt are co-factors of the nitrogenase enzyme, biological nitrogen fixation in root nodules is affected. Seed treatment of green gram with Mo and Co in acid soils of Orissa dramatically improved the yields, N and P uptake (Table 22).

Table 17. Summary of demonstration trials on mixed biofertilizers (Azotobacter, Azospirillum and Pseudomonas) on pearlmillet (var HHB 94) in Haryana (AINP on BF, HAU, Hisar)

Districts	No. of Trials	Mean grain yield ($kg\ ha^{-1}$)		Mean fodder yield ($kg\ ha^{-1}$)		Net return (Rs. ha^{-1})	
		IP	FP	IP	FP	IP	FP
Hisar, Bhiwani, Jhajjhar, Rewari Mahendergarh	50	1987	1891	5015	4732	5897	5116
% increase over FP	-	5.0%		6.0%		15.3%	

IP = Improved Practice: 75% RDF (30 kg N and 15 kg P ha^{-1}) + Mixed biofertilizers
FP = Farmers Practice: 75% RDF (30 kg N and 15 kg P ha^{-1})
Net increase: Rs. 780 ha^{-1} due to inoculation

Table 18. Effect of Azophos* on rice (var. ASD 18) (AICRP-BNF, TNAU, Coimbatore)

Treatment	Grain yield ($kg\ ha^{-1}$) (var. ASD 18)	Grain yield ($kg\ ha^{-1}$) (var. white ponni)
100% N + P		
Uninoculated	4343	5905
Azophos	4520	-
75% N + P		
Uninoculated	3766	5760
Azophos	4416	6000
C.D.	492	240

*Azospirillum + PSB mixed in same packet. 100% NPK was 120: 38: 36

Table 19. Effect of Azophos* inoculation on yield and N P uptake of rice (var. ASD 18) (AICRP-BNF, TNAU, Coimbatore)

Treatment	Grain yield ($kg\ ha^{-1}$)	Nutrient uptake ($kg\ ha^{-1}$)	
		N	P
+ NPK, - Inoculum	2658	49.0	8.7
+ NPK, + Azophos	2881	57.1	10.6
N LCC Grade 3 (105 kg ha^{-1}) + Azophos	3053	58.0	10.7
C.D. = 0.05	190	8.8	1.5

*Azospirillum + PSB mixed in same packet. 100% NPK was 120: 38: 36

Table 20. Yield and N benefits due to Rhizobium inoculation of soybean and Azotobacter inoculation of wheat (mean of 6 years 1999-2005) in Vertisols (AICRP-BNF, JNKVV, Jabalpur)

Treatment	Soybean yield (kg ha^{-1})	Wheat yield (kg ha^{-1})	Soybean N uptake (kg ha^{-1})	Wheat N uptake (kg ha^{-1})	Soil N increment (kg ha^{-1} yr^{-1}) in Soybean-wheat	Total N benefit due to use of inoculants (kg ha^{-1})
	A	B	C	D	E	C+D+E
Uninoculated	1651	4980	132	109	1425	
Inoculated	1855	5296	149	124	1486	
Gain	204	316	17	15	61	93

*N, P and K were applied at 20 : 80 : 20 to all plots in soybean

Table 21. Effect of combined inoculation of Rhizobium (TNAU) and plant growth promoting harmones (PGPR) (Pseudomonas-PS2) on groundnut (AICRP-BNF, Coimbatore)

Treatment	Nodule (no. pl^{-1})	Nodule dry weight (mg pl^{-1})	Pod yield (kg ha^{-1})	% increase over control
100% NP				
Uninoculated	20	120	1333	-
Rhizobium + Pseudomonas	47	220	1492	11.9
75% NP				
Uninoculated	21	100	1001	-
Rhizobium + Pseudomonas	39	270	1278	27.6
L.S.D. (p = 0.05)	3	35	69	-

* Inoculation saved 25% of the recommended doses of N and P in groundnut

Table 22. Impact of combined application of Rhizobium and micronutrients on yield and nutrient uptake of green gram in an acid loam (AICRP-BNF, OUAT, Bhubaneswar)

Treatment	Grain ($kg\ ha^{-1}$)	Stover ($kg\ ha^{-1}$)	N uptake ($kg\ ha^{-1}$)	P uptake ($kg\ ha^{-1}$)
Uninoculated	340	300	21.4	1.90
Rhizobium	430 (25.7)*	340	28.5	2.50
Rhizobium + Mo + Co	610 (78.4)	680	45.4	4.40
L.S.D. ($p = 0.05$)	50	60	2.4	0.48

*Figures in parentheses denote per cent increase over uninoculated control; recommended doses of NPK were applied

Soil test based fertilizer prescriptions

Traditionally, in India by balanced fertilization one is made to believe and understand use of N, P_2O_5 and K_2O in a certain ratio, ideally 4:2:1, on a gross basis both in respect to areas and crops. This ratio was not scientifically designed but was perhaps advocated as a somewhat safe and general prescription from the practical angle with a view to maintain the overall fertility of Indian soils. Yet the area specific or regional fertilizer recommendations are based on short term trials, which do not reflect on long-term impact of fertilizer use or resource base, environmental quality and human health. Moreover, blanket recommendations are static and cannot commensurate with variability and changes in soil nutrient status, crop demand and crop management. Therefore, one alternative approach could be that fertilizer is applied based on recommendations emanating from soil test crop response data or in its absence from soil test reports. Data of the on farm trials comparing the responses to applied fertilizer as per yield targeted vis-à-vis state's recommendations and farmers' practice (Table 23) indicate that state recommendation gives much lower yield as compared to the fertilizer application based on actually testing the soil and yield targetting.

Table 23. Results of on-farm trials with wheat, pearlmillet and mustard at IARI, New Delhi

Crops	Treatment	Nutrient dose (kg ha^{-1})			Yield
		N	P_2O_5	K_2O	(kg ha^{-1})
Wheat	STCR				
	Target 5 t ha^{-1}	126	49	41	4887
	SR	120	60	40	4567
	FP	80	57	0	3662
Pearl millet	STCR				
	Target 5 t ha^{-1}	100	42	43	2540
	SR	80	40	40	2020
	FP	46	23	0	1360
Mustard	STCR				
	Target 2.5 t ha^{-1}	97	75	35	2281
	SR	100	40	40	1890
	FP	60	57	0	1312

STCR=Soil test crop response, SR= State recommendation, FP= Farmers practice

Source: Sharma *et al.* (1999)

Liming of acid soils

Lime seems to be having conspicuous effect in increasing the response ratios (Fig 9) of acid soils. The figure shows about three times improvement in the response ratio of maize, finger millet and wheat in the presence of lime. In another experiment, yield of soybean and wheat showed decline in unlimed plots even with NPK application, over the last three decades of long term fertilizer experiment (Table 24). Even in 150% NPK, there was a reduction in the yield. In NPK + FYM treatment plots, however, there was no yield decline due to non-application of lime over the years. This shows that organic manures can substitute lime where the lime application is not possible. Another problem is that liming effect on soil is not permanent and one has to go for repeated applications.

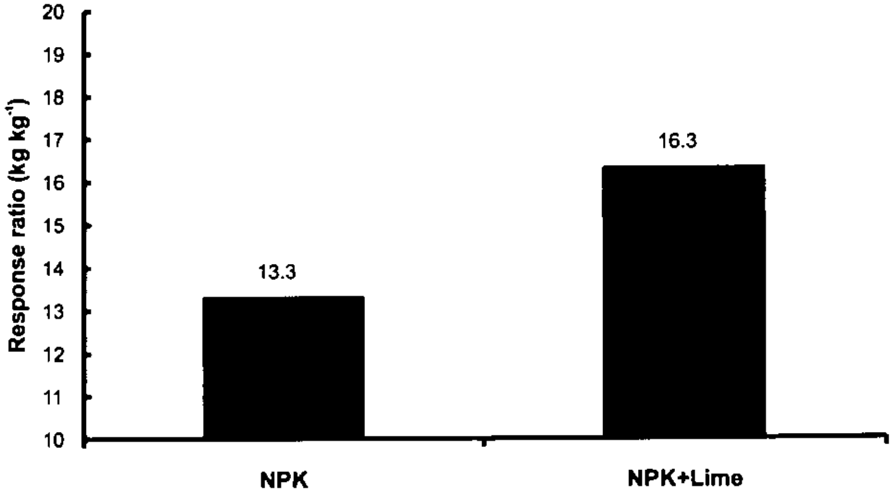

Fig 9. Average response ratio to applied NPK in cereals in presence or absence of lime (LTFE data)

Table 24. Average grain yield of crops (t ha^{-1}) as affected by long term (1973-2001) use of fertilizers, lime and FYM in an acid soil

Treatment	Soybean		Wheat	
	Grain yield	% change over NPK + lime treatment	Grain yield	% change over NPK + lime treatment
100% NPK	1.60	-12.3	2.65	-12.8
150% NPK	1.51	-14.2	2.80	-7.8
100% NPK+FYM	1.87	+7.2	3.19	+4.9
100% NPK+Lime	1.81	-	3.04	-
C.D. (0.05)	0.23	-	0.38	-

Source: Wanjari *et al.* (2004)

The effect of long-term application of N, NP, NPK, Lime and FYM in a maize-wheat rotation on an acid red loam soil (Paleustalf), Ranchi, showed that maize crop responded considerably to N, NP and NPK application over unmanured control during the first 18 years (Lal & Mathur, 1989a; b) and the magnitude of response increased in the order of application of nutrients. In contrast to NPK treatments, NPK plus lime (NPKL) or FYM gave higher yields of maize and wheat throughout the experimental period (1956-1984) by maintaining favourable soil pH. More than 871 trials on farmers' fields at various locations by Sharma and Sarkar (2005) demonstrated an incremental benefit of one tonne ha^{-1} by placing lime with seeding.

Reclamation of saline/alkaline soils

Over 1 million ha of alkaline/saline lands have already been reclaimed successfully in Haryana and Punjab and realized productivity of about 6 tonnes ha^{-1}. About 3 million ha more could be brought under reclamation in Uttar Pradesh, Bihar, Madhya Pradesh, Andhra Pradesh, Rajasthan, Maharashtra and Gujarat. The application of gypsum can increase the productivity of these soils by about 2 t ha^{-1}. The R&D efforts need to be stepped up to make reclamation technology cost effective through moderation of gypsum application rates and reducing cost on the drainage.

Integrated water management

Canal and ground water management

The estimated efficiencies of surface and ground waters are 35 and 70%, respectively and offer opportunities to enhance over all efficiency by their integrated management. The declining trend in ground water level can be reversed by encouraging ground water recharge measures, enacting law for community ground water rights and dispensation of populist policies of free power and water to farmers. Lining of canal irrigation network, surface and sub-surface drainage, biodrainage and proper on-farm water management are recommended to check the rise in water table. On an average about 25% of India's ground water resources are of poor qualities and can be used conjunctively with canal supplies or after amending.

Multiple uses of water for higher productivity

There are large areas of water logged lands (about 10 m ha) in many parts of the country allowing only one crop in a year with a very low yield potential of less than 1 t ha^{-1}. The low productivity of the land resource is the prominent cause of higher poverty in these areas. There is a need to switch over to integrated farming systems that could convert threat of water abundance into greater opportunities of income generation, employment enhancement and nutritional security. A number of diversified farming models integrating fish and prawn culture in dug out ponds, cultivation of vegetables and fruits, poultry, duckery, piggery, rabbitry and cattle on embankment have been evaluated at different locations and found quite promising. In these systems, marginal lands/ wet lands are generally brought into productive use, where pond serves as a focal point for direct or indirect links between other production components. The systems based on multiple recycling of carbon, energy and nutrients from biomass to livestock/poultry/piggery/fishery etc. also help minimize environmental loading with pollutants. The average net returns ha^{-1} $year^{-1}$ from these integrated farming systems may be 5-10 times higher than the prevailing monocultures. Such enterprising ventures need to be promoted in Orissa, Bihar, Assam, West Bengal, eastern Uttar Pradesh and many other areas having large water logged lands.

Use of saline water

The arid and semi-arid regions characterized by water scarcity have aquifers of geogenically low quality. About 32-84 % of ground water used in states representing arid and semi-arid, coastal and water logged regions is of poor quality. There are several agronomical and water quality amending options to use at least 10-15% of such waters to enhance productivity.

Use of waste water

The waste waters have traditionally been used as a source of irrigation to agricultural lands around cities. The waste water rich in organic matter and certain plant nutrients increases soil, fertility and crop productivity. India generates about 17 million cubic metres of sewage water per day with a potential to supply 1-1.5 million tonnes of plant nutrients annually while irrigating about 1.5 m ha of land. Results from long-term field studies (Juwarkar, 1991) have shown that on an average of 15 crops, the maximum productivity was obtained with primary treated sewage followed by diluted (1:1) ratio, untreated sewage and least with well or canal water irrigated crops (Table 25). Even with application of full dose of recommended N, P and K through fertilizers with well/canal water, the yield levels were relatively lower. The growth and yield of crops decreased further with increase in the proportion of dilution water. The nutrient utilization efficiency (9 kg of grain kg^{-1} nutrient) also increased considerably due to dilution of sewage and application of supplemental NPK through fertilizers. However, one has to look into public hygiene, sanitary, phyto-sanitary and food-safety considerations.

Table 25. Relative yield of crops irrigated with amended sewage and fresh quality water

Crops	Yield (t ha^{-1})			
	Well/ canal water	Untreated sewage	Primary treated sewage	Diluted (1:1) sewage
(a) Nagpur				
Rice	3.8	3.3	4.3	4.1
Wheat	2.8	3.1	3.4	3.2
Soybean	1.6	2.1	2.3	1.9
Greengram	0.6	0.5	0.8	0.7
Chickpea	1.2	1.3	1.5	1.4
Cabbage	13.3	14.8	16.4	15.7
Cauliflower	16.4	18.2	19.7	16.9
Okra	3.1	3.4	4.8	4.0
Tomato	13.7	15.5	16.4	16.1
Brinjal	9.1	12.1	12.7	10.1
Potato	6.4	7.1	8.1	7.1
Sugarcane	42.7	44.4	48.5	43.3
Marigold	5.1	7.1	7.6	-
Daizy	8.4	9.7	11.4	-
Jasmin	3.7	3.4	4.4	4.1
Average	8.8	9.7	10.8	9.9
(b) Poon Swage Farm				
Beetroot	8.7	16.2	-	15.6
Carrot	9.7	11.7	-	8.7
Radish	7.2	8.3	-	6.1
Potato	6.1	9.3	-	7.0
Ginger	6.0	9.8	-	9.1
Papaya	26.7	37.0	-	27.9
Knolkhol	9.7	16.5	-	11.7
Cabbage	9.2	12.1	-	11.3
Cauliflower	6.9	9.0	-	7.0
French beans	6.6	8.0	-	8.2
Tomato	10.0	13.3	-	-
Tobacco	1.1	1.2	-	1.2
Groundnut	2.8	2.9	-	2.9
Average	8.5	11.9	-	9.7

Source: Juwarkar (1991)

Improving rainfed agriculture

It is estimated that even after developing the full irrigation potential, nearly 50% of the total cultivated area will remain rainfed and important source of livelihood. The technological interventions in terms of improved seeds, fertilizer use, water conservation, harvesting and micro irrigation etc. have a potential to increase the productivity of rainfed areas by about half a tonne ha^{-1}. The improved practices on 20 million ha of such lands could provide 10 million tonnes of additional food grains. For best results, the management of rainfed areas should be viewed within the perspective of participatory watershed management programmes. The meta analysis of 311 watersheds spread over India has revealed mean benefit-cost ratio of 2.14 (Table 26). The internal rate of return was 22 percent which is comparable with many rural development programmes. Irrigated area increased by 33.6% and cropping intensity by 63.5 due to 13% reduction in run off and soil conservation @ 0.82 tonnes ha^{-1}. The programme fits very well in the framework of National Common Minimum Programme and Rural Employment Guarantee Schemes of the Government.

Table 26. Summary of benefits analysed by meta-analysis of 311 pilot watersheds implemented by various agencies in India

Indicator	Particulars	Unit	No. of studies	Mean
Efficiency	B/C Ratio	Ratio	128	2.1
	IRR	Per cent	40	22.0
Equity	Employment	Person days ha^{-1} $year^{-1}$	39	181.5
Sustainability	Irrigated area	Per cent	97	33.6
	Cropping intensity	Per cent	115	63.5
	Rate of run off	Per cent	36	-13.0
	Soil loss	t ha^{-1} $year^{-1}$	51	-0.8

Source: Joshi *et al.* (2005)

Crop diversification

Diversification of crops and farming systems is becoming essential for maintaining soil health, water balance and overall productivity in many parts of the country, especially in Indo-Gangetic plains. This has to be achieved in synchronization with the soil, climate, availability of water and market potential etc. The rice-wheat monocultures require to be replaced with legumes, oilseeds, vegetables, fruits, medicinal and aromatic crops and other cash crops. The ICAR has evolved a number of viable and productive cropping and farming systems for diversification in different agro-ecological zones of the country by the farmers. The Government should ensure market outlets for the produce.

Popularizing resource conservation technologies

Zero tillage, bed planting, ridge/furrow irrigation, laser land leveling, drip irrigation, mulching, fertigation and sprinklers need to be popularized with the farmers, particularly in Indo-Gangetic plains (IGP), for savings in irrigation water, nutrients, energy and planting time. The zero tillage and bed planting have already spread to about 2.5 million ha in IGP. These are targeted to cover 5 and 3 million ha, respectively in the next five years. About 28 million tonnes of paddy residues are being burnt in India to operationalize conventional zero tillage which leads to burning of nutrients and environmental degradation. Machines like Happy and Turbo seeders are able to pick up residues, shred into small pieces and create mulching after seeding. This avoids loss of nutrients, curtails germination of weeds, regulates soil temperature and conserves soil moisture.

Amelioration of open degraded forest and waste lands

The physically deteriorated open degraded forest/waste lands are to be managed through alternative institutions, leasing, contracting and social capital investments. The interventions could augment the productivity of these lands in terms of food, fuelwood, fodder, fiber and energy supplies. Degraded forest lands are ideal for ground water recharging to benefit agriculture and enhance their own productivity. The Government already has ambitious plans for bringing large chunks of these wastelands under energy plantations of Jatropha (Bio-diesel) and Pongamia.

Conclusions

The total factor productivity is decreasing under intensive agriculture in many parts of the country, especially Indo-Gangetic Plains. A number of factors are being ascribed for productivity decline including gradual depletion of soil fertility, rising and falling water tables, land degradation and associated environmental problems. The soil health is being impaired due to wider fertilizer consumption ratios and emerging secondary and micronutrient deficiencies. The depleting soil health is evidenced in the steadily decreasing nutrient response ratios. The measures suggested for reversing the productivity decline are soil test based balanced fertilizer use, integrated nutrient management (use of organic manures, composts and biofertilizers along with chemical fertilizers), reclamation of wastelands, integrated water management, improved rainfed farming, use of poor quality waters and multiple uses of water.

Future Research Needs

- Preparation of geo-referenced resource maps in terms of soil, surface, ground and waste water resources, cropping systems and intensity.
- Managing scarce resources in system perspective of soil, water, crop, livestock and recycling.
- Converging NRM and bio-technological research for harnessing synergies.
- Recycling of solid wastes, crop residues and waste water for public hygiene, better environment and production of safe food.

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Organic Matter Cycling and Crop Sustainability

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Abstract

Enhancing soil organic carbon (SOC) pool through humification of biomass is an important strategy to offset fossil fuel emissions, improve soil quality, increase and sustain agronomic productivity, and improves water quality. Increasing SOC pool requires biomass C supplied through crop residues and other biosolids, and soil availability of elements such as N, P, and S, without which the C-rich biomass cannot be converted into humus. Conversion of 10 Mg C into 17.2 Mg of humus would require 62 Mg of biomass, 833 kg N, 200 kg P, 143 kg S and small quantities of other minor elements. Thus, achieving global SOC sequestration potential of 0.6 to 1.2 Gt C yr^{-1} would require annual supply of 4 to 7 Gt of biomass, 0.05 to 0.10 Gt of N, 0.01 to 0.02 Gt of P and 0.009 to 0.017 Gt of S. The SOC thus sequestered would offset atmospheric CO_2 abundance by 0.28 to 0.56 ppm yr^{-1}. It is in this context that recommended management practices (RMPs) must involve soil application of crop residues and other biosolids as soil amendments, integrated nutrient management to achieve a positive and balanced soil nutrient budget, water conservation to enhance water use efficiency, and soil conservation to reduce losses of runoff and erosion. In addition to mitigating the climate change, carbon sequestration in soil and terrestrial ecosystems is also essential to achieving regional and global food security and advancing the U. N. Millennium goals.

Keywords: Conservation tillage, residue management, sustainable agriculture, food security

Increase in atmospheric concentration of CO_2, by 36% from 280 ppm during the pre-industrial era to 380 ppm in 2006 (WMO, 2006, Long *et al*., 2006), is a principal cause of global climate change (Kerr, 2006). The current rate of fossil fuel emission of about 7.1 Gt C yr^{-1}, along with additional 1.6 Gt C from tropical deforestation is increasing the atmospheric CO_2 abundance at the rate of about 3.3 Gt C yr^{-1}. Consequently, climate change concerns have made sequestration of atmospheric CO_2 a high priority for research and development. Carbon sequestration implies capture and/or transfer of atmospheric CO_2 and its storage into a long-lived pool. The objective of C sequestration is to reduce net anthropogenic emissions so that atmospheric concentration of CO_2 is stabilized at about 550 ppm. To do so would require total C sequestration of about 600 Gt by the end of the 21st century (Lackner, 2003).

There is a wide range of CO_2 sequestration options to balance the C budget for the 21st century (Fig 1; Lal, 2006a). Carbon sequestration technologies can be broadly grouped into three categories: engineering, chemical and biotic. Engineering techniques involve capture, liquefaction and injection of CO_2 into geologic formations and ocean. Geologic sequestration, with a large capacity, involves four options of injection into: (i) oil wells to enhance oil recovery (OIR), (ii) unmineable coal seams to recover coal bed methane (CBM), (iii) saline aquifer to form carbonates, and (iv) porous stable rock formation for permanent storage. While the cost is high, storage capacity in suitable formations may be hundreds or thousands of Gt (Dooley *et al.*, 2006). A principal concern is leakage, which requires careful measurement and monitoring. Similar to geologic injection, oceanic sequestration is also of four types (Fig 1) (i) 500 - 1000 m below sea surface, (ii) > 1000 m below sea surface, (iii) discharge form a pipe towed behind a ship, and (iv) pumping into a depression at the bottom of the ocean where it creates a liquid CO_2 lake (Seibel and Walsh, 2001). In addition to high cost, there are numerous concerns regarding the impact of CO_2 on marine life and biota (Auerbach *et al.*, 1997). Oceanic storage capacity, and stability of injected CO_2 against leakage to the atmosphere are limited (Lackner, 2003). Chemical options, transformation of CO_2 into stable chemical compounds, is a two-stage process: scrubbing and mineral carbonation. Scrubbing is a process of chemical absorption of CO_2 using an amine or carbonate solvent to produce pure CO_2. The CO_s thus recovered is chemically transformed into stable minerals such as magnesite, olivine, serpentine, etc. (O'Connor *et al.*, 2000). Relatively less known process of chemical sequestration involves weathering of rocks and minerals. Chemical weathering of Ca-Mg silicates (e.g., plagioclase, olivine, pyroxene) to clays (e.g., kaolinite, halloysite, allophane) cause net removal of CO_2 from the atmosphere due to transport of Mg, Ca and HCO_3 from the weathering sites via rivers to the ocean (Gislason, 2005). However, this reaction occurs at a geological timescale.

$$Ca\,Al_2\,Si_2\,O_8 + 2\,CO_2 + 3H_2O \rightarrow Al_2\,Si_2\,O_5\,(OH)_4 + Ca^{++} + 2\,H\,CO_3 \rightarrow Ca\,CO_3 + CO_2 + H_2O \quad \text{.........(Eq. 1)}$$

Biotic sequestration is based on the natural process of photosynthesis by which atmospheric CO_2 is transformed into carbohydrates, polysaccharides, lignin, suberin, cellulose and other stable compounds (Eq. 2.; Gislason, 2005):

$$106\,CO_2 + 16\,NO_3^- + HPO_4^{2-} + 122\,H_2O + 18\,H^+ = C_{106}H_{263}O_{110}N_{16}P + 138\,O_2 \ldots\text{(Eq. 2)}$$

Globally, photosynthesis transfers 120 Gt C into plant biomass annually. About 60 Gt is returned to the atmosphere by plant respiration, and another 60 Gt by decomposition of soil organic matter. However, a small fraction is converted into humus, which has a long residence time. Thus, terrestrial C sequestration is an important natural sink for atmospheric CO_2 (Pacala, 2001); and is an important strategy to mitigate global warming (Pacala and Socolow, 2004).

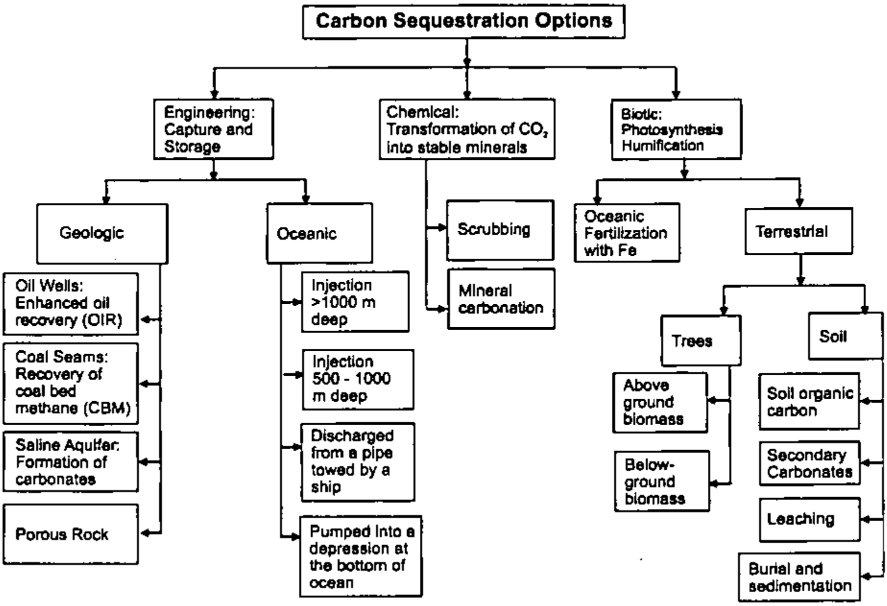


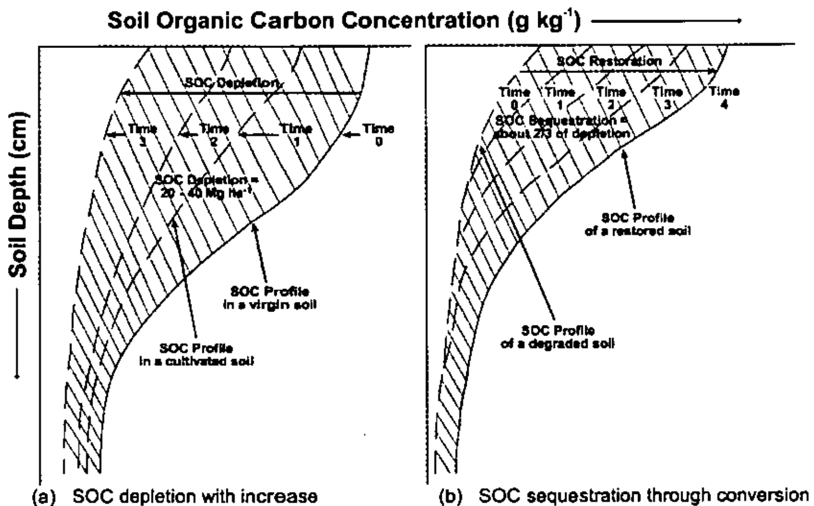
Fig 1. Carbon sequestration options to balance CO_2 budget for the 21st century and stabilize atmospheric CO_2 concentration at 550 ppm

The objective of this paper is to discuss the process of terrestrial C sequestration with a specific focus on C sequestration in agricultural soils, describe the importance of soil fertility management to achieve a balanced and positive nutrient budget, and discuss the need of recycling crop residues and biosolids for enhancing soil quality and C sequestration. A detailed review of literature on management of crop residues and soil fertility is beyond the scope of this manuscript. Therefore, specific examples of soil C sequestration will be cited from India and elsewhere in developing countries of the tropics and sub-tropics.

Agricultural Ecosystems as Source of Atmospheric CO_2

Cultivation of agricultural soils is not as obvious a source of atmospheric CO_2 as fossil fuel combustion, deforestation or biomass burning. Yet, conversion of natural to agricultural ecosystems has been a source of atmospheric CO_2 for 8,000 to 10,000 years since the dawn of settled agriculture, and of CH_4 for 5,000 years since the domestication of livestock and cultivation of rice paddies (Ruddiman, 2003; 2005). Soil disturbance by plowing or any physical manipulation accentuates mineralization of soil organic carbon (SOC) to CO_2 under aerobic conditions and CH_4 under anaerobic conditions. From 1850 to 1998, approximately 270 ± 30 Gt of C was emitted as CO_2 into the atmosphere from fossil fuel combustion and cement production (IPCC, 2000). In comparison, 136 ± 55 Gt of C was emitted into the atmosphere through tropical deforestation, drainage of wetlands and soil cultivation (WMO, 2006). Presently about 1.6 Gt of C is annually emitted into the atmosphere through tropical deforestation, biomass burning, drainage of wetlands and soil cultivation.

World soils constitute the third largest global C pool, estimated to contain 1550 Gt of SOC and 950 Gt of soil inorganic carbon (SIC) to 1-m depth (Batjes, 1996). Total soil C pool of 2500 Gt is about 3.3 times the atmospheric pool of 760 Gt and 4.2 times the biotic pool of 600 Gt. Conversion of natural to agricultural ecosystems leads to emission of CO_2 into the atmosphere. Most agricultural soils in temperate regions lose about 50% of their antecedent pool within 50 to 100 years of conversion of natural to agricultural ecosystems. In contrast, soils of the tropics may lose 50 to 75% of their antecedent SOC pool within 10 to 20 years of conversion to agricultural ecosystems (Lal, 2004, Fig 2). There is a close link between SOC pool and the atmospheric pool. One Gt of SOC pool emitted as CO_2 would raise atmospheric concentrations of CO_2 by about 0.47 ppm, and vice versa.



(a) SOC depletion with increase in duration of cultivation from Time o to Time 3

(b) SOC sequestration through conversion to a restorative land use and adoption of recommended menagement practices

Fig 2. Temporal changes in SOC profile as affected by land use and management. In general, the cumulative amount of SOC depleted is more than what can be restored. The attainable sink capacity is about two-thirds of the historic SOC loss

In contrast to the emission from fossil fuel, which is precisely documented at national and global scales, it is difficult to obtain accurate estimates of the amount of CO_2-C emitted through mineralization/gasification of SOC and SIC pools. Conversion of natural to managed ecosystems depletes the SOC pool (Fig 2a) because of a range of interactive factors. Important among these are: (i) less rate of biomass-C returned to the soil, (ii) replacement of deep-rooted perennials with a large below-ground biomass input by shallow-rooted annuals, (iii) increase in rate of mineralization of soil organic matter (SOM) due to changes in soil temperature and moisture regimes, (iv) reduction in activity and species diversity of soil fauna (e.g. earthworms) which reduces mixing and transport of SOM to sub-soil where it is protected, and (iv) increase in losses by erosion and leaching. Consequently, the magnitude of SOC depletion increases with increase in duration of cultivation until it reaches a new equilibrium level, which is only 25 to 50% of the antecedent SOC pool (Fig 2a; Fig 3a). The rate and magnitude of depletion are more in the soils of the tropics and those prone to accelerated erosion than those of the temperate climates. Agricultural practices that exacerbate the rate and magnitude of SOC depletion include plow tillage, drainage, residue removal, negative nutrient balance, summer fallowing, etc., (Table 1A). Global estimates of the historic loss of SOC pool range from 40 to 537 Pg (Lal, 1999). Ruddiman (2003) estimated that world soils contributed as much as 320 Gt of C as CO_2. Lal (1999) estimated that 66 to 90 Gt of CO_2-C is contributed by world soils, of which 19 to 32 Gt is contributed by accelerated soil erosion.

As a consequence of the historic C loss, SOC pool in world soils is lower than their potential capacity determined by climate and other pedologic factors (e.g., clay mineralogy and clay content, depth of weathering, internal drainage, landscape position, vegetation, mean annual temperature, precipitation and its seasonality). The deficit in soil C pool (deficit = C pool in a virgin soil - C pool in a cultivated soil), which equals the maximum soil C sink capacity, can be restored through conversion to a restorative land use and/or adoption of recommended management practices (RMPs). The rate of restoration of SOC sequestration depends on a range of interacting factors. Important among these are temperature (more in cooler than warmer climates), precipitation (more in humid than arid climates), soil (more in soils containing high amount especially of high-activity clays than those containing low amount and of predominantly low-activity clays), drainage (more in poorly drained soils of low permeability than excessively drained soils of low water retention capacity), and landscape opposition (more in soils located on foot slopes, than side slopes or summit positions). All other factors remaining the same, the rate of SOC sequestration and total sink capacity are lower than rate and cumulative magnitude of SOC depletion (Fig 2b). In most soils, SOC accretion occurs only in the surface layer, until the restorative land use and management practices (e.g., perennial land use with deep/tap root system and high biomass return) are followed for a long duration of several decades if not centuries. The rate of depletion follows an exponential decay curve until the SOC pool attains a new equilibrium at a very low level (Fig 3a). In contrast, the SOC accretion/sequestration follows a sigmoidal response characterized by low initial rates of accumulation (Fig 3b). For an equivalent duration of land use conversion, the rate of SOC depletion upon conversion from natural to agricultural ecosystem is generally more than rate of SOC sequestration upon adoption of a restorative land use and RMPs. Technological options which enhance SOC pool include no-till farming, retaining crop residue as mulch, controlled grazing at a limited stocking rate, water conservation and harvesting/ recycling, effective erosion control, cover cropping, agroforestry and complex rotations (Table 1B, Lal 2004; 2005b; 2006a). An important factor in SOC sequestration is maintaining a positive nutrient balance (Himes, 1998).

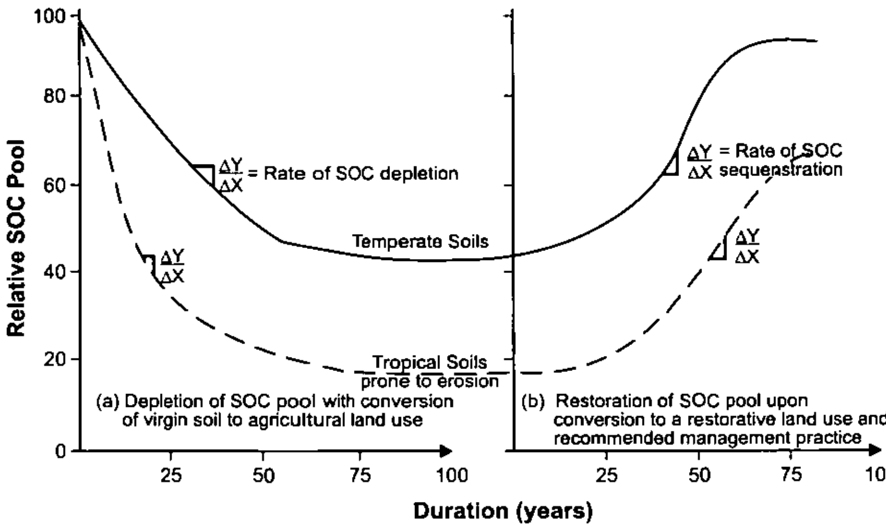


Fig 3. Schematics of the rates of SOC depletion and restoration for soils of temperate versus tropical climates. The depletion curve follows an exponential decay curve whereas the sequestration curve follows a sigmoidal response. The restored SOC pool may never reach the original level in soils which have lost the topsoil because of accelerated erosion

Positive Nutrient Balance for Soil Carbon Sequestration

Humification of C-rich lignocellulosic materials into nitrogen-rich soil humus requires availability of essential elements such as N, P, S among others. Humus is a complex material comprising a wide range of compounds with variable turn over times. Thus, humus concentration in soil depends on the availability of C provided through biomass and other building blocks comprising of essential elements. Assuming that soil humus has C:N ratio of 12:1, C:P ratio of 50:1 and C:S ratio of

70:1, Himes (1998) estimated that to sequester 10 Mg of C in humus would require 28 Mg of C or 62 Mg of oven dry residue, 833 kg N, 200 kg P and 143 kg S. These building blocks would produce 17.2 Mg of humus leading to increase in SOC concentration by 0.7% in the surface 20 cm or the plow layer. Extrapolating these results to global SOC sequestration potential of 0.6 to 1.2 Gt C yr^{-1} would require the following building blocks for humification of biomass: 3.7 to 7.4 Gt of biomass, 0.05 to 0.10 Gt of N, 0.012 to 0.024 Gt of P, and 0.0086 to 0.0172 Gt of S.

Table 1. Land use and management practices which affect soils organic carbon (SOC) depletion and sequestration

(A) Factors which exacerbate SOC depletion	(B) Factors which enhance SOC pool in agricultural soils
1. Plow tillage	1. No-till farming
2. Residue removal	2. Retaining crop residue as mulch
3. Excessive/uncontrolled grazing	3. Controlled grazing and limited stocking
4. Drainage	4. Water conservation, harvesting and recycling
5. Erosion prone practices	5. Erosion control and soil conservation
6. Negative nutrient balance	6. Positive nutrient balance with INM
7. Summer/bare fallowing	7. Growing cover crops and continuous cropping
8. Simple rotations	8. Agroforestry and complex rotations
9. Fertility maintenance by chemical fertilizer	9. Use of compost, manures, biosolids and fertilizers
10. Pest control by using pesticides	10. Integrated pest management by enhancing terrestrial biodiversity

The humus thus created would be equal to 1.0 to 2.1 Gt, and would offset the atmospheric concentration of CO_2 by 0.28 to 0.56 ppm yr^{-1}. However, C sequestration of this magnitude would need a vast amount of resources, and their availability must be carefully planned. With biomass production potential of 10 Mg ha^{-1}, land area dedicated to biomass production would be 370 to 740 Mha under intensive land and RMPs. In comparison, total amount of crop residue produced in the world is estimated at about 3.8 Gt (Lal, 2005b). Establishing biomass plantations (comprising warm season grasses, short-rotation woody perennials, evergreen shrubs, and saline culture of halophytes) on agriculturally surplus/marginal soils, and degraded/ decertified soils would be an important option (Lal, 2006b).

Nutrient management and recycling are also essential to SOC sequestration.

A positive nutrient balance would have to be achieved in all managed ecosystems. The net primary productivity (NPP) and, thus, biomass production may increase with increase in atmospheric CO_2 concentration. However, the controlling/limiting factors in CO_2 fertilization effect may be adequate availability of water and nutrients needed for enhanced plant growth (e.g., N, P, K, Mn, Cu). Some of the nutrients required for humification would be recycled through crop residues and soil application of biosolids (e.g., compost, sludge), applied through supplemental irrigation with surface water containing suspended and dissolved materials, added through biological nitrogen fixation by growing legumes in rotation or conjunction with cereals and non-leguminous species, and recycling nutrients from sub-soil by adopting simultaneous or rotational mixed farming systems whereby deep-rooted species are grown in synergism with shallow rooted crops. The strategy is to achieve a positive total elemental budget as well as for individual elements, especially for N, P, K, S and essential micro-nutrients.

Crop Residue Management

Removing crop residues for animal feed, residential fuel, and construction purposes has been a cultural tradition in most ancient civilizations. Crop residues, animal dung and other biosolids are still the main source of energy for about 3 billion people in developing countries (Ravindernath and Hall, 1995; Hoogwijk *et al.*, 2005; Lal, 2006b). Crop residue removal may have been a sustainable strategy when population was low and land rotation involving lengthy fallows could be used to restore soil fertility. Such extensive land use systems are presently not sustainable in view of the high population density, low per capita land area, scarcity of prime soil resources, and shortage of renewable fresh water supply. In the context of shrinking per capita land area and competing demands by industry and urbanization for soil and water resources, sustainable use of soil and water resources imply a quantum jump in crop yields per unit area, per unit time and per unit input of energy and other non-renewable resources. Thus, crop residues and other biosolids (e.g., compost, animal manure, urban waste, byproduct of food industry) must be returned to the soil for harnessing ecosystem services such as soil C sequestration, nutrient cycling, erosion and desertification control, water conservation in the root zone, increasing terrestrial biodiversity, denaturing pollutants (e.g., pesticides), and filtering pollutants out of the percolating water. Residue removal, for any purpose, is a luxury that the world with population of 6.5 billion and increasing at the rate of 1.3% yr^{-1} cannot afford. Yet, alternative sources of residential fuel, feed for livestock and construction materials must be developed. Land use planning and adoption of diverse farming systems is crucial to meeting needs of food, feed, fiber and fuel.

Soil Carbon Sequestration and Food Security

The world population and global food production have both increased drastically, especially since 1800. The population is projected to be 7.5 B by 2020, 9.4 B by 2050 and may stabilize around 10 billion by 2100. All of the future increase in population will occur in developing countries of Asia, Africa, South America and the Caribbean (Cohen, 2003). During the last 10,000 years, the world population doubled at least 10 times. However, it will never double again, because the increase in world food production, especially during the second half of the 20th century, has a strong stabilizing effect on world population. To meet the future demand for food, however, the global average cereal grain yield of 1.64 Mg ha^{-1} and total cereal production of 1267 million Mg in 2000 will have to be increased to 3.60 Mg ha^{-1} and total production of 1700 million Mg by 2025, and 4.30 Mg ha^{-1} and 1995 million Mg by 2050 (Wild, 2003). The required increase in grain yields (+ 35% by 2025 and + 58% by 2050) will have to be even more (+ 62% by 2025 and + 121% by 2050) if there were a shift in dietary intake of population in China and India from a primarily vegetarian to the one based more on animal protein. Because the CO_2 fertilization effect, if any, may be nullified by soil degradation (Schimel, 2006), such a quantum jump in food production will have to come through improvements in soil quality and restoration of degraded soils. Without bringing about a drastic improvement in soil quality, however, hunger and malnutrition which have plagued mankind since the beginning of time will continue to remain even a bigger concern during the 21st century. Global hotspots of hunger, where soil and resource degradation are also a problem (Brown, 2004; WRI, 2005), will perpetuate in South Asia, sub-Saharan Africa, the Caribbean and other regions in developing countries. Therefore, high crop yields must be achieved and sustained just to maintain the same level of nutrition and calorie intake because of the increase in population of these countries. It is in this regard that use of organic amendments and improvements of soil fertility (Smil, 2000) are essential to enhancing soil quality and increasing agronomic productivity.

There are only a limited number of experimental data available from the tropics relating SOC concentrations to crop yields. The results of available literature briefly summarized in Table 2, indicate significant increases in crop yields with increase in SOC pool. Kapkiyai *et al.* (1999) conducted a long-term soil fertility management experiment on a Nitisol in Kenya for maize-bean rotation involving three treatments: (a) using chemical fertilizers consisting of 120 kg N and 52 kg P $ha^{-1} yr^{-1}$, (b) applying cattle manure at 10 Mg $ha^{-1} yr^{-1}$ and (c) retention of maize stover. The highest maize and bean yields of 6.0 Mg ha^{-1} yr^{-1} were obtained when stover was retained and fertilizers and manure were applied compared to 1.4 Mg ha^{-1} when neither mature nor fertilizer were used. The SOC pool to 15-cm depth after 18 years was 23.6 Mg ha^{-1} with stover removal and 28.7 Mg ha^{-1} with chemical fertilization and stover retention. The highest rate of SOC loss of 557 kg C $ha^{-1} yr^{-1}$ with cultivation was observed in a treatment receiving fertilizer but without residue return (Table 3).

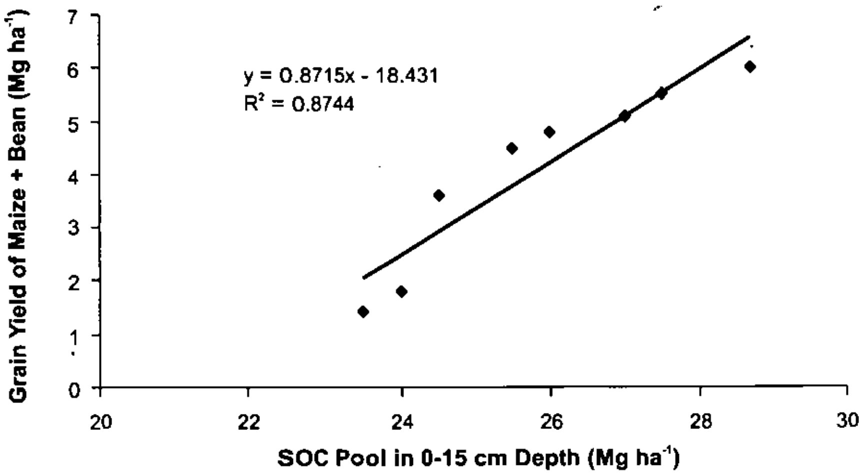


Fig 4. Relation between SOC Pool in 0-15 cm depth and combined yield of maize and bean on a Kenyan Nitisol (Redrawn from Kapkiyai *et al.*, 1999)

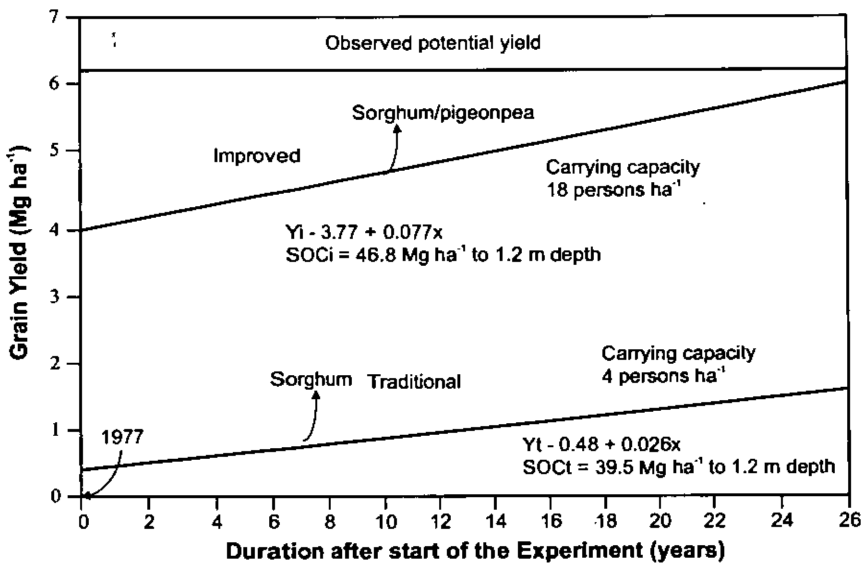


Fig 5. Grain yield from improved vs. traditional watershed management technologies on Vertisols in India (Redrawn from Wani *et al.*, 2003)

The strong and positive correlation between grain yield and SOC pool (Fig 4), indicate that grain yield increased at the rate of 871 kg ha^{-1} with increase in 1 Mg of SOC pool in 0-15 cm depth. Wani *et al.* (2003) conducted a watershed management experiment to identify systems for sustainable management of Vertisols in central India. They observed improved systems of management comprising integrated land management to conserve soil and water, water harvesting and storage to minimize drought, integrated nutrient management (INM) to improve soil fertility, and legume-based complex crop rotations. The average grain yield from improved system over a 24-year period was 4.7 Mg ha^{-1} yr^{-1} or about five times the average yield of 0.9 Mg $ha^{-1}yr^{-1}$ for the traditional system. The rate of growth in productivity between 1977 and 2002 was 77 kg $ha^{-1}yr^{-1}$ with improved management with a carrying capacity of 18 person ha^{-1} compared with 26 kg ha^{-1} yr^{-1} in traditional management with a carrying capacity of only 4 person ha^{-1}. Total SOC pool to 120-cm depth was 46.8 Mg ha^{-1} in the improved system compared with 39.5 Mg ha^{-1} in the traditional system (Fig 5). Crop yields in the improved system was approaching the maximum observed potential yield of about 6.4 Mg ha^{-1}. The increase in crop yield with improved system was due to a multitude of interacting factors such as inclusion of legumes in the cropping system which improved soil fertility, increase in water availability, and increased availability of nutrients other than N. An experiment conducted in Thailand also indicated a strong positive correlation between maize yield and soil organic matter content ($Y = 2.91 X + 0.2$, $R^2 = 0.88$ where Y is yield in Mg ha^{-1} and X is soil organic matter content in %) (Petchawee and Chaitep, 1995). Indeed, there is a critical level of SOC concentration below which soil becomes physically unstable, and prone to accelerated erosion, compaction, sealing, etc. The critical level may vary among soils, crops and the climate. Loveland and Web (2003) reported that the critical level is 2.0% for soils of the U.K. and elsewhere in the temperate regions. In contrast, Aune and Lal (1997) reported that critical level of SOC concentration was 1.1% for soils of the tropics. Juo *et al.* (1995; 1996) reported the effect of maize stover removal on soil properties and crop yields for an Alfisol in western Nigeria. Two crops of maize were grown per year for 12 consecutive years. Average maize grain yield with and without stover retention, respectively was 4.0 Mg ha^{-1} and 3.2 Mg ha^{-1} for the first season, and 2.9 Mg ha^{-1} and 2.1 Mg ha^{-1} for the second growing season. Soil quality (e.g., SOC concentration, earthworm activity and water infiltration rate) were high in soil with than without residue retention.

Increase in crop yields by improvements in SOC pool are attributed to numerous factors. Important among these are increase in soil structure, improvement in available water capacity, decrease in losses due to runoff and erosion, less susceptibility to crusting and compaction, increase in activity of soil fauna, and improvement in soil fertility. Positive and balanced soil nutrient budgets are needed (Sanchez and Swaminathan, 2005) to achieve the required yields listed in Table 4. Soil C sequestration is also an important strategy to achieve global food security (Lal, 2006c).

Table 2. Increase in crop yield with increase in soil organic carbon (SOC) concentration for some soils of the tropics and sub-tropics

Crop	Soil	Country	Δ Yield (kg ha^{-1} Mg^{-1} of SOC)	Reference
Beans	Kikuyu red clay	Kenya	243	Kapkiyai *et al.* (1999)
Cowpeas	Alfisols	Nigeria	20	Lal (1981)
Maize	Kikuyu red clay	Kenya	243	Kapkiyai *et al* (1999)
Maize	Alfisols	Nigeria	254	Lal (1981)
Maize	Alfisols (N.E. region)	Thailand	408	Petchawee and Chaitep (1995)
Maize	Inceptisol (Haryana)	India	210	Kanchikerimath and Singh (2001)
Mustard	Inceptisol	India	360	Shankar *et al.* (2002)
Rubber	Alfisol/Ultisol	Sri Lanka	66	Samarppuli *et al.* (1999)
Wheat	Haplustoll	Argentina	64	Diaz-Zorita *et al.* (1999)
Wheat	Inceptisol (Haryana)	India	38	Kanchikerimath and Singh (2001)

Table 3. Combined yield of maize and beans and soil organic carbon (SCO) pool of a Nitisol in Kenya

Treatment			Grain yield in 1994 Mg ha^{-1}	SOC pool to 0-15 cm depth (Mg ha^{-1})
Fertilizer	Manure	Stover		
0	0	+	1.4	23.5
0	0	0	1.8	24.0
0	+	+	3.6	24.5
+	0	+	4.5	25.5
+	0	0	4.8	26.0
0	+	0	5.1	27.0
+	+	0	5.5	27.5
+	+	+	6.0	28.7
L.S.D. (0.05)			1.1	2.0

Source: Recalculated from Kapkiyai *et al.* (1999)

Table 4. Average actual, projected and required cereal yields in developing countries

Year	Average cereal yield (kg ha^{-1})
I. Actual	
1988-1990	1900
1997-1999	2610
II. Projected	
2010	2600
2030	3600
III. Required	
2025	3600 (4400)
2050	4300 (6000)

Numbers in parentheses refer to the yields required to account for any dietary changes in population of China and India

Source: modified from Bruinsma (2003); Wild (2003)

Soil Quality and Food Production in India

The catastrophic forecasts of mass starvation during 1975 made by Paddock and Paddock (1967) and others did not come true. While doomsayers expressed apprehension and pointed fingers, agricultural scientists and farmers of India ushered in the Green Revolution. Consequently, the food grain production in India quadrupled over the second half of the 20th century, from 50 million Mg around 1950 to 200 million Mg in 2000. The wheat production in India increased from 6 million Mg in 1947 to 72 million Mg in 1999, with increase in average yield from 900 kg ha^{-1} in 1964 to 2300 kg ha^{-1} in 1999 (Swaminathan, 2000). There is a linear relationship between energy input and crop yield (Panesar, 1996).

Those holding neo-Malthusian views will be proven wrong again because the soils of India, similar to those of sub-Saharan Africa, have the capacity to increase production to meet the demand of the current and projected population expected to reach 1.5 billion by 2050. Principal strategies to realize the potential and increase crop yields, especially in rainfed production system, are: (i) restore degraded soils, (ii) create positive and a balanced nutrient budget through INM and enhance the nutrient use efficiency (NUE), (iii) conserve, harvest and recycle water and enhance the water use efficiency (WUE), and (iv) improve SOC pool by recycling crop residue, animal manure and other biosolids, and increase yield per unit of SOC pool. Technological options to implement these strategies are known, and will not be repeated here. However, policy, economics and the issues related to the "human dimensions" need to be addressed to put these concepts into practice. For example, subsidized price of nitrogenous fertilizers have discouraged the use of P and K leading to net nutrient deficit in soils of India due to mining of these elements by extractive farming practices. High crop yields can be obtained merely by a balanced use of N, P, K and some micro-nutrients (Roy, 2000). Crop residues, especially of wheat, are sold as fodder at a premium price. Whatever little residues and stubbles remain in the field are grazed by uncontrolled grazing. Furthermore, animal dung is used as a residential energy source (Table 5). Therefore, alternate sources of animal feed and household fuel will have to be identified so that these biosolids can be used as amendments to improve soil quality and enhance SOC pool.

Table 5. Estimates of traditional biofuel use Tg C yr^{-1} in India and Asia in 1995

Country/Region	Fuel wood	Cattle dung	Crop residue	Total	
				Range	Average
India	109 - 409	35 - 108	20 - 67	164 - 584	374
Asia	800 - 930	130 - 200	430 - 565	1360 - 1675	1018
World	1324 - 1615	150 - 410	442 - 707	1916 - 2732	2324

Source: Venkatraman *et al.* (2005)

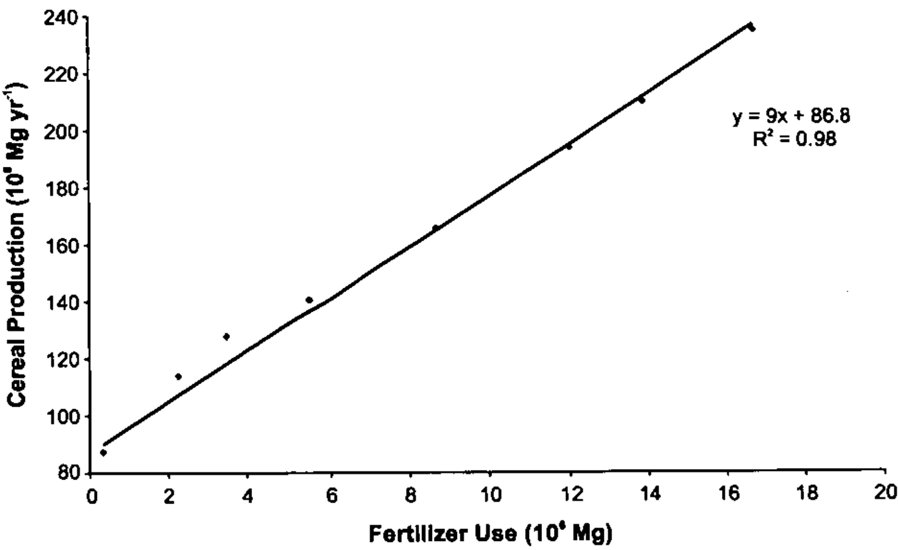


Fig 6a. Cereal production in India in relation to fertilizer use between 1961 and 2003 (Replotted from the data of FAO, 2005, and IFDC, 2004)

Impressive gains in food production in India since the onset of the Green Revolution in the 1960s were made due to increase in area under irrigation, and fertilizer consumption (Fig 6a, b). While environmental concerns, especially with regards to water pollution, have been raised by some, others have argued in favor of agricultural intensification to meet food needs of the growing population (Borlaug, 2002). Despite the impressive gains in national average yields of wheat and rice (Table 6), there is no cause for complacency. National average yields of most crops in India are low compared with those of China, U.S.A. or the world (Table 7). For example, the ratio of crop yield of India:China is 0.38 for maize, 0.50 for millet, 0.48 for rice, 0.75 for wheat, 0.31 for sorghum and 0.56 for soybeans. While part of the yield differences may be due to differences in climates and soil types, the importance of management practices among countries cannot be over-emphasized. Low crop yields in India are exacerbated by removal of crop residues for competing uses, and use of animal dung for residential fuel. Total amount of crop residues produced in India is about 440 million Mg, of which 90% is from cereal crops (Table 8). Total amount of nutrients contained in crop residues is about 19 million Mg of which NPK comprise 15 million Mg or 80% of the total nutrients. In comparison, total amount of NPK fertilizer used in India during 2003 was about 16 million Mg. Therefore, residue removal is a principal cause of nutrient depletion and elemental imbalance in soils of India. Residue retention is essential to improving soil quality, and to sustainable use of soil and water resources.

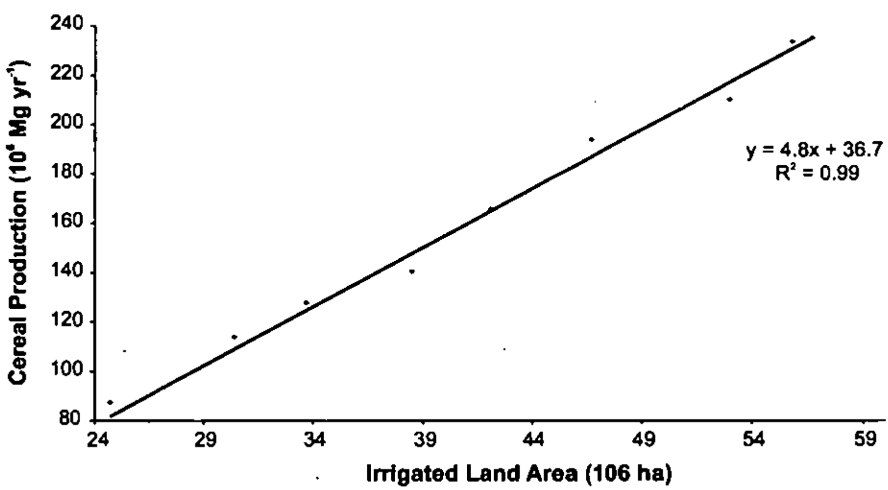


Fig 6b. Cereal production in India in relation to increase in irrigated land area between 1961 and 2000 (Replotted from the data of FAO, 2005)

Table 6. Increase in yields of rice and wheat (Mg ha^{-1}) in India between 1977 and 2005

Year	Rice	Wheat
1977	1.9	1.4
1987	2.9	2.5
1999	3.0	2.6
2000	2.9	2.7
2001	3.0	2.7
2005	3.0	2.7

Source: Adapted from Kaosa-Ard and Rerkasem (2000); FAO (2005)

Table 7. National average yields (Mg ha^{-1}) of principal crops in India compared with other countries

Crop	India	China	U.S.A.	World
Maize	1.77	4.67	3.60	4.23
Millet	0.75	1.51	1.11	0.76
Potatoes	18.07	16.32	42.79	16.59
Rice	3.01	6.23	7.11	3.90
Wheat	2.78	3.73	2.82	4.23
Sorghum	0.91	2.90	3.82	1.39
Soybeans	0.95	1.71	2.56	2.21

Source: Adapted from FAO (2000)

Conclusions

Soil carbon sequestration is an important strategy to address serious global issues of climate change, soil degradation, water quality and food security. In contrast to geologic and oceanic sequestration, the process of SOC sequestration is natural, economic, ecologically compatible and necessary to enhance soil quality. It also has numerous ancillary benefits such as reducing soil erosion and non-point source pollution, improving biodiversity and decreasing anoxia of coastal ecosystems. However, SOC sequestration requires: (i) application of crop residues and other biosolids as soil amendments, (ii) creation of a positive and balanced nutrient budget especially with regards to N, P and S which are essential for humification of biomass C and for plant growth, (iii) identification of alternative sources of animal food and residential fuel so that crop residues and animal dung can be used as soil amendment, and (iv) an enhanced awareness of farmers, land managers and policy makers about the need for restoration of degraded soils and ecosystems.

Table 8. Estimate of crop residue production in India in 2004

Crop	Residues (10^6Mg yr^{-1})[2]	Nutrients contained in residue (10^3Mg)[1]						
		N	P	K	Ca	Mg	All Nutrients	NPK
Cereals								
Barley	2.1	31.5	4.2	52.5	16.8	4.2	109.2	88.2
Corn	14.0	308.0	56.0	364.0	84.0	56.0	868.0	728.0
Millet	12.0	264.0	48.0	312.0	72.0	48.0	744.0	624.0
Rice	186.6	2239.2	373.2	4291.8	746.4	373.2	8023.8	6904.2
Sorghum	10.0	220.0	40.0	260.0	60.0	40.0	620.0	520.0
Sugarcane	61.3	257.5	490.4	490.4	367.8	245.2	1851.3	1238.3
Wheat	108.2	1406.6	108.2	2055.8	432.8	216.4	4219.8	3570.6
Subtotal	396.2	4726.8	1120.0	7826.5	1779.8	983.0	16436.1	13673.3
Legumes[3]								
Beans	3.0	36.0	3.0	21.0	48.0	3.0	111.0	60.0
Groundnut	7.5	90.0	7.5	52.5	120.0	7.5	277.5	150.0
Lentils	1.1	13.2	1.1	7.7	17.6	1.1	40.7	22.0
Chickpeas	5.8	69.6	5.8	40.6	92.8	5.8	214.6	116.0
Soybean	7.0	84.0	7.0	49.0	112.0	7.0	259.0	140.0
Subtotal	24.4	292.8	24.4	170.8	390.4	24.4	902.8	488.0
Oil Crops[4]								
Rapeseed	10.2	71.4	10.2	102.0	163.2	40.8	387.6	183.6
Safflower	0.1	0.7	0.1	1.0	1.6	0.4	3.8	1.8
Seed Cotton	10.8	378.0	43.2	313.2	302.4	86.4	1123.2	734.4
Sunflower	1.0	7.0	1.0	10.0	16.0	4.0	38.0	18.0
Subtotal	22.1	457.1	54.5	426.2	483.2	131.6	1552.6	937.8
Grand Total	440.7	5476.7	1198.9	8423.5	26534.4	11390.0	18891.5	15099.1

[1]Estimates of nutrient concentrations in crop residue are obtained from Lal (1995), and Singh *et al.* (2005)

[2]Estimates of crop residue production are obtained from Lal (2005a)

[3]Nutrient contents of soybean residues were used for all legumes

[4]Nutrient contents of sunflower were used for rapeseed and safflower

Despite the impressive gains in food production in India during the second half of the 20th century, even greater challenges lie ahead. The projected food demand for India may be 250 million Mg by 2010, 308 Mg by 2021 and 338 million Mg by 2025 (Table 9). In comparison with food grain production of 200 million Mg in 2001, increase in food production by 2011, 2021 and 2025, respectively, will be 20%, 39% and 46% for low food demand; 23%, 50%, and 64% for high food demand; and 53%, 87% and 105% for very high food demand. Achieving these targets would necessitate a quantum increase in food grain production through adoption of innovative technology. The required increase in food production would have to come through increase in crop yields in both irrigated and rainfed agriculture. Soil degradation, by nutrient depletion and erosion, is especially severe in rainfed agriculture where SOC concentration in the root zone is as low as 2 g kg^{-1}. Increasing SOC concentration, enhancing soil fertility, and improving soil structure and other determinants of soil quality can only be achieved through soil application of crop residues and other biosolids. The challenge of maintaining a positive nutrient budget can be met through using crop residues in conjunction with animal manure, biological nitrogen fixation, and chemical fertilizers.

Table 9. Present and projected food demand in India

Year	Food Demand (10^6 Mg yr^{-1})		
	Low	High	Very High
2001	206	206	206
2011	247	253	315
2021	286	308	385
2025	301	338	423

Source: Sekhon (1997)

Scarcity of arable land area in India necessitates restoration of degraded soils and ecosystems. Estimates of soil area prone to severe degradation include 33 Mha prone to water erosion, 11 Mha to wind erosion, 3 Mha to nutrient depletion, 3 Mha to waterlogging and inundation, and 4 Mha to salinization (FAO, 1994). Alarming as these statistics are, estimates of soil degradation by FAO are rather conservative compared with those made by ICAR and other institutions in India (Pachauri and Sridharan, 1999). Restoration of these soils would require application of biosolids to enhance SOC pool, improve soil structure, and increase available water capacity. Restored soils could be used for establishing biofuel plantations of kallar grass, mesquite, jatropha, mahua so that crop residues and animal dung can be used as soil amendments. Being at a cross roads, there is a strong need for India to change the culture of its agriculture from extractive farming to a sustainable and commercial enterprise.

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Characterization and Quantification of Micas and Smectites in Potassium Management of Shrink-swell Soils in Deccan Basalt Area

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Abstract

Despite the research initiative during the last two decades on the fundamental aspects of K release and adsorption/fixation in shrink-swell soils in relation to their layer silicates, hurdles in their proper characterization and quantification remained for a long time. Shrink-swell soils are dominated by smectite minerals and contain very small amount of sand, silt and clay size micas. Muscovite and biotite micas co-exist in these soils. Weathering of muscovite in presence of biotite is improbable. Thus there is a need for selective quantification of biotite in the common situation in soils containing biotite and muscovite micas. There is no precise method available for quantification of soil biotite. Recent study at NBSSLUP (ICAR), Nagpur, however, provides a reliable method to find out biotite content. The contents of sand and silt biotite are less in these soils and thus the presently available K status appears to be not sustainable for longer periods.

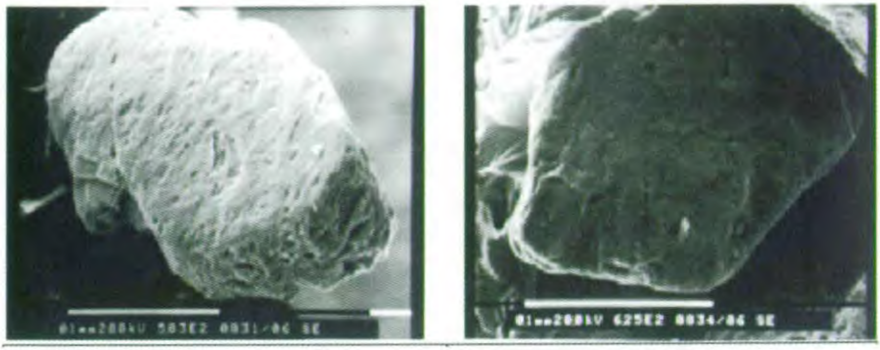
Potassium adsorption/fixation in shrink-swell soils does not appear to be sufficiently severe so as to conclude that potassium becomes completely unavailable to plants. The smectites of these soils belong more to montmorillonite of the montmorillonite-nontronite series and thus it is very difficult to reconcile that smectites can adsorb K selectively. The observed adsorption of K in these soils is related to the presence of small amount of vermiculite, which is generally not deleted on glycolation of Ca/Ca-saturated samples. Recent studies at NBSSLUP (ICAR), Nagpur in determining layer charge of smectites indicate their layer charge ranges from 0.28 to 0.78 mol(-)/$(SiAl)_4O_{10}(OH)_2$ and the low charge smectite constitutents >70% in them. The portion of higher charge with 0.78 unit and less appears to be due to the presence of small amount of vermiculite (5-9%). The actual quantification of fine-grained biotites of soils and the determination of layer charge of 2:1 expanding minerals appear to be mandatory to predict release of K and also to understand the intricacies of the adsorption/fixation of K in clay minerals, respectively, for sustainable K management of shrink-swell soils.

Keywords: Potassium release, mica, biotite, shrink-swell soils

There is a general belief that except for highly weathered ferruginous soils, most of the Indian soils are well supplied with K and for most crops there is a little need of K fertilizers (Pal *et al.*, 2001; Pal and Rao, 2002). In fact, crop removal of K often equals or exceeds that of nitrogen. Under intensive cropping with high yielding crop varieties and imparity in nutrient use, K from soils is getting depleted as is evident from a number of long-term field experiments conducted across the country (Swarup and Wanjari, 2000). Potassium is thus recognized as deficient nutrient after nitrogen and phosphorus in Indian soils. The potassic fertilizers in India are mostly imported and since the gap between removal of K and its application to crop is widening, it is all the more important that the country makes efficient use of them to conserve its foreign exchange.

The shrink-swell soils (Vertisols and Vertic intergrades) represent a large production resource in many countries, including India. These soils occupy a total area of 72.9 m ha in India (Murthy *et al.*, 1982). About 80% of these soils form a typical soilscape in the central Peninsula lying between 16-20°N and 73°40'-80°50'E. These soils are extensively spread in the states of Maharashtra, Madhya Pradesh, Andhra Pradesh and northern Karnataka. The majority of Vertisols in India occur in the lower piedmont plains or valleys or in microdepressions and are developed in the alluvium of weathering Deccan basalt (Pal and Deshpande, 1987; Bhattacharyya *et al.*, 1993).

Of the prime K-bearing minerals, only micas are more important than K-feldspars in supplying K to plants (Rich, 1972). As the Deccan basalt does not contain micas (Pal and Deshpande, 1987), the shrink-swell soils derived from its alluvium are not expected to be micaceous like the soils of the Indo-Gangetic Plains (IGP) (Pal *et al.*, 2001; Pal, 2003). The small amounts of micas in these soils are concentrated mainly in their silt and coarse clay fractions (Pal and Durge, 1987; Pal *et al.*, 2001) and their parental legacy is ascribed to erosional and depositional episodes experienced by the Deccan basalt areas during the post Plio-Pleistocene transition period (Pal and Deshpande, 1987). Petrographic and scanning electron microscope (SEM) examination of muscovites and biotites of these soils indicates little or no alteration (Fig 1) (Pal *et al.*, 2001; Srivastava *et al.*, 2002). Therefore, high available K status of these soils appears to be related to the retention of elementary layers of the micas that favours the release of K^+ even though its content is less. This suggests that the nature, content and weathering stages of micas have a definite role to play in K management.



(a) (b)

Fig 1. Representative SEM photographs of muscovite and biotite grains of Vertisols (a) a muscovite grain with general lack of interlayer opening, (b) almost unaltered biotite grain with tiny etch pits (Source: Nimkar, 2004)

Potassium adsorption/fixation in these soils is rarely related to the presence of vermiculite which is known to be the best fixer of added K. In routine identification of clay minerals in shrink-swell soils the presence of vermiculite may often be overlooked (Pal and Durge, 1987). Smectites do not have K selectivity as their layer charge is too low (Brindley, 1966) unless the charge density is high (Pal and Durge, 1989).

Despite the research initiative on the fundamental aspects of K release and adsorption/fixation in relation to layer silicate minerals in recent years (Pal *et al.*, 2000; 2001), hurdle still remains in their proper characterisation and quantification that are to be related to release and adsorption/fixation of K. Thus it is appropriate to see how such hurdles can be overcome in characterizing and quantifying the micas and 2:1 expanding minerals.

Characterization and Quantification of Fine-grained Micas

Shrink-swell soils are dominated by smectite minerals and contain very small amount of sand, silt and clay size micas (Pal and Durge, 1989). So far attempts made in highlighting the precise nature of soil mica in the silt and clay fractions have been based on the X-ray intensity ratio of peak heights of 001 and 002 basal reflections of mica (Pal *et al.*, 2001). The ratio is in general greater than unity in the silt but close to unity in the clay fraction (Fig 2a, b). The ratio >1 suggests the presence of both muscovite and biotite minerals. If muscovite minerals were present alone the ratio would have been very close to unity (Tan, 1982). In the event of a mixture of these two micas, both will contribute to the intensity of the 1.0 nm reflections, whereas contribution of biotite to the 0.5 nm reflection would be nil or negligible, thus giving a higher value to the intensity ratio of these reflections (Kapoor, 1972). Thus, silt fractions of the soils contain both muscovite and biotite whereas the clay fractions are more muscovitic in character (Fig 2b). The enrichment of soils with muscovite is not favourable so far as the K release is concerned. This is evidenced with the reduced rate of K release in these soils as compared to much higher rate of K release from biotite enriched soils of the IGP (Fig 3a, b) when they were subjected to repeated batch type of Ba-K exchange under identical experimental conditions. (Pal and Durge, 1989)

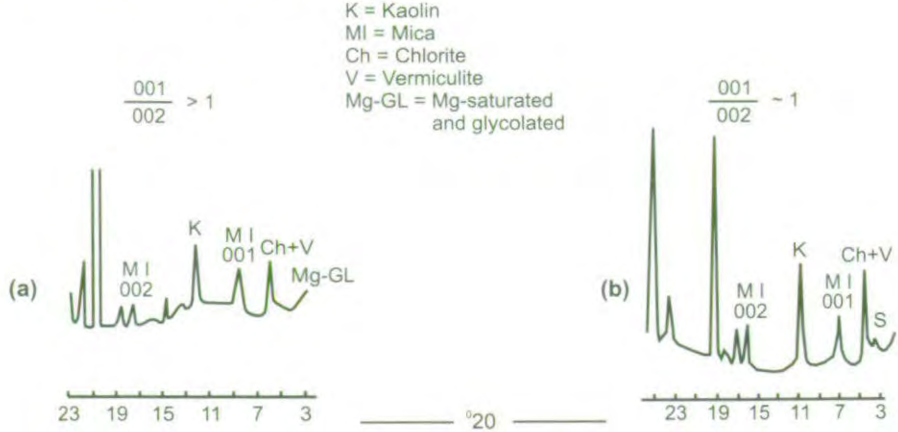


Fig 2. Representative XRD diagram of the silt (a) and clay (b) fractions of Vertisols (Source: Pal and Despande, 1987)

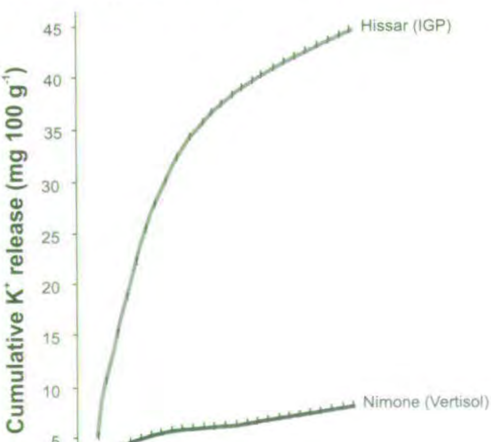


Fig 3. Relation between cumulative K release of soils and number of extractions (Source: Pal *et al.*, 2001)

Muscovite and biotite micas co-exist in soil environments. Weathering of muscovite in the presence of biotite is improbable. Therefore, the quantity of muscovite can not be used as an index of K reserve in soils (Pal *et al.*, 2001). Thus, Pal *et al.* (2001) pointed out a need of a selective quantification of biotite mica in the common situation in soils containing mixtures of biotite and muscovite for determining the stock of K in soils. However, till date no precise method is available for its quantification. Recently, Nimkar (2004) estimated the contents of biotite in shrink-swell soil and their size fractions through a rigorous and exhaustive Ba-K exchange reactions. The cumulative amount of K released at the end of final extraction by the soil's size fraction, when release of K almost ceased, was considered as released amount mainly from biotite (Fig 4). The amount of clay biotite, silt biotite and sand biotite in representative Vertisols of central India ranged from 1.0 to 1.6, 0.2 to 0.3 and 0.2 to 0.4%, respectively and it constituted 7-19, 2-3 and 2-5% of the total micas in respective size fractions. In <2 mm fine earth fraction, biotite quantity hardly exceeds 1% which constitutes about 6-8% of total micas. Nimkar (2004) reported that for any size fraction, the cumulative amount of K released on biotite weight basis > cumulative amount of K released on whole mica weight basis > cumulative amount of K released on weight basis of size fraction (Table 1). The fact that the K release of soils and their size fractions is mainly from biotite is realized from statistical analysis of bivariate data sets of several parameters that directly or indirectly influence K release. The significant positive correlations between cumulative K release from sand, silt and clay and their corresponding total K contents, respectively (Table 2) indicates that the K release is a function of total K content in micas and feldspars. However, the positive correlations between total K contents in sand, silt, clay and soil and their mica contents (Table 2) indicate the predominant influence of mica to supply K to the plants grown in the shrink-swell soils. Further significant positive correlations between cumulative K release of sand, silt, clay and soil and their respective mica contents (Table 2) indicate that the K release from either the soils or different size fractions are controlled mainly by mica. However, better correlations than these between cumulative K release of sand, silt, clay and soil and their biotite contents (Table 1) provide an incontrovertible evidence that the K release in soils is primarily controlled by biotite mica. This further supports the earlier observations on the inertness of muscovite mica in releasing K in presence of biotite (Pal *et al.*, 2001). Recently Nimkar (2004) reported the lack of notable difference in the cumulative K released by sand, silt and clay-sized biotite (Table 2). This is in contrast to the relation observed between cumulative K release and particle size of biotite by earlier workers

Table 1. Cumulative K release from a representative Vertisol and its size fraction

Horizon	Depth (cm)	Fine earth (>2 mm) cumulative K release in 75 extractions			Sand (2-0.05 mm) cumulative K release in 10 extractions			Silt (0.05-0.002 mm) cumulative K release in 35 extractions			Clay (<0.002 mm) cumulative K release in 60 extractions		
		SF	MB*	BB*	SF*	MB	BB	SF	MB	BB	SF	MB	BB
		mg K 100 g⁻¹											
Ap	0-15	69	429	6059	20	272	7000	16	191	7004	114	561	6990
Bw1	15-41	41	277	4230	12	162	7006	15	195	7009	92	509	6998
Bw2	41-70	39	267	4097	23	297	6997	13	184	7011	88	502	6999
Bss1	70-95	45	261	4638	15	191	6986	14	161	6990	91	433	7000
Bss2	95-135	49	286	4793	24	334	6991	15	162	6991	92	462	6999
Bss3	135-155	37	235	3849	13	147	6907	16	184	7008	94	471	6984

* SF = on the basis of size fraction; MB = on the basis of mica content; BB = on the basis of biotite content

Source: Nimkar (2004)

Table 2. Coefficient of correlation (r) between relevant soil properties

Parameter		r
Cumulative K of sand	Total K in sand	0.635**
Cumulative K of silt	Total K in silt	0.771 **
Cumulative K of clay	Total K in clay	0.822**
Total K in sand	Sand mica	0.933**
Total K in silt	Silt mica	0.766**
Total K in clay	Clay mica	0.981**
Total K in soil	Soil mica	0.979**
Cumulative K of sand	Sand mica	0.524*
Cumulative K of silt	Silt mica	0.694**
Cumulative K of clay	Clay mica	0.851**
Cumulative K of soil	Soil mica	0.429*
Cumulative K of sand mica	Sand biotite	0.894**
Cumulative K of silt mica	Silt biotite	0.917**
Cumulative K of clay mica	Clay biotite	0.978**
Cum K of soil mica	Soil biotite	0.435*

* significant at 0.05 level; ** significant at 0.01 level

Source: Nimkar (2004)

(Reichenbach 1972; Pal, 1985; Pal *et al.*, 2001). This indicates that large-sized biotite particles have lower K selectivity than finer ones. Comparable values of amounts of cumulative K released by sand and silt biotite (Table 1) indicate that not only the sand-sized biotite, but also some portions of silt-sized biotite of shrink-swell soils have more number of elementary layers along with more weathered biotite. This suggests that during the formation of Vertisols since the Holocene (Pal *et al.*, 2006), there has been no substantial weathering of biotite under semi-arid climatic environments. This validates the earlier hypothesis of Srivastava *et al.* (2002) that formation of Vertisols reflects a positive entropy change due to lack of any substantial weathering of primary minerals. The relevance of such combination of different stages of weathering of biotite (Fig 1) lies in the fact that both sand and silt biotites have highly favourable K release potential that is reflected in medium to high available K status of shrink-swell soils.

The study of Nimkar (2004) points out that the rigorously determined biotite content of each soil size fraction through exhaustive Ba-K exchange reactions can help to build up the permanent data set of biotite contents of shrink-swell soils developed in alluvium of weathering Deccan basalt. The data may also be considered as standard reference value of biotite mica present in shrink-swell soils for any further modelling work on K.

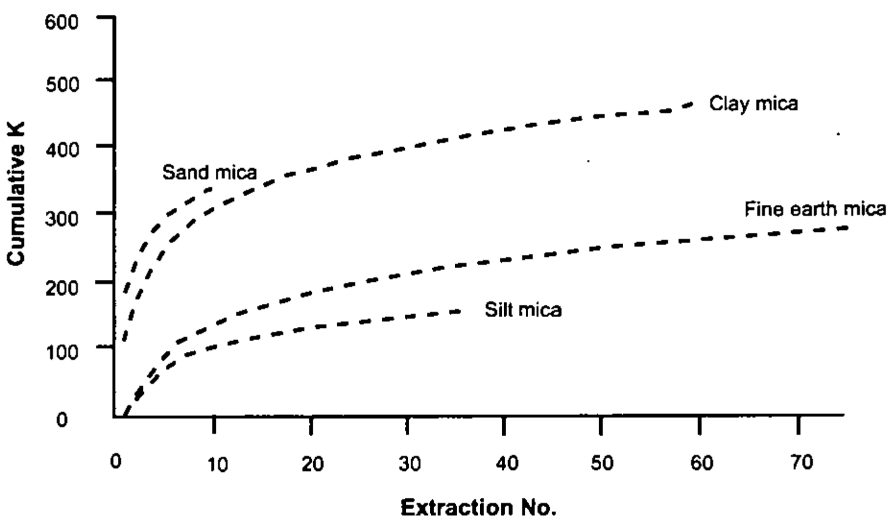


Fig 4. Relationship between numbers of extractions and cumulative K release (mg 100 g^{-1} mica) of micas in various size fractions of a Vertisol (Source: Nimkar, 2004)

Characterization and Quantification of K Fixing Layer Silicates

Potassium adsorption/fixation in shrink-swell soils does not appear to be sufficiently severe so as to conclude that K becomes completely unavailable to plants (Finck and Venkateswarlu, 1982). Review on the mineralogy of Indian shrink-swell soils (Ghosh and Kapoor, 1982) indicates that these soils are dominated by beidellite-nontronite type. Bajwa (1980) has reported that soil clay beidellites can fix more K than vermiculite, being nearly 80% against added K whereas clay montmorillonites can fix only about 18% meaning much less than the vermiculitic clays. However, the study on adsorption of shrink-swell soils of the Peninsular India (Pal and Durge, 1987) indicates that fine clay smectites adsorbed 50-60% of added K, amounting to 25-30 mg K/100g clay and this may apparently suggest that the fine clay smectites are close to beidellite (Bajwa 1980). Pal and Deshpande (1987) through a series of diagnostic methods (Fig 5) characterized fine clay smectites of shrink-swell soils as nearer to montmorillonite of the montmorillonite-nontronite series. However, it is very difficult to reconcile that smectites can adsorb K selectively (Brindley, 1966). Thus, further characterization of fine clay smectites (Pal and Durge, 1987) indicated the presence of vermiculites which is generally not detected on glycolation of Ca-saturated samples (Fig 5). However, the presence of vermiculite can be detected on the reinforcement of 1.0 nm peak region while saturating the samples with K^+ ions at 25°C and subsequent heating to 110°C (Fig 5). Similar experience has also been expressed by Ruehlicke (1985) while reporting K adsorption of 60 mg K/100g in bentonite (montmorillonite) deposit. Pal and Durge (1987) quantified the vermiculite following the method of Alexiades and Jackson (1965) and reported a value of 5-9% vermiculite in the fine clay fractions. They concluded that the observed K adsorption by the silt and clay fractions is not due to the presence of smectite but due to vermiculite. The smectites of shrink-swell soils are considered to be of low charge ones (Pal *et al.*, 2000) as they expand beyond 1.0 nm to about 1.4 nm with glycolation of K saturated and heated (300°C) samples (Fig 6). Recent studies in determining the layer charge by alkylammonium method (Lagaly, 1994) of such smectites (Ray *et al.*, 2003) showed the presence of both monolayer to bilayer and bilayer to pseudotrilayer transition (Fig 6). Thus smectites showed heterogeneity in layer charge density. The layer charge of half unit cell of smectite ranges from 0.28 to 0.78 mol(-)/ $(SiAl)_4O_{10}(OH)_2$ and the low charge smectite constitutes >70% in them (Fig 7). The position of higher charge with 0.78 unit and less appears to be due to the presence of small amount of vermiculite (5-9%) as determined quantitatively by Pal and Durge (1987).

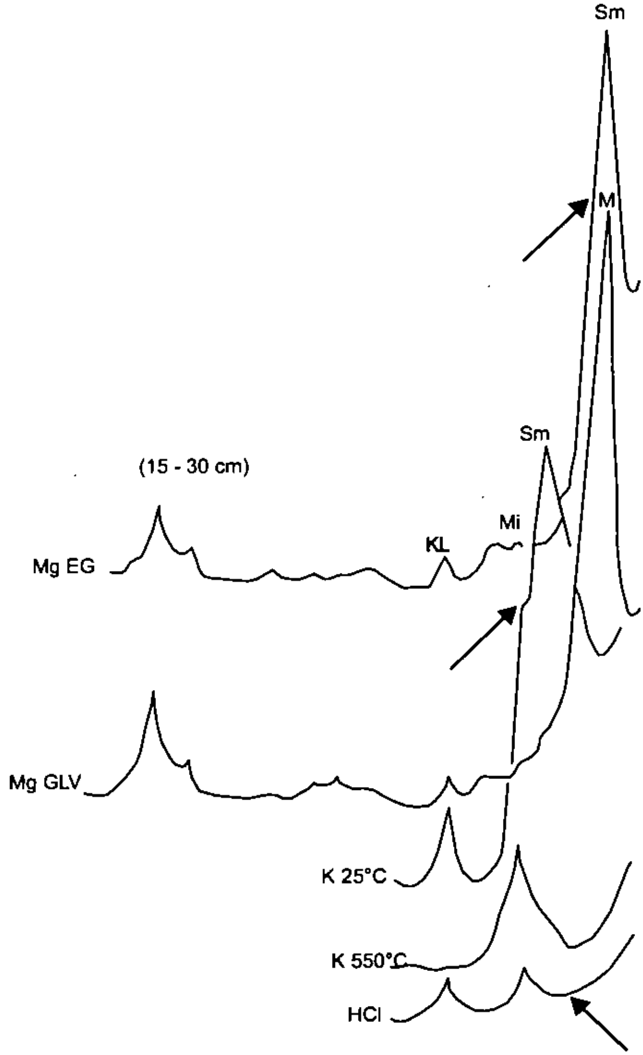


Fig 5. Representive XRD diagram of fine clay (< 0.2μ) fraction of Vertisols.On glycolation it expands to 1.7 nm indicating the dominant presence of smectite (Sm). With glycerol vapour treatment it expands to about 1.8 nm, indicating that the smectite is nearer to montmorillonite. On K-saturation, its 1.0 nm region gets reinforced, indicating the presence of small amount of vermiculite which is not detected on glycolation. With HCl treatment it is destroyed indicating the smectite belonging to montmorillonite-nontronite series (Source: Pal and Despande, 1987)

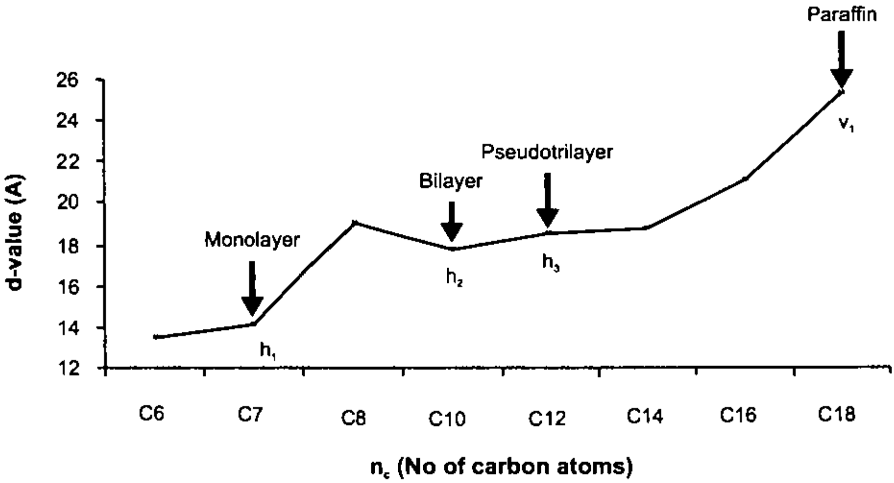


Fig 6. Representative XRD diagram of the fine clay smectite of Vertisols treated with alkyl ammonium chlorides (Source : Ray *et al.*, 2003)

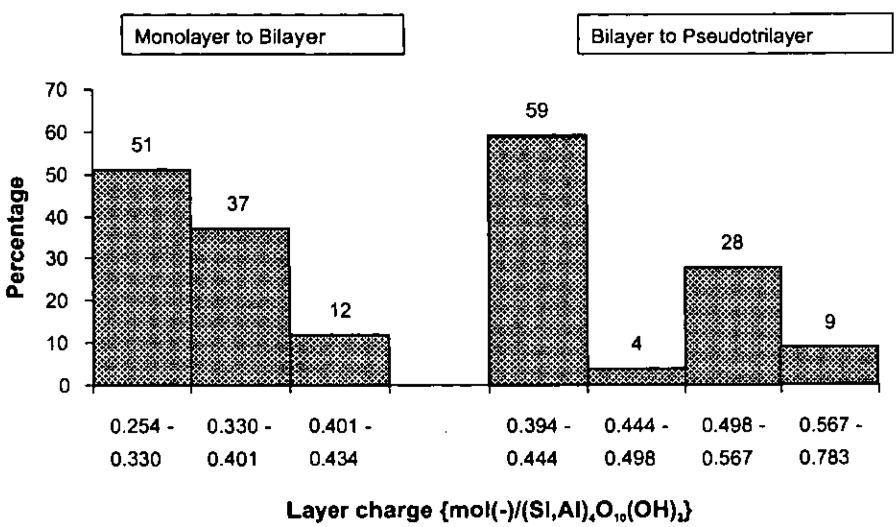


Fig 7. Distribution of layer charge in a representative fine clay smectite of Vertisols (Source : Ray *et al.*, 2003)

Biotite Content, Low Charge Smectite and K Management

It is generally stated that shrink-swell soils are adequately supplied with K and responses to applied K are rarely obtained (Finck and Venkatewarlu, 1982). However, agronomic experiments on shrink-swell soils of Central India (Nagpur) indicated crop responses to K fertilizer treatments after two years of cropping with hybrid cotton (Pal and Durge, 1987). Therefore, the presently available medium to high K status may not be sustainable for longer period, because the contents of sand and silt biotites are less. This information helps in dissolution of the myth that the shrink-swell soils are rich in available K that may not warrant the application of K fertilizers.

It is generally presumed that K adsorption/fixation in shrink-swell soils may not be severe (Finck and Venkatewarlu, 1982). However, this is in contrast to the reported presence of smectite clay minerals of beidellite-nontronite type (Ghosh and Kapoor, 1982), which are known for the fixation of K because they have a high layer charge and/or a high tetrahedral charge. Thus, the observed lack of K adsorption/fixation in shrink-swell soils (Pal and Durge, 1987) is due to the low layer charge of smectites (Ray *et al.*, 2003). This property along with the limited leaching of K in poorly drained shrink-swell soils is expected to favour availability of K ions mostly in labile form, i.e., in more available form. Therefore, dose of K fertilizer in such soils, if required, will be less due to small amount of vermiculite in these soils as compared to soils of the Indo-Gangetic plains endowed with considerable amount of vermiculite and high charge smectites. In addition, ammonium retention by low charge smectites of these soils is expected to be less and thus addition of K may not cause reduction in crop yield as experienced elsewhere with high charge smectite (Chen *et al.*, 1989).

Conclusions

A selective quantification of biotite mica in soils has been lacking. Recent study, however, provides a rigorous but reliable method to determine the biotite content. The biotite content obtained this way might be useful for modelling sustainability of available K vis-à-vis soil-micas. Such models might enable us to project K requirements of shrink-swell soils of the basaltic region. The determination of layer charge of smectites appears to be mandatory for a precise understanding of reactions relating to adsorption/fixation of K in soils for judicious application of K fertilizers.

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Mineralogy and Management of Soils Rich in Potassium-Containing Minerals

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Abstract

Soils, which have more than 1 percent K, are distributed over the Indo-Gangetic Plain, Australia, UK, China, USA, and many other countries. They are dominated by micas and feldspars groups of minerals. The potassium dynamics in these soils are enigmatic. Most of these soils showed negative K balance that accelerates weathering of soil-minerals. Recent advances in the rhizosphere research suggest that K can be taken-up by plant-roots and microorganisms directly from the solid phases of soil-minerals, although the exact mechanism is not yet known. The equilibrium thermodynamics of K movement in soil-plant system has been widely used, which is based on the principle that the rate-determining step is the rate of replacement of soil solution, and that there is a dynamic equilibrium between soil solution K, exchangeable K, fixed K, and mineral-K. It has been applied to an open system, where K moved unidirectionally from mineral to fixed to exchangeable to solution states; and rarely, loss from mineral state was compensated. This indicates absence of a steady state or real equilibrium environment; which perhaps precluded a rigorous application of theory to field situation. The chaotic dynamics (non-linear dynamical system) can be a useful tool to explain such phenomenon. It envisages that determinism does not imply either regular behaviour or predictability. The NDS has the capacity to utilize apparently noisy data, and helps to make short-term prediction and use data for controlling the system. It also makes it possible to link statistical mechanics with chaotic dynamics. The management protocol in the K-rich soils may be from the existing "crop response regime experiments" to "soil restoration of potassium regime experiments", and from agronomic "yield gain" mindset to eco-system "potassium dividend for nutritional security of man and animal" mindset. It must focus on identifying variables that control K dynamics, take-up task to understand weathering of soil minerals and soil mineral-soil organics interfaces to address soil fatigue.

Keywords: Equilibrium thermodynamics of K, nonlinear dynamical systems of K, release of non-exchangeable K, weathering of soil-minerals

Soil is the seat of civilization; potassium is the seed of heritage. Depletion of heritage leads to bankruptcy of civilization. So, almost all field and greenhouse experiments in the potassium-rich (≥1% K) soils (PRS) in the past decades focused on implications of K application for yields of crops and timbers. These experiments sometimes inferred significant contribution of potassium to yield formation, but in most of the cases, interpretations were short of insight or got lost in over simplified maze of hypotheses. In either case, farmers could not be persuaded to include potassium in their fertilizer treatments. In fact, non-application of potassium, which leads to imbalances in soil-plant continuum, is a serious global ecological concern in post 2nd World War agriculture and forestry (Maene, 1995. Bijay-Singh *et al.*, 2004). The grave situation of negative K balance (Table 1), even when K was applied to rice-wheat system in predominantly micaceous (illite in clay fraction) soils of the intensively cultivated Indo-Gangetic plain, was reported by Yadvinder-Singh *et al.* (2004).

Table 1. Negative K balance in predominantly micaceous (illite in clay fraction) soils of intensively cultivated Indo-Gangetic plain under K application regime (Data of a long-term rice-wheat experiment during 1988-2000 at the Punjab Agricultural University, Ludhiana) [a]

Treatments	Input				Output		Balance
	In-organic	Orga-nic	Other sources[b]	Total	Total uptake by rice and wheat	Loss[c]	(input output)
	kg ha^{-1}						
T1–Control; 0 N	600	0	1292	1892	2540	284	- 932
T2-Urea-N; 150 kg N ha^{-1}	600	0	1292	1892	3418	284	-1810
T3-GM+Urea-N	600	0	1292	1892	3407	284	-1799
T4-WS+Urea-N	600	732	1292	2624	3376	394	-1146
T5-WS+GM+Urea-N	600	732	1292	2624	3406	394	-1176
T6-FYM+Urea-N	600	972	1292	2864	3254	430	-820
T7-FYM+GM	600	972	1292	2864	3677	430	-1243

[a] Adapted from Yadvinder-Singh *et al.*, 2004 with modification

[b] Other sources = irrigation + rain + seed

[c] Loss is calculated as 15% of the total K input

Total N additions in T3, T5, and T6 were adjusted to 150 kg N ha^{-1} with urea. No inorganic N was applied to T7

Evidence suggests that all pre-life soils were dominated by mica; a principal group of K-containing (~ 5-8 % K) minerals and precursor to many descendant minerals; and perhaps 95 percent of the clay minerals of the world's soils are produced by weathering of micas (Fölster *et al.*, 1962). In fact, soils are prosperous in potassium only when they are thriving in potassium containing minerals. In these soils, minerals are the near exclusive supplier of K, and thereby, blossoms bloom at the expense of pedospheric potassium and every harvest depletes it. Potassium uptake by plants is detrimental to soils, and when produce from farm or forest fields moves to consumer zones, there is pedosphere-debt of K. In the eco-system escribe, over-drafting of pedospheric potassium has disastrous consequences, like rapid opening-up of cleavage planes of K-containing minerals, loss of active cation holding sites, leaching of silicic acid, and narrowing of Si:O ratio; all of which lead to weathering, which is detrimental to life support system. In ecological perspective, K loss is related to a larger issue of loss of bases, because of its intrinsic association with them. In a practical sense, if K loss is not compensated, or bio-consumed K is not recycled back to soil, then soil pH is lowered towards acidity.

Modern high-yielding crop species, genetically modified crop plants, and fast-growing tree species deplete more than 300 kg ha^{-1} of K from the top 0-15 cm surface soils (Yadvinder-Singh *et al.*, 2004). If the average potassium reserve in K-rich soils is calculated at 40 000 kg ha^{-1}, then at this rate the entire amount may be depleted in 125 years. Considering a history of more than 40 years of intensive cropping in developing world, and over 60 years of intensive cropping in developed countries, and vulnerability of these soils to the lack of response to K application, it could be discerned that many of these soils are depleted of K to the extent that irrecoverable pedosphere K debt might have spiraled into an ecological disaster without visible yield-symptoms.

In the coming decades, modern agronomic practices (e.g., use of carbon dioxide as fertilizer, precision irrigation and agriculture) are likely to deplete even more K from soils. Kubiske *et al.* (2006) exposed model aspen (*Populus tremuloides* Michx.) forest stands to an elevated atmospheric carbon dioxide ([CO_2]; 518 $\mu L\ L^{-1}$) concentration for 7 years using free-air CO_2 enrichment technology and observed that elevated [CO_2] increased tree heights, diameters, and main stem volumes by 11 percent, 16 percent, and 20 percent, respectively, none of which can occur without enhanced depletion of K. Similarly, Presley *et al.* (2004) had shown how 30 years of irrigation in the semi-arid region of Kansas triggered faster rate of mineral weathering in irrigated soils than their un-irrigated counterparts. Drainage practices also intensified weathering of soil minerals (Osterholm and Astrom, 2004). These findings could mean that increased rate of weathering in PRS involves loss of non-exchangeable K from crystal lattice of K containing minerals. The impact of the perceptibly accelerated depletion of pedospheric K requires to be studied in depth, and must be included in the future K trials. Another emerging outcome of depletion of pedospheric K vis-a-vis weathering of soil minerals is potential threat to ground and surface water quality. With every increment of rise of atmospheric CO_2, there is ten times higher increase of CO_2 in the soil atmosphere, which leads to higher concentration of carbonic acid in soil; a strong agent of mineral weathering. Mineral weathering causes release of ions from soil minerals to soil solution, and thereby leaves the solid phase depleted; often severely. A classic example of depletion of exchangeable K from surface soils due to decades of exploitative farming, and its subsequent recovery under application of fertilizer on an Udipsamments in New York was offered by Nowak *et al.* (1991).

The primary objectives of K management in K rich soils need to be 'restoring' of potassium to soil, in place of 'response' to plants; K dividend in plants/trees in relation to produce-quality and nutrition-security, in place of mere K uptake; and preventing solution (through leaching) and salt losses (through wind and water erosions) of potassium. Present chapter is an attempt in these directions.

Soil-Minerals Rich in K and their Geographical Distribution

The group of minerals that have K in their structures; in order of the amount of K they hold; are micas, feldspars, vermiculite, allophone and other poorly ordered aluminosilicates, zeolites, smectites, chlorites and hydroxyl interlayered expansible phyllosilicates, kaolinite and halloysite, potassium-tarankite, and potassium-alunite (Schroeder, 1978; Sparks and Huang, 1985). Amongst them, micas and feldspars are found almost universally and considered key groups of minerals that are principally responsible for K dynamics in soils.

It is important to place on record proper nomenclature and diagnostic criteria of mica group of minerals. The Clay Minerals Society (1971a, 1971b, 1979, 1984) and Association Internationale Pour L'Etude Des Argilles (1972) Nomenclature Committees define mica as a group of 2:1 phyllosilicate minerals with tightly held, non-hydrated interlayer cations balancing a high layer charge. Species reference of 'mica' used for macroscopic crystals is either dioctahedral (e.g., muscovite), or trioctahedral (e.g., biotite). Clay-micas with a particle size smaller than 2 μm equivalent spherical diameter often contain less potassium than well-crystallized mica, and are called illite (Martin *et al.*, 1991). Except for the revisions reported by Martin *et al.* (1991), Guggenheim and Eggleton (1988) and Guggenheim and Martin (1995), the treatise by Brown *et al.* (1978) should be followed for the nomenclature and for identification from X-ray peaks for all soil minerals. The weathering states of these minerals are illustrated with electron micrographs in the reviews by Graf (1972), Rich (1972), and Schroeder (1978).

Potassium dynamics in soil is controlled by the slow diffusion from the interlayer spaces formed by cleavage planes between mica layers into the soil solution, which results in cleavage at the weathering edges of mica (Hensel and

White, 1960; Marel, 1954; as cited by Jackson, 1964). Denison *et al.* (1929) (cf. Jackson, 1964) showed that on weathering of biotite, there is a gain in Al, Si, and H_2O content, oxidation of Fe, and loss in Mg and K. Jackson (1964) made a remarkable observation that silicic acid acts as a 'proton sink'. This is a key to driving the release of aluminohydronium ion from layer edges by H_2CO_3. Weathering situation is generally explained in the framework of Al_2O_3-SiO_2-H_2O; H_4SiO_4 for all soils, but especially in alkaline and neutral soils, and Al_2O_3 for the acid soils. The pH in combination with a rate limiting ion, which is K for most of the alkaline and neutral soils, is an essential variable. The rate limiting ion(s) are always be deduced from the mineralogical assemblages (Brinkman, 1982; Garrels and Christ, 1965; Velde and Meunier, 1987). The weathering of feldspars depends on crystal properties, solution properties, and over and above pedogenic properties (Schroeder, 1978).

Distribution: For effective K management, reserve K could be an index, and therefore geographical distribution of high-K soils is crucial for sharing and diffusing knowledge. Although K containing minerals are universally present in soils, the total K content exceeds 1% only in some regions. Compilation from the huge amount of data is difficult. Nevertheless, we found that the soils in the northeast, west-north-central, and south-west-central regions of US have high amounts of K. Soils on the east-south-central region of US have higher total K than Atlantic Coast in US, but both the regions are grouped into moderate K levels. The eastern corn-belt, the alluvial soils in the mountain and Pacific regions of US are also rich in K, and generally not responsive to K fertilizer application (Bertsch and Thomas, 1985). Red soils developed over granite parent material, soils developed over arenaceous shale, and soils under paddy in China are rich in K (Cao and Hu, 1995). The red and lateritic soils of India, on the other hand, are poor in K reserve, because they are developed over oldest terrestrial landmass, and have undergone tropical weathering process. The soils of the Himalayas spread over seven countries (Mukhopadhyay, 1987) and the soils of the Indo-Gangetic Plains (IGP) spread over three countries (Mukhopadhyay and Dutta, 2001) are high in reserve K. In general, the intensity of weathering decreases from west to east in IGP. Illite-vermiculite, illite-vermiculite-smectite, and illite-smectite/chlorite-kaolinite are principal clay mineral phases in IGP.

Concept of Potassium Availability

Equilibrium thermodynamics: The equilibrium thermodynamics of K supply mechanism in soil-plant system is based on the principle that the rate-determining step is the rate of replacement of soil solution (Brinkman, 1982), and that there is a dynamic equilibrium between soil solution K, exchangeable K, fixed K (popularly, boiling HNO_3 extractable fraction) and mineral K (Sparks and Huang, 1985).

Potassium supply to plants was thought to occur through concentration dependent K diffusion in the soil solution, and dynamic-kinetic mechanisms (Schroeder, 1974; Benipal *et al.*, 2006). Attempts were also made to explain K availability to plants through quantity-intensity relationships (Evangelou *et al.* 1994), or its derivatives, like K buffering capacity (Wang *et al.*, 2004), but with limited success. In some soils of the Uttaranchal Himalaya, that had high content of total potassium, but low status of available K, Ghosh and Singh (2001) observed that non-exchangeable fraction contributed significantly to plant supply, but dynamics of this fraction was difficult to explain. They opined that exchangeable K, non- exchangeable K, and clay mineralogy should be considered together, while making fertilizer recommendations for those soils, but offered no methodology to resolve such a complex issue.

Equilibrium thermodynamics has been widely used to explain phenomena in macroscopic systems. It has been applied to an open system, where K moved unidirectionally from mineral to fixed to exchangeable to solution states; and rarely, loss from mineral state was compensated. This indicates absence of a steady state or real equilibrium environment; which perhaps precluded a rigorous application of theory to field situation. Experiments were also constructed employing equilibrium methodology, but interpretations were stretched to the practical demands of an open system.

In understanding solid phase-solution equilibrium environment that exists in soils, thermodynamics is indispensable. Nevertheless, it is important to acknowledge that many of the challenges that essentially originate from natural soils; an open system in non-equilibrium state, are yet to be resolved. For example, Woodruff's (1955) assumption of activity co-efficients of Ca+Mg and K as unity in his theory on energy of replacement of Ca by K was found inadequate in some soils of Punjab. The activity co-efficients in the bathing solutions were 0.56±0.02 for Ca+Mg, and 0.85±0.02 for K (Mukhopadhyay *et al.*, 1992).

Rhizosphere concept: Recent research suggests that plant roots and microorganisms can directly lift nutrient ions from solid phase of minerals that includes so-called susceptible (easily weatherable) as well as non-susceptible minerals. There exists a close reciprocal relationship between plant root and soil micro-organisms, and therefore all soil-plant nutrient transport systems are to be seen from this angle. Jongmans *et al.* (1997) have shown that feldspars and hornblends in eluvial (E) horizons of podzols contain abundant narrow tubular pores ranging in diameter from 3 to 10 μm. In field soils these pores are sometimes occupied by fungal hyphae, and van Breemen *et al.* (2000) have suggested that these hyphae themselves are directly responsible for the spatially localized mining of the mineral grains. Scanning electron micrographs (Fig 1) of some the forest soils of U.K. (van Hees *et al.*, 2004) demonstrated *Paxillus involutus* plant roots deeply penetrated into the grains of feldspars. They had also shown that hyphae mobilization of Fe and Si by ectomycorrhizal fungus was positively correlated with hyphal length, soil respiration and concentrations of oxalate in the soil solution; and mobilization of Al was strongly correlated with plant weight. Scanning electron microscopy (Fig 1) revealed that most fungal hyphae were associated with mineral surfaces with little occupation of cracks and micropores within mineral grains. Kim *et al.* (2004) demonstrated that microorganisms can promote the smectite-to-illite reaction by dissolving smectite through reduction of structural Fe^{3+} at room temperature and 1 MPa pressure within 14 days (Fig 2). Trivalent iron bound in clay minerals can be an important electron accepter supporting the growth of bacteria in natural environments. It is essentially a K-capturing reaction.

Nonlinear dynamical systems: The enigmatic nature of potassium in soils may be examined through the theory of chaotic dynamics (nonlinear dynamical systems, NDS). The theory envisages that determinism does not imply either regular behaviour or predictability. The NDS has the capacity to utilize apparently noisy data (e.g., contradictory data of available K and reserve K in many benchmark soils of India, and also at other places; Sekhon *et al.*, 1992; Subba-Rao and Srinivasa-Rao, 1996), and helps to make short-term prediction and use data for controlling the system. It also makes it possible to link statistical mechanics with chaotic dynamics (Baker and Gollub, 1996). The application of NDS has been advocated for soil formation (Phillips, 1998), and also for modeling soil formation (Bridges and Mukhopadhyay, 2003).

There are many difficult to comprehend potassium-fluxes in the soil-plant system, and factors that influence them include soil, crop and climate, and chemical, physical, microbiological, biological, and geological processes. Experimental studies cannot embrace all these interactions simultaneously. To study complicated processes in the soil-plant system, whether by experimentation or simulation, they must be divided into subsystems. There exists a wealth of scientific information about the various potassium processes in different soils and plants. Some of these processes are described mathematically in considerable detail. Fundamentally, interpretation of experimental results and better understanding of the processes in the soil-plant system can be attained by the application of chaotic dynamics, especially by the application of 'self-organization'. It is an important feature of open nonlinear systems that are far from thermodynamic equilibrium and have energetic maintenance from the environment. Soil is an open and nonlinear system. It has a number of positive and negative feedback effects, and functioning of the processes is constantly supported by solar energy. Therefore, according to the laws of non-equilibrium thermodynamics, all the soil regimes including potassium must be self-regulated. In natural soils, steady stationary states of the soil regimes are established that are characterized by steady stationary values of the system variables, for example exchangeable soil K. Stationary means that the values of

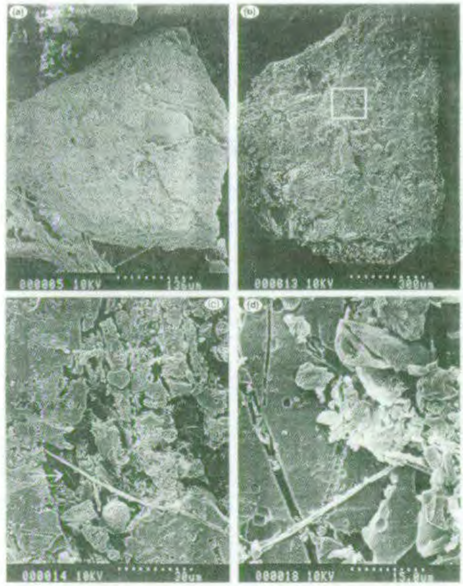

Fig 1. Scanning electron micrograph of soil with plant and *Paxillus involutus (M-)*: (a) Na (Ca) feldspar grain with hyphae on the surface; (b) Ca (Na) feldspar (with inclusions of Na and K feldspars) grain with hyphae entering a crack; (c) magnification of rectangle in (b), arrow points at possible interior hypha; (d) possible trace of hypha on mineral surface of Ca (Na) feldspar (Adapted from van Hees et al., 2004)

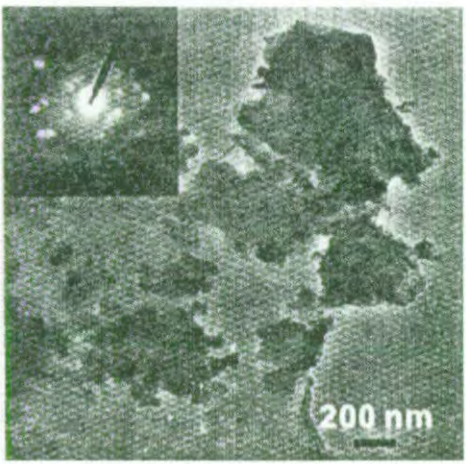

Fig 2. Transmission electron micrograph of bio-reduced smectite (Adapted from Kim *et al.*, 2004)

the system variables do not change with time. Their steadiness or stability means that the values of the system variables are outcome of self-organization of the soil system, which implies that if a natural soil is subjected to external influences then the processes and fluxes are directed toward the system variables returning to their steady state values. In fact, this self-regulation ability defines long-term dynamics of K in soil-plant systems, provided they are not subjected to strong external influences (Karpinets and Greenwood, 2003).

To comprehend dynamics of K, soil-plant system must be treated holistically, and sub-divided into components, each with realistic independent system-variables coupled with the processes, which tie these system variables. Structure and function of every component and their time hierarchy and interactions with the environment must also be taken into account (Karpinets and Greenwood, 2003). Bhonsle *et al.* (1992) deciphered relationships between K forms, and between them and release characteristics as functions of soil mineralogy in some benchmark soils of India (Fig 3). The striking feature of their work was use of various K forms and release characteristics as variables, and as functions of each other. A reexamination of their data shows non-linear relationships, which were perhaps masked into linear relationships because of large sample size. In the light of advances in the rhizosphere research and NDS theory, a modern K dynamics is proposed in Fig 4.

Weathering of soil minerals: It is well established that K dynamics is intrinsically related to weathering of soil minerals; especially K containing soil minerals. Therefore, attempts were made to develop theoretical values of weatherability of soil minerals using classical and equilibrium thermodynamics (Varadachari, 1992). These values, however, failed to explain field situations. For example, in some normal and experimentally-induced weathered soils of Punjab

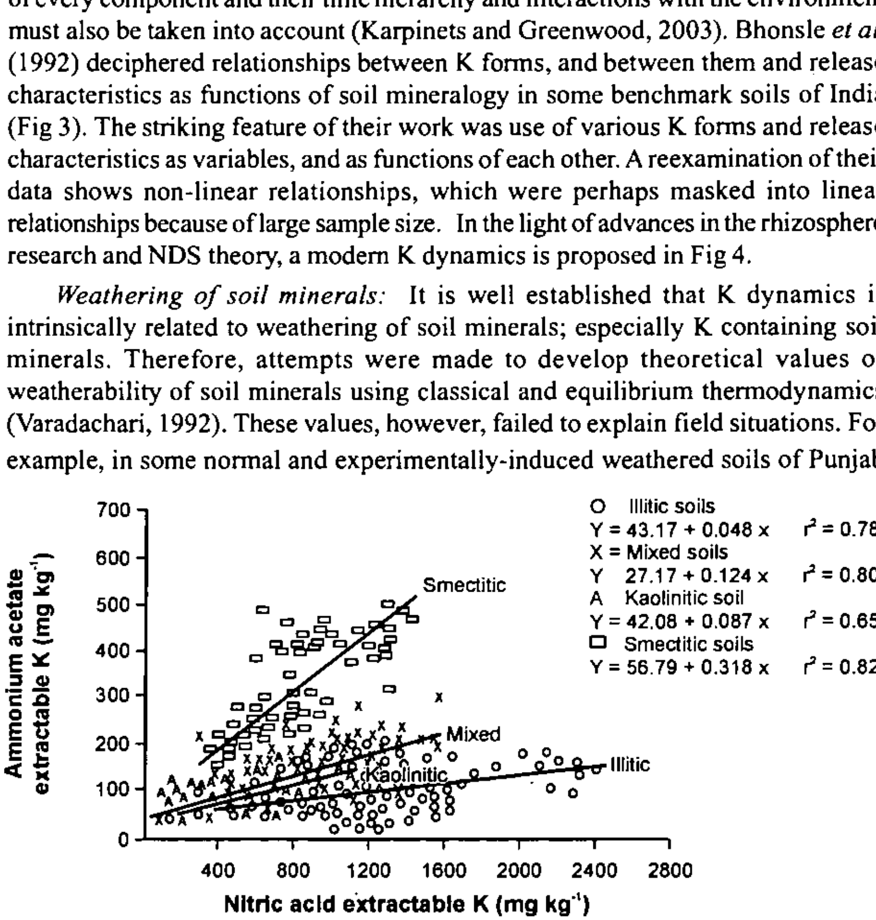

Fig 3. Relationships of forms of K with release characteristics in relation to clay Mineralogy (Adapted from Bhonsle *et al.*, 1992)

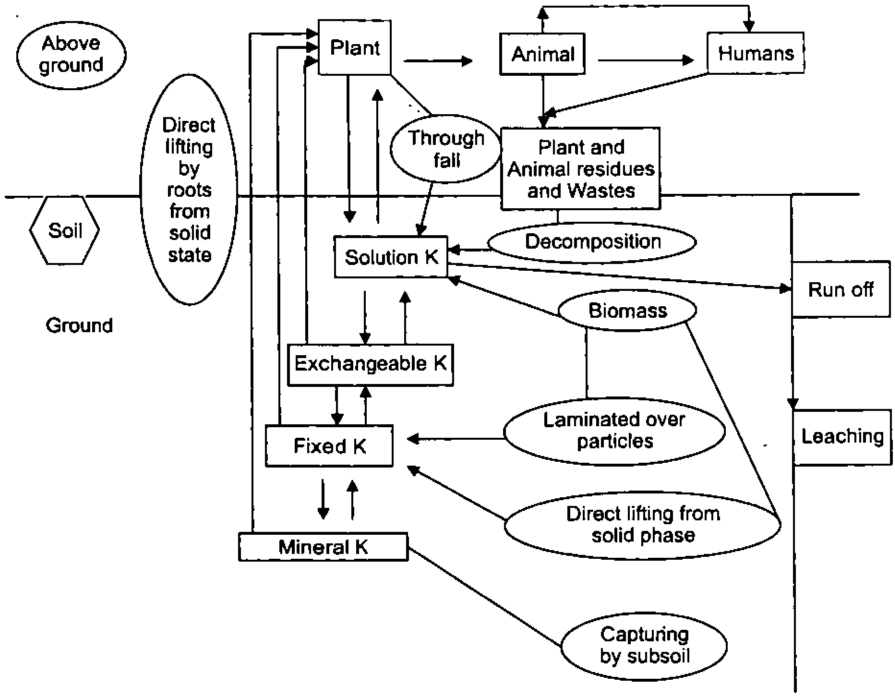

Fig 4. Proposed potassium cycle in soil-plant system

Himalayas, Bhardwaj (1999) obtained stability values (ΔG_d°) between 99 to 119 kJ for illites and between 103 to 117 kJ for vermiculite, while the corresponding values reported by Varadachari (1992) were 51.403 kJ and 127.94 kJ, respectively. The striking differences were perhaps because of use of ideal unit cell formula, assumption of perfect crystallinity of the mineral species, and contradictions inherent in the law of mass action that ignores variations in the selectivity co-efficients of the exchanger phase (Mukhopadhyay, 2005).

Some clay minerals significantly affect microbial life by modifying the physicochemical characteristics of microbial habitat, and through direct surface interaction (Theng and Orchard, 1995). The ability of microorganisms to weather soil minerals and transform nutrients may be substantially influenced by interactions with mineral colloids. Glowa *et al.* (2003) demonstrated that Piloderma (a broad host range ectomycorrhizal fungal genus) can extract K^+ and Mg^{2+} from biotite, microcline, and chlorite. This study provides a new insight into K management in soils.

It is generally thought that both hydrogen and organic acids drive the dissolution of susceptible soil-minerals, and many soil-minerals (e.g., feldspars, quartz) are difficult to dissolve. However, it is now found that high molecular weight humified acids (e.g., fulvic and humic acids) are less active in the weathering process than previously thought, which emphasizes the role of simple acids (e.g. citric and oxalic acids) (Drever and Stillings, 1997). These acids; released by the microorganisms, act as metal complexing agents, and thereby they enhance mineral dissolution (Boyle and Voigt 1973; Jones, 1998). Dissolution of orthoclase feldspars involves K release.

These studies highlight the importance of advancing theories of nutrient availability from the view point of soil mineral weathering.

Zeoponics: Zeoponics; a system founded on the concept of interconnected nature of all life-forms and life-support-forms; relies on recycling and operation of system-components. It opened new vistas in the traditional fields of agriculture and forestry by demonstrating that a system can be made self-supporting, and can supply nutrients to plants for a long time, if a balance is struck between loss and gain of nutrients. The system provides a framework where impetus and response are almost equal. This implies that the first law of thermodynamics can be translated to near implementation level in an open system. Soil minerals, like hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$] are successfully used for this system. Similarly, exchange of NH_4^+ and K^+ are regulated effectively through substituted clinoptilolite (Allen *et al.*, 1995; Ming *et al.*, 1995; Sutter *et al.*, 2002; Sutter *et al.*, 2003). Perhaps, they can be used to check K loss through leaching and to surface water bodies, and regulate K supply to plants and trees.

Assessing Potassium Supplying Power of Soils

Paradox of K rich soils vs. low/medium available K status: In many terrestrial soils which have high (> 1%) K reserve, traditional K availability methods show low K saturation (< 5%), or low to medium K availability (through chemical extractions, e.g., NH_4OAc). Incidentally, many of these soils do not show K deficiency symptoms, or respond to K application. Two outstanding compilations by Sekhon *et al.* (1992), and Subba-Rao and Srinivasa-Rao (1996) on the benchmark soils of India expose this paradox that a soil that contains large amounts of K as an essential part of its matrix may still fail to supply adequate amounts of nutrient to meet the normal needs of the plant. Out of the 29 bench mark soil series studied by Sekhon *et al.* (1992), 19 series had > 1% total K, out of which two series were low (< 0.128 cmol kg^{-1}), and 10 series were medium ($0.128 < x < 0.281$ cmol kg^{-1}) in available K status.

Release of non-exchangeable K: McLean (1978) advocated that non-exchangeable potassium moves to exchange sites, when exchangeable and solution forms are depleted from the system. Bhonsle *et al.* (1992) observed that among some benchmark soils of India that differ considerably with clay mineralogical make-up, the K supply power and release characteristics were more in illite dominated soils, followed by smectite and then kaolinite dominated soils. Within the soils of comparable mineralogical make-up, K supply power differed considerably, which reconfirmed that the coarse fractions of soils contributed to available K pool (Brar and Sekhon, 1986; Brar *et al.*, 1986; Parker *et al.*, 1989a, b; Rahmatullah and Mengel, 2000); a phenomenon rarely found for plant-nutrients other than K. An examination of their data indicated that K supply power varied with the mineral-species, and perhaps also with the intensity of weathering of the minerals.

One of the challenges in understanding K supply power comes from the K containing minerals. They hold cations at different sites with different tenacity. Two major approaches to deal with this situation are: (1) Ca-K exchange using binary and trinary exchange isotherms and thermodynamic parameters, and (2) quantity-intensity (Q/I) relationships. In K rich soils, Ca-K exchange showed very high to high K preference by the exchangers at low to moderate amounts of K in solution (Mukhopadhyay, 1996). Sparks and Huang (1985) explained that K^+ has a polarizability equal to 0.088 nm^3, which is higher than for Ca^{2+}, Li^+, Mg^{2+}, and Na^+ ions but lower than for Ba^{2+}, Cs^+, NH_4^+, and Rb^+. Ions with higher polarizability would be preferred by the exchangers in ion exchange reactions. The experimental techniques of quantity-intensity relationships are based on the concept that ion availability of a given ion can be described in the electrochemical potential gradients of that ion between the solid phase and the solution phase as well as between the solution phase and the root surface phase, or the electrochemical potential difference between the soil surface phase and the root surface phase. The intensity factors represented soil solution K. Quantity factors normally represent exchangeable K. But in soils rich in K, quantity factors have to take into consideration, apart from exchangeable K, pliable sites of non-exchangeable K. These sites have complex geometry, and the K rich soils do not satisfy the assumptions made (e.g., uniform distribution and bonding of charge sites of the exchanger, activity co-efficients of ions near unity) for successful use of Q/I relations analysis (Mukhopadhyay *et al.*, 1992).

Management Issues

Relationship with pedogenesis: In the neogenic soils, parent material has profound influence, and geochemical cycles predominantly govern the K dynamics. With the increasing maturity of soils, pedochemical cycles become the driving force of K dynamics. The foundation of Soil Taxonomy lies on this postulation. Only a few attempts have been made to deduce K management practices considering the series as a unit. The most valuable works were perhaps generated by the Potash Research Institute of India (Sekhon *et al.*, 1992). Bertsch and Thomas (1985) reported that parent material, climate, hydrological cycles, land use, and state of mineral weathering were the driving pedogenic factors in deciding K management in the soils of U.S. They described how these factors were more important than commonly-accepted factors like soil texture, organic matter, cation exchange capacity, base saturation, wetting-drying sequence, and crop. In a Himalayan catena, Sharma *et al.* (2006) noticed that spatial distribution of forms of potassium was related to land-forms, and recommended that K management under precision farming regime must adhere to land-form characteristics.

Relationship with soil organic matter: Since an overwhelming part (= 90%) of potassium resides in the soil minerals in fixed and lattice bound forms, very little role is ascribed to organic matter in interpreting potassium dynamics. In mineral soils, soil organic matter, which is measured through Walkley-Black's method, rarely exceeds 5%, and most often it is < 1%. Modern scientific evidence however, suggests that more than 90 percent of soil organic matter is dispersed among or bound to the surface of soil-formed (pedogenic) clay minerals (phyllosilicates), as indicated by strong correlations with surface area, data from physical separations, and microscopy (Derry, 2006; Kennedy *et al.*, 2006). The history of earth suggest that the radical evolutionary diversification of Neoproterozoic occurred due to enhanced burial of organic carbon, which protected it from reoxygenation, allowing a corresponding quantity of O_2 to accumulate in the environment. Kennedy *et al.* (2006) argued that late Precambrian oxygenation led to the inception of 'clay mineral factory'. The paradigm of K sheltering under mineral interlayer and lattice, may be looked at from this angle also to understand the exact role organic matter plays in governing K dynamics.

The K dynamics could possibly be tested from the paradigm advocated by Kennedy *et al.* (2006) that derives it from the elemental and mineralogical trends of loss of K relative to Al with a shift from tectosilicate-dominated (feldspars and quartz) system with minor amounts of illite-mica-chlorite accessory clays, to smectite- and kaolinite dominated system. Incidentally, there is strip in India from the Kangra valley in the central Himalayas to the Western Ghat on the coast of Arabian Sea that has similar mineralogical transition. Similarly, continental-weathering intensity allows us to suggest different behaviour of K dynamics to pedogenic clay minerals and detritus clay minerals.

From response to restore: Ever since Justus von Liebig graphed nutrient application to soils with uptake in plants in 1840, it has been ruling the field of nutrient management in general and K management in particular (Russell, 1973; p. 11-13). In long-term fertilizer experiment at Ludhiana (India) K application at the prevailing rate caused declining K uptake with years of cropping (Biswas and Benbi, 1997). Long-term fertilizer experiments in India had shown that with the application of K in K-rich soils, there is significant increase of yields of crops. But these observations have failed to translate their results to farmers. In fact, these experiments inadequately focused on soil system (loss of K from soils), and did not take into account the demand of eco-system.

From uptake to K dividend: Three hundred years of research on potassium showed that it has numerous beneficial roles in soil-plant-animal continuum, but no adverse roles to soils or to life forms or to terrestrial environment. Numerous publications by the International Potash Institute vouch for it. With the realization of inadequacy of feeding for a more humane 'food and nutritional security of human and livestock', K research needs to be reoriented from deciding-paradigm of 'K uptake in plant vis-à-vis yield benefit' to judging the remunerative content of K in food, fibre, and industrial raw materials. There is a need to redefine 'recommended doses of K'. Long-term fertilizer experiments in India and many other experiments (Yadvinder-Singh *et al.*, 2004) have conclusively shown a negative balance of K in soils due to anthropogenic farm and forest management practices. These practices require to be examined for environment audit.

Soil mineralogy centric precision farming: It is now universally accepted that the key mechanism of fluxes and dynamics of K is controlled by the weathering processes of soil minerals. However, the occurrence and state of soil minerals are rarely taken into consideration for planning experiments; more seriously, major conclusions are drawn without consideration of mineralogical variations between soils. Bhonsle *et al.* (1992) had shown how soils of comparable mineralogical make-up behaved similarly, and how soils of different mineralogical make-up behaved differently. As precision farming is becoming face of modem agriculture, variable K management recommendations must rely on spatial variability of mineralogy of soils.

Epilogue

Agricultural research in general, and soil science research in particular are moving at a fast pace. Perhaps, it is no exaggeration to state that this research arena is generating a knowledge explosion through new paradigms and new methodology, and offering new challenges to decades old belief systems that hindered acceptance of the agricultural disciplines in the larger scientific realm. Scientific research has always been and perhaps would remain "idea driven". It is unlikely to become "instrument driven". Nevertheless, with the greater accessibility to sophisticated instruments, scientists are able to gather new insight to shape their field experiments. Research on potassium management in soils-rich-in-potassium must capture this momentum. The time has come to switch over from "crop response regime experiments" to "soil restoration of potassium regime experiments". Potassium management research must reorient itself from agronomic "yield gain" mindset to eco-system "potassium dividend for nutritional security of man and animal" mindset. It must focus on identifying variables that control K dynamics, take-up task to understand weathering of soil minerals and soil mineral-soil organics interfaces. Many field trials, especially in the developing countries are based on scientific theories postulated in 19^{th} century (e.g., fertilizer and crop trials, routine elemental and mineralogical analysis of soils, and routine description of soil profiles). Time and again these experiments are showing sluggishness to be translated to the emerging demands of agriculture, forestry, and environment.

The other areas that require attention are that although the contribution of non-exchangeable K release to K availability has been studied extensively, the majority of the K release data in the literature have been reported for highly weathered, relatively acid, K responsive soils of moderate to high rainfall climates (Benipal and Pasricha, 2002). Renewed research efforts for upscaling the paradigm of Q/I theory, especially to amend it for variable bond sites of K, and asymmetric distribution of charge and deducing ion activity on the exchanger in K containing minerals must be future goal of research in this arena.

Let the slogan be "restore K to soil – store K in plants", and 'grow crops - regain soil quality'. Potassium research calls for:

Grow:	**Remember:**
P → Paddy,	P → Promote
O → Onion,	O → Organisms,
T → Tea	T → Treat
A → Apple	A → Agriculture
S → Soybean	S → Superbly,
S → Sugarcane	S → Soil
I → Indigo	I → Intimately,
U → Unjal	U → Unplug
M → Millets	M → Mind

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Integrated Nutrient Management through Precision Agriculture and Remote Sensing

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Abstract

Precipitation distribution and nitrogen (N) application determine biomass production, soil water depletion, and wheat grain quality in semi-arid regions. The overall goal of this research is to develop a new precision fertilization management strategy that accommodates spatio-temporal variability in wheat NPK requirements, for both base and top dressing N applications. Three options to quantify base application were tested: grid soil sampling, management zones, and previous crop N uptake. To determine the need for mid-season N applications, a decision support system (DSS) was developed. Remote sensing can assist in both management zone delineation and as a data source for the DSS. In all our experiments, adequate levels of P and K exist and prevent us from testing variable-rate application (VRA) of these nutrients. A combination of variable-rate N application at planting and at mid-season, according to the DSS recommendations, significantly improves nitrogen use efficiency (NUE), crop quality, and economic returns. The rationale is that applying N according to spatial patterns in fertility and crop productivity and to critical stages of crop growth is more efficient than a single large, uniform application, at or near planting.

Keywords: Nitrogen, phosphorus, potassium, precision agriculture, remote sensing

Precision agriculture (PA), or site-specific farming, is a system that aims to better manage farm resources; PA allows farmers to identify, analyze, and manage the spatial and temporal variability of soil and plants for optimum profitability, sustainability, and protection of the environment (Robert *et al.*, 1995). Part of its intensification of information relies on new sensing technologies that hold the promise of prescriptive rather than prophylactic treatment of crops (Zhang *et al.*, 2002). This paper briefly describes different aspects of PA crop nutrition management and remote sensing, focusing on wheat production in Israel.

Conventional Management

Wheat is an important grain crop and an important component of dryland agricultural systems. Grain protein concentration is an important standard for determining the end-use quality of wheat produced in Israel. In new identity-preserved marketing systems, growers now face the challenges of producing high quality wheat that meets buyer's specifications and documenting the end-use quality of what they have produced. Premiums are commonly paid for exceeding quality baseline levels, and penalties are imposed for falling below them (Bonfil *et al.*, 2004b). This quality system is essential to maintain one's reputation as a reliable supplier of high quality grain thus preventing loss of market share. Wheat that does not meet quality standards is usually sold at a discount in other markets that have lower quality requirements. However, grain quality standards are not consistently met in any given year due to adverse weather, being this the overriding factor controlling grain test weights and protein concentrations. In the northern Negev of Israel, for example, wheat often suffered droughts, which have restricted yields and affected grain quality. Many growers have been unable to benefit from price premiums because of low quality grain with shriveled kernels and low test weights. In years with good moisture, wheat yields have been less restricted, but this has also led to low grain quality with kernels below standard limits for protein concentrations. Under conditions of abundant water content, low grain quality has been attributed to dilution of grain protein by larger grain biomass (Terman, 1979). Consequently, producers may not capture price premiums in wet years with high yields.

Proper management of fertilizer is important for maximizing wheat yield and quality. Therefore, the most profitable strategy for dryland wheat is to add just enough NPK to reach the yield potential. Growers may apply N fertilizers to control grain yields, test weights, and protein concentrations (Grant and Flaten, 1999). Traditionally, growers rely upon the conventional practice of applying the fertilizers required for crop needs all at once during, or near the time of seeding. Common fertilizer management in crop production is based on a uniform NPK application and does not account for spatial and temporal variability of plant response to environmental conditions (Raun and Johnston, 1999). Natural and acquired variability in production capacity within a field will cause the average rate to be excessive in some parts and inadequate in others. This practice leads to unnecessary over application of NPK, excessive N leaching and potential ground water contamination by NO_3-N, and even to reduction in yield and/or yield quality. On the other hand, adjacent areas may remain nutrient deficit, resulting in reduced yield and decreased quality. Worldwide, two-thirds of every metric ton of N applied to cereals by conventional fertilization practices are not consumed for plant growth, but instead they are lost from soil-plant systems via gaseous plant emission, soil denitrification, surface runoff, volatilization, and leaching (Raun and Johnson, 1999). Topography modifies crop yields, due to the redistribution of water and soil materials, and thus the temporal variability in crop yields and grain quality ought to be predictable (Moore *et al.*, 1993; Gessler *et al.*, 2000). Field (elevation, slope, rotation etc.) and soil (fertility, organic matter, tillage etc.) variability that significantly influence agricultural production (crop and yield variability) are not usually treated by conventional management.

Precision Management

Precision NPK management is a relatively new cropping practice that combines navigation and variable-rate application (VRA) technologies to place fertilizers in fields according to spatial patterns of soil productivity. The new approach benefits mainly from the emergence and convergence of several precise technologies, including the global positioning system (GPS), geographic information system (GIS), miniaturized computer components, automatic control, in-field scouting and remote sensing, mobile computing and advanced information processing (Pierce and Nowak, 1999). Variable-rate nutrient application to meet plant needs as they vary spatially across the landscape, promises to accommodate spatial variability in production potential within fields (Raun and Johnston, 1999).

Recent studies have demonstrated that variable-rate fertilizer applications that specifically target low to moderate fertility sectors in dryland wheat production systems are economically prudent, even when dry conditions prevail (Mulla *et al.*, 1992; Long *et al.*, 1995; Long and Engel, 1998; Long *et al.*, 2000). Moreover, differentiated N management has been shown to increase the N use efficiency (NUE) of crops (Stone *et al.*, 1996). Variability management can be achieved through two approaches: the map-based approach and the sensor-based approach. Due to the availability of such technologies as GPS, remote sensing, yield monitoring, and site specific soil sampling, the map-based approach is generally easier to implement. This approach requires the following procedure: grid sampling the field, laboratory analysis of soil samples, generation of a site-specific map, and finally, use of this map to control a variable-rate applicator. Spatially variable application of inputs to field crops requires specific spatial (GPS aided) application equipment, or sub-division of a field into management zones (MZ): areas that show relatively little internal variation and which may be treated uniformly.

A detailed fertility map is needed before precision NPK fertilization can be successfully implemented for a given field. To produce an accurate fertilization map, intensive soil sampling is required as a base for variable-rate fertilizer management (Mallarino and Wittry, 2004). The number of sampling points in a field is derived from the temporal variability and the autocorrelation between points

(Pierce and Nowak, 1999). This autocorrelation is given by a semi-variogram, which relates variability with distance. Since the available P and K content in the soil is related to soil characteristics, high autocorrelation usually exists and fewer sampling points are needed to prepare accurate maps representing their spatial variability. This is illustrated in an example for available NPK from a field in Israel (Fig 1), where it can be seen that P and K variability ceases to have any effect beyond a range of about 140 meters, meaning that samples should be collected within that distance. For this case, even the lowest available P and K content in soil was suitable for wheat growth, therefore the field was not spatially treated for P and K. On the other hand, in many fields no strong autocorrelation exists for the available levels of N. This prevents development of an accurate map, without a much greater number of samples. Based on poor N autocorrelation, it could be said that samples should be taken every 50 meters, at least. In most situations such extensive soil sampling is too costly, relative to the value of the wheat. Hence, commercial application is limited. Therefore, field sampling based on known MZ is an option for decreasing costs.

Site-specific applications of agricultural inputs can be implemented by dividing a field into smaller management zones that are more homogeneous in properties of interest than the field as a whole. A management zone is defined as a portion of a field that expresses a homogeneous combination of yield-limiting factors for which a single rate of a specific crop input is appropriate. Thus, management zones within a field may vary for different inputs, and therefore, delineation of management zones for a specific input involves only the factors directly influencing the effectiveness of that input in achieving certain goals. Management zones are selected based on known features of the field, such as: topography; areas of common yield; crop nutritional levels; soil properties (texture, electrical conductivity (EC), NPK, pH, and organic matter levels, etc.) and past management practices. Topography was found to be the main limiting factor for wheat production in the same experiment considered in Fig 1, and thereafter management zones were successfully created according to topography (Oberelender, 2005). Generally, most field features are mapped through geostatistics analysis, based on soil and crop sampling and on remote sensing (RS) images (e.g. Stafford, 2000; Fraisse *et al.*, 2001; Wong *et al.*, 2001; Boydell and McBratney, 2002; Kozar *et al.*, 2002; Kravchenko *et al.*, 2003; Fridgen *et al.*, 2004; Corwin and Lesch, 2005; Kitchen *et al.*, 2005; López-Granados *et al.*, 2005; Magri *et al.*, 2005). Soil EC mapping systems identify areas of similar soil properties. In non-saline soils, EC values represent soil texture (relative amounts of sand, silt, and clay). Soil texture is directly related to both water-holding capacity and cation-exchange capacity, key ingredients of productivity. Since these characteristics are relatively stable, one measurement

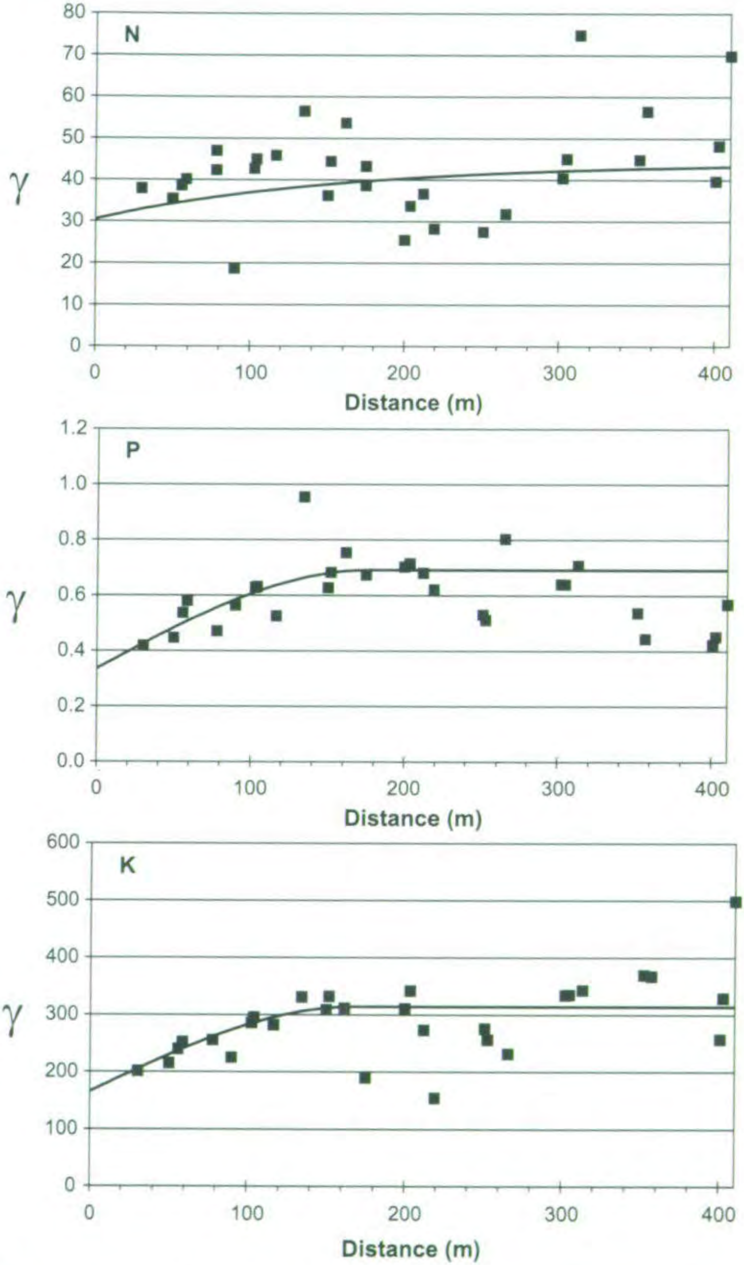

Fig 1. Semivariogram for available N, P and K content in a 144 by 750 m field in Saad

suffices for many years. Based on EC data, fields are usually divided into three areas (Fig 2). EC systems can measure the top soil as well as deeper soil layers. In some cases, these layers are similar and MZ delineation based solely on surface measurements can produce the same MZ. In such cases, RS data can be used to create the same MZ. An example of this situation is shown in Fig 2. A satellite image of bare wet soil collected by the Advanced Land Imager (ALI) sensor shows almost the same delineation (Fig 3). In remotely sensed images, only the soil surface is sensed and therefore, soil mineral content can not be directly determined by multispectral (MS) images. The greatest potential inherent in this kind of MZ, however, lies in its ability to provide reliable spatial information, which can then be used to direct soil sampling for identification and characterization of the spatial variability of edaphic properties influencing crop yield (Corwin and Plant, 2005). Management zones can encounter other difficulties. Since their delineation is based on yield and stable growth determining factors, they usually don't contribute much toward an understanding of the observed yield variations nor of the dynamic relationships that exist between crop, soil and environment, which change between and within seasons (Van-Alphen and Stoorvogel, 2000). Moreover, crop rotation with other crops disrupts the accumulation of yield data in consecutive years, causing difficulty in identifying crop MZ solely from grain yield maps.

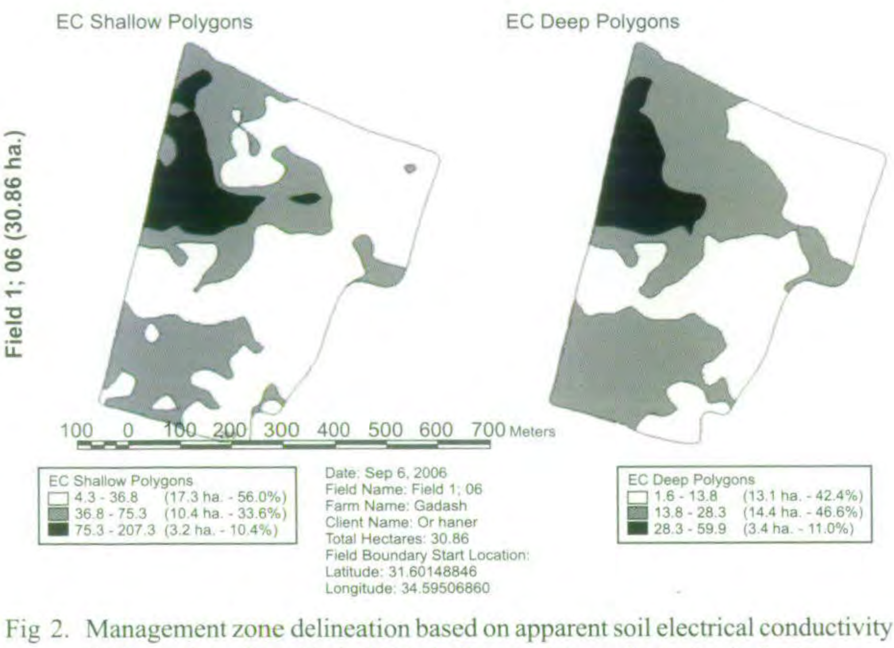

Fig 2. Management zone delineation based on apparent soil electrical conductivity (EC) readings from Veris 3100 shallow and deep electrodes in Or-Haner

Remote Sensing

Remote sensing has the big advantage of rapidly covering large areas, and has been enormously helpful to producers in providing spatial information about their croplands. The usefulness of RS imagery is linked to its spatial resolution, timeliness, repetitive coverage capability, its provision of easy-to-use map products, and its attractive cost. With RS, the key word is resolution, which can be classified into four types. Spectral resolution, which represents the width and number of wavelengths that can be detected. Spatial resolution, which relates to the size of an image pixel and which determines the smallest separation between two objects that can be resolved. Radiometric resolution, which is the number of digital levels used to express the data. Lastly, temporal resolution, which is the revisit period and which refers to the length of time it takes for a satellite to acquire information from the site. Until recently, most multispectral earth-observation satellites (e.g., Landsat, SPOT) have been characterized by relatively low spatial and spectral resolutions. Therefore, the use of remote sensing technologies was mainly limited to land-use and land-cover studies on a national and regional scale. Recently, new sensors have been developed and deployed on satellites such as IKONOS, QUICKBIRD and SPOT-5, providing high spatial resolution of less than 5 m. Hyperspectral sensors, such as Hyperion, provide high spectral resolution over several hundred bands. These sensors represent a potentially valuable technology for agricultural applications, suitable for increasingly adopted site-specific management.

Satellite remote sensing has held out much promise for within-field monitoring but has yet to demonstrate hard evidence for complete success. Problems include timeliness, cloud cover, cost, poor spatial and/or spectral resolution, and lack of suitable products (type of information) that meet the crop managers' needs. Hyperspectral sensing is a relatively new technology, capable of providing information over a nearly continuous spectrum in the visible, near infrared (NIR), and shortwave infrared (SWIR) wavebands. Images acquired from hyperspectral sensors have been used to estimate crop vigour and predict yield; to discriminate among crops, weeds, residue, and soil; to quantify and measure crop water content and leaf area index (Huang *et al.*, 2004; Christensen *et al.*, 2005; Ferwerda *et al.*, 2005; Fitzgerald *et al.*, 2006; http://edc.usgs.gov/products/satellite/eo1.html). Hyperspectral sensors improve the ability of remote sensing to make accurate and precise measurements of individual materials; they are today's state of the art sensors. They can usually supply reflectance data over a range of 400 to 2500 nm, with a resolution of 1 to 10 nm. This spectrum contains rich information, however, handling and analyzing this spectrum is complicated and requires sophisticated manpower.

Most land observation satellites have MS sensors, usually with 4 or more bands in the blue, green, red, and NIR wavelengths and with spatial resolutions that fluctuate between 2.5 and 30 meters. For RS interpretation, many vegetation

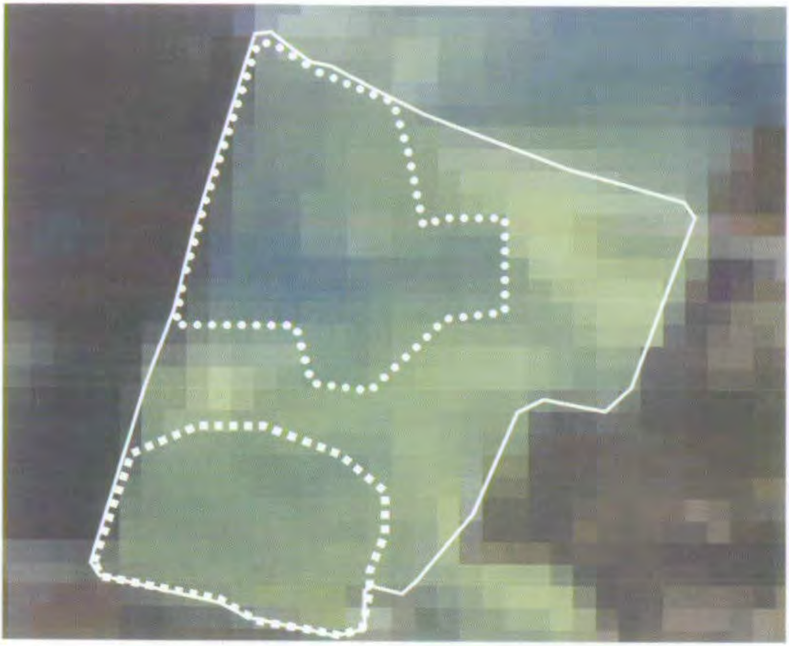

Fig 3. ALI image of 1/Mar/06 showing Or-Haner field management zone delineation, based on bare soil reflectance. RGB composite: Red: layer 8, Green: layer 9, Blue: layer 4

When dealing with cropping parameters with high temporal dependence, such as soil N supply and crop N demand, precision N management based on general MZ may be ineffective (Pierce and Nowak, 1999; Fergusson *et al.*, 2002). However, in semi-arid climates, identifying N management zones from crop N removal maps derived from yield and protein measurements during harvest, eases the need for grid soil samples. Rather than predicting the N supply from soil samples, it is easier to allow the crop to indicate its own N status. This method is suitable by on-combine sensor for mapping grain yield and protein levels. Use of grain protein content as a diagnostic tool for evaluating fertility status was first proposed by Goos *et al.* (1982). While effects of N fertilization on wheat protein are well established (e.g. Smika and Greb, 1973; Terman, 1979), testing of other practical means for analyzing grain protein as an indicator of N fertility has recently begun. The underlying assumption is that plant status at harvest expresses an integrated response to the conditions that prevailed during the growing season, with soil moisture and N fertility being the most critical limiting resources to crop productivity. Yield and grain protein concentration are, therefore, good indicators of these limiting factors.

indices have been developed for crop monitoring, yield, and nutrient estimation (Stanhill *et al.*, 1972; Peñuelas and Filella 1998; Adamsen *et al.* 1999; Ma *et al.* 2001; Shanahan *et al.* 2001; Cohen and Shoshany, 2002). Since the seventies, the Normalized Difference Vegetation Index (NDVI, Rouse *et al.*, 1974) has been the best known and most widely used index (Seelan *et al.*, 2003). Monitoring and analysis of natural and agricultural environments by means of remotely sensed images have been mainly based on the use of spectral vegetation indices or other band-combination algorithms. Linear relationships dominate during the beginning and middle of the season, but when the index reaches its maximum at a certain point towards the end of the vegetative growing period the relationships become exponential rather than linear (Buschmann and Nagel, 1993; Aparicio *et al.*, 2002; Hansen and Schjoerring, 2003). This represents the saturation constraint of several indices that affect the site-specific management objectives of identifying and separating differences within the crop after full coverage of the ground surface has developed. Several studies have shown that saturation of the NDVI occurs when the Leaf Area Index (LAI) has reached 2-3, which corresponds to an early stage of development (Buschmann and Nagel, 1993; Aparicio *et al.*, 2002; Hansen and Schjoerring, 2003). Therefore, this index has strong limitations for crops of high biomass development that reach LAI higher than 3. The main advantage of these indices is their simplicity; however, they often represent change without the ability to determine what caused it. The use of multi- and hyperspectral images validated with ground based sensors of spectral reflectance can be used to address both spatial and temporal variability to mainly improve mid-season N management.

Studies have shown that spatial patterns in N deficiency and crop N response can be detected and mapped through analysis of multispectral aircraft or satellite imagery, thus opening the possibility for identifying N deficiencies within an entire field at once (Blackmer and White, 1997; Sims *et al.*, 2002; Flowers *et al.*, 2003a, 2003b). In a preliminary work, we demonstrated an interaction between water and nitrogen deficiency on reflectance of flag leaf (Raz, 2003). Use of chemometric techniques was shown to be useful for N content prediction in wheat and corn leaves (Curran *et al.*, 2001; Hansen and Schjoerring, 2003; Huang *et al.*, 2004; Alchanatis *et al.*, 2005; Bonfil *et al.*, 2005; Christensen *et al.*, 2005; Pimstein *et al.*, 2006) and a specific spectrum signature can be defined (Thenkabail *et al.*, 2004). A very good calibration has been established in the lab equating the wheat leaf reflectance spectrum with its water and N content (Bonfil *et al.*, 2005). *In-situ* spectrum measurements (350-2500 nm) can be used to estimate wheat biomass, LAI, and water and nitrogen content (Pimstein *et al.*, 2003; Alchantis *et al.*, 2005; Pimstein *et al.*, 2006). By combining canopy thermal and spectral properties, varying water and N stat, can be potentially identified, thus facilitating targeted N applications to those parts of a field where N can be used most efficiently by the crop (Fitzgerald *et al.*, 2006).

Other nutrient deficiencies can modify the reflectance as well (Batten and Blakeney 1996; Masoni *et al.* 1996; Ayala-Silva and Beyl, 2005; Christensen *et al.*, 2005; Mutanga *et al.*, 2005). Ayala -Silva and Beyl (2005) demonstrated the changes in spectral reflectance of wheat leaves in response to specific macronutrient deficiency in the visible and near infrared spectra. It is clear that when one nutrient is deficient it causes differences in the reflectance spectrum; however, the difference between the direct effect of the deficit nutrient on the spectrum and its indirect effect given by decrease in biomass must be identified. Spectra may be affected by many other factors (Filella *et al.*, 1995; Peñuelas *et al.*, 1997; Osborne *et al.*, 2002). Therefore, spectrum analysis is useful to determine different stresses in addition to nutrient stress, e.g. weeds (Lamb and Brown, 2001; Jurado-Exposito *et al.*, 2003; Shaw, 2005), diseases (Ibragimov *et al.*, 1994; Kobayashi *et al.*, 2001; Danielsen and Munk, 2004; Nicolas, 2004; Moshou *et al.*, 2006) and insects (Willers *et al.*, 2005; Yang *et al.*, 2005). Therefore, remotely sensed images have the potential to detect crop stress and diagnose its cause long before a farmer can spot the problem in his field with the naked eye (Ferwerda, 2005; Kosaka, *et al.* 2005; Zarco-Tejada *et al.*, 2005; Zhao *et al.*, 2005). However, we must remember that RS gives only some knowledge based on only one sampling date.

Top Dressing N Application and Decision Support System (DSS)

To reduce financial risk and losses of nitrogen to the environment, fertilization methods are needed for improving NUE and increasing wheat quality. Late applications of a small amount of N may be effective in increasing both NUE and grain quality of an entire field. To make N management decisions at mid-season, growers must become more flexible so they can react to rainfall events and apply N at appropriate times for plant uptake. Within farm fields, there can be distinct variations in the spatial distribution of crop vigor, biomass, plant water, and nutrient content. The information from reflectance data may serve as a basis for spatially variable N applications.

The sensor-based approach measures the desired properties, such as soil and plant properties, using real-time sensors in an 'on-the-go' fashion and controls variable-rate applicator based on the measurements, therefore GPS is not always needed. Examples of simple top-dressing nitrogen application devices include the Hydro-N-Sensor system (http://www.hydro.com) and the Green-Seeker (http:// www.greenseeker.com). These devices integrate optical sensing of only a few wavelengths and application system. Correct application of the right amount of nitrogen at the right time and at the right place, thereby optimizing yield and N input expense. However, both need a within-field reference; moreover, they supply only nitrogen data, as they relate exclusively to changes in nitrogen deficiency and ignore other stresses.

We, recently developed a simple DSS that uses flag leaf N (FLN) and flag leaf water (FLW) status to determine the need for in-season foliar applied N to improve yield and quality in hard red spring wheat (Bonfil *et al.*, 2004a, 2004b). Using a minimum of four input parameters (expected late-season rainfall, expected high or low yield, FLN and FLW at heading), the DSS provides one of three production recommendations for wheat: grow for forage, grow for grain, or apply in-season N and grow for grain. When applied to commercial wheat fields in Israel, the DSS predictions enhanced grain quality, and increased yield value by an average of $125 per ha (Bonfil *et al.*, 2004b). The DSS correctly predicted the final grain protein concentration and grain test weight in about 75% of 1038 plots in field experiments in the Negev region, and in 185 commercial fields all over Israel (Bonfil *et al.*, 2004b and unpublished data). Almost the same level of accuracy was achieved for the calibration and validation of Gilat experimental plots and fields. Thus, irrespective of the cultivar, field, and growing conditions, by using only flag leaf data, about 75% of the recommendations produced by the DSS were correct. However, that yield value increase is only twice the cost of late nitrogen application. Therefore, it is more important to correctly define the fields that really need that nitrogen application.

To incorporate the DSS into precision N management, growers must have timely and detailed information on spatial patterns in crop N and water status. Rapid and cost-effective methods are needed for obtaining crop information at the scale of fertilizer application. Acquiring this information by ground survey is costly and does not provide sufficient spatial resolution. Success with optical leaf reflectance meters to determine crop N and water status in the laboratory and in the field suggests that RS is applicable for DSS purposes and facilitate site specific recommendations (Raun *et al.*, 2002; Yang *et al.*, 2003; Bonfil *et al.* 2005). Preliminary results indicate that RS, an approach that is potentially cheaper than ground testing, is feasible for determining wheat N status for in-season N management (Long *et al.*, 2000). These findings point to the possibility of using multi- and hyper-spectral imagery to predict FLN and FLW, which can be used to support decisions concerning N and water in fertilizer and irrigation programs.

Using RS to produce the DSS recommendation for each field or for each part of the field presents the option of submitting them directly to farmers without resorting to sampling. To reach that point, images from wheat-heading period are needed in Israel from middle February to middle March. Ignoring delivery period, current RS systems could supply images a few times during this period provided that cloud cover doesn't prevent it. For example, during the last three years, the sky on the relevant Landsat over flight days was often covered by clouds and no data was obtained; even when images were obtained, many fields were still obscured by clouds. In 2009, the VENUS satellite is to be launched. VENUS is a research demonstrator joint mission of the Centre National d'Etudes Spatiales (CNESS) in France and Israel Space Agency (ISA). The system has sophisticated characteristics, suitable for PA, namely, 12 narrow spectral bands in the visible and NIR region of the electromagnetic spectrum, a ground resolution of 5.3 m, two-day revisit periodicity, and a 30 degree tilting capability along and across its track. The primary objective for setting the spectral bands is to allow monitoring of vegetation state and dynamics (e.g., phenological changes). This goal can be achieved by a series of derived products, such as vegetation indices, LAI, and Red Edge position. Moreover, due to its unique combination of high spatial, spectral, and temporal resolutions, and its relatively low price per unit area, the system is expected to open a great opportunity to apply PA concepts over large areas and to widely investigate their efficiency under a variety of environmental conditions. We hope that the new VENUS and other spaceborne systems will resolve most of the PA problems, keeping in mind that the revisit time is currently the major drawback. With a two day revisit periodicity, we anticipate at least one cloud-free image every week.

Conclusions

In all our experiments, adequate levels of P and K existed, which prevent us from testing the VRA of these nutrients. A combination of variable-rate N application at planting and at mid-season, based on DSS recommendations, can significantly improve NUE, crop quality, and economic returns. The rationale is that applying N according to spatial patterns in fertility and crop productivity and with critical stages of crop growth is more efficient than a single, large, uniform application at or near planting.

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Integrated Nutrient Management in Cropping Systems in China

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Abstract

This paper summarizes the problems and challenges in food security faced by China and presents the approach of integrated nutrient management for improving crop productivity with efficient resource utilization and environmental protection. The current progress on technical measures for integrated nutrient management in major cropping systems in China is reviewed.

Keywords: Nutrient use efficiency, nutrient cycling, integrated nutrient management, crop productivity

Since the establishment of the People's Republic of China in 1949 the growth in agricultural production has been one of the main accomplishments of the country. By the year 1999, China was successfully feeding 22% of the global population with only 9% of the world's arable land, and per capita food availability reached the level of developed countries. Increased input of fertilizer and water has played a crucial role, accounting for about 50% of the yield increase.

In spite of the achievements in agricultural production, there are still great challenges ahead as growth rate in food-grain production is gradually declining and the population pressure is increasing. For example, the growth in cereal production decreased from 2.2% in 1970s to 1.1% in the 1990s, and it was almost zero between 1996 and 2000. Furthermore, food-grain production declined from 508 Mt in 1999 to 430 Mt in 2003 (National Bureau of Statistics of China, 1996-2003). But China has to produce 150-200 Mt of more food to feed an increasing population, which is projected to plateau at 1.6 billion within 50 years. This will need an annual growth rate in food at 1.4% during the next 30 years. The improving living standards will also drive demand for high-value food products. Currently, China is using 30% of the world's total fertilizers on farm land that accounts for only 9% the total arable land of the world. The average application of N is 317 kg ha^{-1} which is far in excess of the safe limit of 225 kg ha^{-1} for protection of surface and ground water quality in developed countries. The partial factor productivity (PFP) for fertilizers in crop production systems in China remains considerably lower than that in developed countries. For example, the PFP for fertilizers during 2000 was 17.2 kg kg^{-1} in China as compared to 22.4 kg kg^{-1} in the USA, and 69.2 kg kg^{-1} in France (Table 1). The situation is further aggravated due to loss of agricultural land at a rate of approximately 1% per year through rapid industrialization and urbanization, shortage of available water and fertilizers and by environmental degradation. Irrational use of fertilizers has led to environmental pollution. For example, the losses of N and P through leaching and run-off have led to pollution of drinking-water (affecting 30% of the population) and eutrophication in 61% of lakes in the country. The amount of nitrogen oxide emissions from agricultural lands accounted for about 30% of total agricultural emissions in the world.

The Chinese government regards agriculture as the primary field of development of the national economy in the 21st century. However, concerns about China's food security and agricultural production have raised a number of questions. Will China continue to be able to feed its increasing population? What is the best approach for improving grain production with efficient resource utilization and environment protection?

This paper focuses on the approach of integrated nutrient management (INM) for high productivity, efficient resource utilization, and environmental conservation. The paper presents a review on current progress on technical measures for INM in the major cropping systems in China.

Table 1. Fertilizer application rate, grain yield, and partial factor productivity (PFP) in China, USA and France in 2000

Country	China [a]	USA[b]	France[b]
Rate of fertilizer (kg ha^{-1})	248.2	212.1	200.5
Crop grain yield (kg ha^{-1})	4261	4745	13881
Partial factor productivity (kg kg^{-1})	17.2	22.4	69.2

[a]*Farmer survey data of the Ministry of Agriculture of the PR China, 2000*

[b]*Global survey of International Fertilizer Association (IFA) in 1997-1999*

Integrated Nutrient Management

Sustainable agricultural production implies that natural resources should be used to generate increased output without depleting the natural resource base. However, despite past achievements in crop production in China, both the over- and under-application of fertilizers, de-coupling between crop and animal production, and poor management of resources have led to low resource use efficiency and damages to the environment. The future strategy for sustainable crop production should focus on integrated nutrient management.

The INM approach involves the integrated use of nutrients from fertilizers, agricultural and industrial wastes, and from soil and environmental sources, such as atmospheric deposition and irrigation water. China is producing large amount of organic wastes. It is especially true for livestock production from which 4000 Mt of organic waste was produced in 2000. However, organic manures are applied to only 47% of the agricultural land in the country. Other inputs of nutrients have been ignored. For example, N input through rainfall was up to 60-90 kg ha^{-1} in wheat-maize cropping system in Huiming and input from irrigation water was estimated to be 180-250 kg ha^{-1} in the tomato production system in Shouguang, Shangdong province.

Nutrient management should also be integrated with sound soil management practices and other farming techniques such as high yielding cultivation systems (Zhang *et al.*, 2005).

With the support of the Chinese Ministry of Agriculture and the National Natural Science Foundation of China, a project is being carried out since 2002, which features INM for 12 cropping systems at 58 sites across the country. The N fertilizer applications have been split to match crop requirements at different growth stages based on the total fertilizer N required at the specific sites to minimize N losses from the soil-plant system. The N application time and rates has been determined using N-kit and chlorophyll meter or leaf color chart (LCC). The fertilizer P or K management focuses on maintenance of adequate soil available P or K levels to ensure that P or K supply does not limit crop growth and N-use efficiency. Therefore, the maintenance fertilizer P or K amounts are recommended through constant monitoring of soil nutrient supply capacity (Wang *et al.*, 1995). The integrated nutrient management strategies for selected cropping systems are presented below.

Integrated Nutrient Management in Different Cropping Systems

Rice production systems

In China rice is cultivated on 29 million ha area, which accounts for 20% of the rice production area in the world. Rice production in China consumes about 37% of the world's total N fertilizer used for this crop. The N application rate for a rice crop is about 180 kg ha^{-1}, which is 75% higher than the world average. In some cases, the N application rates are much higher than the average. For example, in the Taihu area of Jiangsu the fertilizer N application rate is ~270-300 kg ha^{-1}.

Excessive N application and poor N management result in low fertilizer-N use efficiency and reduce the profit of farmers by increasing production costs and reducing the grain yields.

The recovery efficiency of applied fertilizer N is usually 30-35% (Zhu, 1997), which is lower than the world average. In Jiangsu province where excessive N is applied to rice, recovery efficiency is only 19.9%. Low fertilizer-N use efficiency coupled with high N loss has led to a number of environmental problems such as groundwater pollution and eutrophication of surface waters. Therefore, increasing fertilizer-N use efficiency through improved nutrient management is a major challenge for sustainable rice production (Cassman *et al.*, 1996), and environmental conservation.

Nutrient management practices for rice have been developed and implemented throughout China in cooperation with IRRI since 2002. There are 7 rice-producing provinces viz. Jiangsu, Zhejiang, Hunan, Hubei, Guangdong, Heilongjiang, and Hebei taking part in the program on nutrient management in rice. The overall strategy is to integrate soil nutrient supply with optimum fertilizer-N application rate and time in combination with maintenance of P and K supply.

The fertilizer-N application rate for a rice field can be estimated from the difference between crop N requirement and soil N supply (Dobermann and Fairhurst, 2000). On an average, irrigated rice requires 17.5 kg N, 3.0 kg P and 17.0 kg K to produce one tonne of grain. The crop requirement can be calculated from a yield target selected as 75-80% of the potential yield for a climate zone. Soil N supply is estimated from N omission plots, which includes nutrient inputs from atmospheric deposition (rainfall and dust), irrigation, floodwater, and sediments (dissolved and suspended nutrients) and biological N_2-fixation. The soil N supply capacity in some areas of China is presented in Table 2.

Table 2. Soil N supply capacity and rice yield (kg ha^{-1}) in some areas of China (2003-2005)

Province	Crop type	Yield	Soil N supply capacity
Heilongjiang	Single season rice	4000-5000	68-85
Hebei	Single season rice	3500-8000	60-136
Hubei	Early rice	3000-3500	51-60
	Late rice	3500-4500	60-77
	Single season rice	4500-6000	77-102
Guangdong	Early rice	3500-4500	60-77
	Late rice	4000-5000	68-85
Sichuan	Middle rice	4500-5500	77-94

Based on soil N supply capacity, the basal fertilizer N is recommended. Top-dressings are done through soil plant analysis development (SPAD)/leaf color chart (LCC) fine-tuning. Therefore, the splitting pattern is in accordance with soil N supply capacity, crop growth stage, cropping season, the variety used, and the crop establishment method. Critical levels of SPAD and LCC and the corresponding fertilizer application rates have been developed for fertilizer-N distribution at different growth stages in China.

If SPAD/LCC is not available, a simplified distribution method for fertilizer N can be used according to the nutrient uptake pattern by the rice crop at a specific site. The fixed distribution rates such as 35-40% as basal application, 20-25% at early tillering, 25-30% at panicle initiation and 0-10% at heading are based on previous studies on nutrient management.

The project on nutrient management in rice has been carried out since 2002. The results show that fertilizer N rates could be reduced by 20-30% and input costs by 20%. Fertilizer-N agronomic efficiency could be increased by 20-80% without any reduction in rice yield (Table 3).

Table 3. Effect of optimized nutrient resource management on rice production in China during 2004

Site	Reduction in N rate (%)	Reduction in cost (%)	Increase in yield (%)	Increase in AE (%)
Jiangsu	52-69	-	8.9-9.3	200.9-276.4
Guangdong	32.9	33.9	-	-
Heilongjiang	24.8-53.8	10-15	balance	6-10
Hebei	28.4	32.1	3.7	53.7
Hunan	20.3-22.8	-	5.6-7.5	12.9-15.7
Hubei	balance	-	7.9-9.6	49.7
Zhejiang	106	-	-	-

AE: Agronomic efficiency

Wheat-maize cropping system

The North China Plain (NCP), located in the northeast of the country, covers an area of 0.444 million km^2 and is one of the most important crop production areas in China. Winter wheat-summer maize is the main cropping rotation in the NCP. Usually, winter wheat is sown at the beginning of October and harvested at the beginning of June in the following year, and afterwards summer maize is immediately sown and is harvested at the end of September. This cropping system produces about 40% of wheat and 28% maize on national basis.

Farmers use excessive N fertilizer in this cropping system. For example, in high-yielding regions of the NCP, N fertilizer application is usually over 500 kg N ha^{-1} for wheat and maize together. According to Cui (unpublished), average N application rates are 424 kg N ha^{-1} for winter wheat 59 kg manure N ha^{-1} (n=370) and 249 kg N ha^{-1} for summer maize (n=368) in Huiming county, Shandong province, which is about 2-fold higher than the total N demand of wheat and maize. Overuse of fertilizers is not only wasteful, but it also degrades the environment. For example, NO_3^--N can accumulate in the subsoil when large amounts of fertilizer N are applied. As shown in Table 4, the average NO_3^--N accumulation in soil to 90 cm depth in farmers' fields were 233 kg N ha^{-1} after the wheat harvest and 292 kg N ha^{-1} after the maize harvest. If the accumulated NO_3^--N is not utilized by crops it is eventually lost through leaching and/or denitrification. Thus, fertilizer recommendations that take into account NO_3^--N accumulation in soil is urgently required in NCP.

Table 4. Soil NO_3^--N accumulation after winter wheat harvest (n = 117) and summer maize harvest (n = 135) on the North China Plain in 2003-2004

Soil depth	After winter wheat harvest (kg N ha^{-1})			After summer maize harvest (kg N ha^{-1})		
	Mean	Range	CV (%)	Mean	Range	CV (%)
0-30 cm	55	10-183	35	76	18-212	42
0-60 cm	137	25-489	51	168	31-527	49
0-90 cm	233	25-663	56	292	45-689	53

Fertilizer recommendations based on soil testing

Integrated Nutrient Management for wheat-maize cropping system involves nitrogen management based on the soil N_{min} test and nitrogen nutrition diagnosis index. Phosphorus and potassium fertilizers are recommended through regular monitoring as shown in this paper.

The N_{min} method is based on measurement of mineral N to quantify soil N supply and fertilizer recommendations are made for two or three different growth stages during the crop growth season. For example, the growth of summer maize is divided into three periods: from sowing to the three-leaf stage, three leaves to the ten-leaf stage and the ten-leaf stage to harvest. The N rate for each growth stage is dependent on target N demand and measured soil N_{min}.

Nitrogen supply for some target yield is calculated as:

Nitrogen supply for target yield = N from the environment (dry and wet depositions, biological N_2 fixation, irrigation) + mineral N in the rooting layer (N_{min}) + fertilizer N

In this method, the effects of N mineralization, immobilization and N losses on plant available N during the preceding growth stage are included in the results for the next soil N_{min} analysis as well as in the next N fertilization recommendation. Therefore, synchronization of soil N supply (N_{min} in the rooting layer), fertilizer N application and subsequent crop demand for N can be attained to a certain extent.

The present results show that low N rate and high N-use efficiency could be achieved without any reduction in grain yield by optimized N management. During the winter wheat growing season, N fertilizer application rate in the optimum N treatment was reduced by 69% from 369 to 98 kg N ha^{-1} compared to the conventional N treatment, and N fertilizer recovery efficiency was improved from 15% to 44% and agronomic efficiency from 3 to 10 kg kg^{-1}. Similar results were also obtained for summer maize.

Reduction in N fertilizer dose and improvement in fertilizer use efficiency may be partly ascribed to adequate crop utilization of accumulated as well as mineralized soil N and N inputs from environmental sources (e.g. irrigation and rainfall) during the crop growth season. As shown in Table 5, during the winter wheat growing season, initial soil N_{min} supply (soil N_{min} after harvest - soil N_{min} before sowing) and apparent N mineralization rate were 48 kg N ha^{-1} and 28 kg N ha^{-1}, respectively, which accounted for 32% and 18% of crop N uptake. During the summer maize growing season, apparent N mineralization rate was 100 kg N ha^{-1} accounting for 56% of crop the N uptake.

Table 5. Mean apparent N balance in the no N, optimum N (Opt.) and conventional N (Con.) treatments across all experimental sites

Treatment code	Winter wheat			Summer maize		
	No N	Opt.N	Con.N	No N	Opt.N	Con.N
1) N rate (kg N ha^{-1})	0	98	369	0	142	244
2) Soil N_{min} before sowing (kg N ha^{-1})	158	158	158	106	106	106
3) Apparent N mineralization (kg N ha^{-1})	28	28	28	100	100	100
A) N input: 1+2+3	186	284	555	206	348	450
4) Crop N uptake (kg N ha^{-1})	118	152	173	144	177	194
5) Soil N_{min} after harvest (kg N ha^{-1})	68	110	266	63	117	172
B) N output: 4+5	186	262	439	207	294	366
Apparent N losses: A-B (kg N ha^{-1})	0	22	116	0	53	84

Rice-wheat cropping systems

Rotations of rice and other crops are practiced widely along the Yangtze River Basin where they occupy a total area of about 13 million hectares (Timsina and Connor, 2001) and account for 30% of cereal crop production in China. However, emerging water crisis and environmental pollution arising from improper nutrient management threaten the sustainability of these crop rotations and a trend of declining or stagnating yields has been observed (Bouman, 2001; Ladha *et al.*, 2003). Improvements are therefore required in the management of nutrient resources, soil, water and straw. Since 2000, integrated nutrient management (INM) technologies have been developed for rice-wheat cropping system (R-W) in southwest China.

Non-flooded straw/plastic film mulching cultivation

Non-flooded mulching cultivation, a new water-saving rice cultivation technique, was introduced in China during late 1980's. Lowland rice fields are irrigated and a shallow water layer is maintained before transplanting. The soil surface is then covered with plastic film (0.005-0.010 mm thick), straw or paper and the soil is maintained at 70-90% of water holding capacity or rain fed during the rice development stage, depending on rainfall and the underground water level (Fan *et al.*, 2005). After the rice harvest each year, the plastic film is moved from the field by hand and wheat is sown directly into the zero tillage soil.

Several long-term field studies indicated that non-flooded mulching cultivations may be alternative options for farmers using rice-wheat rotations for saving water, enhancement or maintenance of system productivity (Table 6) and soil fertility (Fan *et al.*, 2005). At the present crop yield levels (rice, 6.6-7.6 t ha^{-1}; wheat, 4.8-5.5 tha^{-1}), the plastic film mulching in rice can maintain stable soil and crop productivity over time. Non-flooded straw mulching cultivation resulted in decreased rice yields, but system productivity could be maintained. Non-flooded straw mulching cultivation led to increase in soil organic matter, soil total N, Olsen-P, and exchangeable K in the topsoil (Fan *et al.*, 2005).

Table 6. Mean yields and the amount of irrigation in a 5-year rice-wheat rotation under non-flooded mulching cultivation

Cultivation system[a]	Grain yield (kg ha^{-1} y^{-1})			Irrigation
	Wheat	Rice	System[b]	(mm y^{-1})
Traditional flooding	4920 a	6013 b	10933 b	1100
Plastic mulching cultivation	5325 a	6763 a	12088 a	100
Straw mulching cultivation	5201 a	5381 c	10583 b	100

[a]Within each column, values with the same letter are not significantly different by LSD at the 5% level across all cultivation systems

[b]Total rice + wheat grain yields

Combination of cultivation techniques and nutrient management

In the traditional nutrient management approach, the emphasis has been solely on fertilizer application, with no regard for the utilization of indigenous nutrients or integration with other agricultural practices. The following describes the nutrient management strategy integrated with cultivation techniques in rice-wheat system.

In rice season, the cultivation technique involves planting 3 young seedlings per hill in a triangular pattern with 10-12 cm spacing between the plants. The hills are planted in a staggered 50×50 cm grid. In the wheat season, the wheat seeds are sown directly into the zero tillage soil at two spacing of 10 cm ×15 cm and 10 cm ×25 cm. Nitrogen is applied in split dressings according to crop development stage. Fertilizer P and K doses are recommended using the constant monitoring soil nutrient supply capacity method.

Contrasting experiments at farmers' fields in Sichuan province and Chongqing showed that integrated systems could solve the problems of insufficient or excessive N fertilizer application. Compared to the average N application rate of 156 kg N ha^{-1} and an average rice yield of 6890 kg ha^{-1} at farmers' fields (n=12), integrated nutrient management reduced fertilizer N application by 24% while increasing rice yield by 24%. In the wheat season, integrated nutrient management decreased N fertilizer inputs by 30%, without any decline in wheat grain yield. This indicates that integrated management system is a feasible solution for harmonization of nutrient inputs, crop production and environmental protection in rice-wheat sequence.

Intercropping systems

Intercropping continues to be widely employed in both tropical and temperate regions. Both wheat/maize and faba bean/maize strip intercropping are established practices in major grain production systems in northwest China, especially in irrigated areas that are limited to only one cropping season annually due to temperature constraints. The area under wheat/maize intercropping in 1995 was 75,100 ha in Ningxia province, producing 43% of the total grain yield for the area. In Gansu province 200,000 ha are intercropped annually. Faba bean/maize intercropping occupies a smaller area than wheat/maize intercropping. However, little is known about the relationship between interspecific interactions (competition and facilitation) and efficient nutrient utilization in these intercropping systems. Farmers applied more and more chemical fertilizers in the systems, which resulted in low fertilizer use efficiency and high risk of environmental pollution. We have studied interspecific interactions between intercropped species and have used our results in agricultural production.

Influence of interspecific facilitation on nutrient utilization in cereal/legume intercropping

Interspecific root interactions between intercropped faba bean and maize played an important role in the yield advantage and nitrogen and phosphorus acquisition by the intercropping system (Li *et al.*, 1999). Faba bean showed a greater capacity in mobilising insoluble phosphorus than maize and an interspecific facilitation of P uptake was also observed. Phosphorus uptake by maize from Al-P, Fe-P, or Ca-P was 86%, 49% and 19% higher when their roots were intermingled than when their roots were separated. One mechanism behind the facilitation was that faba bean had a greater ability to acidify its rhizosphere than maize. Biomass and P uptake of wheat were significantly increased when the roots of intercropped wheat and chickpea intermingled compared to treatments with either a solid root barrier or nylon mesh, regardless of whether P was supplied as phytate or $FePO_4$. Wheat is less able to use organic P than inorganic P, whereas chickpea can use both P sources equally effectively. The mechanism behind this facilitation was that chickpea had a greater rhizosphere acidification ability and more activity of phosphatase released from the roots.

Both field and greenhouse experiments showed that the improvement in the Fe nutrition of peanut intercropped with maize was mainly caused by rhizosphere interactions between the two crops. In the treatment where the roots of the two species were physically separated, the peanut plants were chlorotic, with most of the peanut plants in the row closest to maize showing slight signs of chlorosis. In contrast, in the treatment where a 37-mm nylon mesh was inserted into the ground between the two crop species to prevent direct root contact but allow interactions through mass flow and diffusion, the peanut plants in rows 1 and 2 remained completely green, while those in rows 3-10 were chlorotic to varying extents (Zuo *et al.*, 2000).

These studies showed that nitrogen fixation was increased by cereal/legume intercropping (i.e. maize/faba bean intercropping), compared to sole faba bean. At the same time, phosphorus utilization by cereals can be enhanced by associated legumes (i.e. faba bean or chickpea). Therefore, the rate of nitrogen fertilizer application can be lowered to 150-200 kg N ha^{-1} by inoculating the legumes with selected rhizobium strains, from the conventional 250-300 kg N ha^{-1} for cereal/legume intercropping in this area, which saves substantial amounts of nitrogen fertilizer and reduces the risk of environmental pollution. Field experiments showed that phosphorus fertilizer could also be reduced to 50-75 kg P ha^{-1} from the conventional 120 -150 kg P ha^{-1}.

Competitive-recovery production principle and nutrient management in cereal/ cereal intercropping

In the wheat/maize or wheat/soybean intercropping systems in northern China, there is a 70- to 80-day overlapping growth period that causes intense interspecific interactions between the intercropped species. The yield advantage in the border row of intercropped wheat probably derived from the differences in interspecific competitiveness, and wheat was more competitive relative to maize and soybean during overlapping growth periods in the wheat/soybean and wheat/maize intercropping systems (Li *et al.*, 2001a). There is a recovery of nutrient uptake and growth after harvest of the earlier-maturing species, which makes the later-maturing species compensate for impaired early growth once the early-maturing species has been harvested (Li *et al.*, 2001b).

Farmers usually apply more than 350 kg N ha^{-1}, and sometimes up to 600 kg N ha^{-1} in cereal/cereal (i.e. wheat/maize and barley/maize) intercropping to get more than 12 tonnes ha^{-1} of grain yield in irrigated areas of northwest China. Based on our proposed 'competition-recovery principle', wheat or barley, which have much more competitive ability for soil nutrients at the co-growth stage of the two crops, can utilize more soil nutrients, whereas maize growth and yield are more dependent on fertilization. Therefore, we emphasized that the key point of nutrient management lay in the subordinate species, for instance maize, at late growth stages in this type of intercropping. We recommend that a total of 230-300 kg N ha^{-1} is distributed as 120 kg N ha^{-1} basal application for both wheat and maize, 80 kg N/ha at the elongation state for maize only, and 100 kg N ha^{-1} for maize only at the pretasseling stage. The application rate of nitrogen fertilizer was greatly reduced by these recommendations compared to conventional rates of more than 350 kg N ha^{-1}. All in all, intercropping plays an important role in efficient nutrient management if a suitable crop combination is chosen.

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Balanced Fertilization for High Yields of Rice: Chinese Experience

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Abstract

Rice has been cultivated in China for more than 7000 years and is the staple food for 700 million people. The yield of rice in China is now ranked in the front of the world. To gain such high yields of rice, the main experiences in balanced fertilization are the followings: balanced input of N, P, and K, co-application of organic and inorganic fertilizers, rational distribution of fertilizers in the rotation crops, and adjustment of fertilizer use rate at different growing stage. These measures not only kept the high yields of rice, but also contributed to environmental protection.

Keywords: Rice, balanced fertilization, organic fertilizer, crop rotation

China is the largest rice production and consumption country in the world. As the staple food for 700 million people, the consumption of rice is about 190 Mt, which accounts for about 1/3 of the total amount in the world (Pang, *et al.*, 2004). In 2004, the total food crop yield was 469.47 Mt, among which the yields of the three main crops viz. rice, wheat and corn were 179.09, 91.95, and 130.29 Mt, respectively in China. The cultivation area of the total food crop was 101.6 Mha this year, and the area ratios of rice, wheat and corn were 27.9%, 21.3%, and 25.0%, respectively (China Agriculture Yearbook Editors Committee, 2005). With only 27.9% of the cropping area, rice contributed 38.1% of the total food crop yield, which obviously demonstrated the important role played by rice in Chinese agriculture and food security.

Rice is mainly cultivated in some southern areas in China, such as plains in the middle and lower reaches of Yangtze River, Sichuan basin, Zhujiang River Delta, and plains in west of Taiwan, all of which holding 93% of the total rice fields area in China (Li, 1992). Rice has been cultivated in China for more than 7000 years. In the most time of the history, rice yield was very low with no chemical fertilizers application; however, the soil fertility was kept at a stable level for a very long time, which is surely concerned with the tradition of organic fertilization. Nowadays, with the production and input of chemical fertilizers, and the research and development of the super high yielding varieties of rice (Zhao and Yuan, 2005), the rice yield has got a large increment. In 2004, the rice yield of China was 6347 kg ha^{-1}, which was only less than that of the U.S., 7580 kg ha^{-1}, in the world (China Agriculture Yearbook Editors Committee, 2005). Evidently, the application of chemical fertilizers has greatly contributed in the rice production for high yields. For the long history of rice cultivation and the persistently precise management in practice, certainly there are unusual experiences in balanced fertilization for such high rice yields in China.

Chinese Experience in Balanced Fertilization for High Rice Yields

Balanced input of N, P and K

With a large population, the pressure for high yields of crops is very big in China. Therefore, since the significant effect of nitrogen application on yield increment was found, the input of N fertilizers has been accepted and practiced by the farmers. The history of using chemical fertilizers started from the use of nitrogen fertilizer in China. Even now, chemical fertilizers are still only meant nitrogen fertilizer for some farmers. The growth of crops can be promoted with N fertilizer application, at the same time, the uptake of P and K by crops could also be enlarged. For the lower price of ordinary P fertilizer, and the poor movability of P in soil, increasing the input of phosphorus is a common practice to meet the requirement of P for normal growth of crops. However, K mineral resource is scarce in China and K fertilizer sources were not easily available before 1980's, causing the very low input of K fertilizer. As a result, the apparent balance of field nutrients in China is characterized by the surplus N, balanced P and greatly deficient K (Zhou *et al.*, 2004). Which is quite evident from the results of an investigation on the balance of N, P, and K input and output in fields of 3 southern rice-cropping provinces (Table 1). Therefore, controlling N input and increasing K input are the main steps in the balanced fertilization for high yields in current Chinese agriculture.

Table 1. Apparent balance of N, P, and K input and output in fields of Jiangsu, Hunan, and Sichuan provinces

Provinces	N (kg ha^{-1})			P (kg ha^{-1})			K (kg ha^{-1})		
	Input	Output	Balance	Input	Output	Balance	Input	Output	Balance
Jiangsu	481.1	394.3	86.8	154.9	91.4	63.5	162.6	195.9	-33.3
Hunan	582.7	253.2	329.5	188.0	155.8	32.3	318.1	360.7	-42.6
Sichuan	322.5	249.0	73.5	121.5	67.5	54.0	75.0	196.5	-121.5

Source: Zhou *et al.* (2004)

The Taihu Lake area located in the lower reaches of Yangtze River is always regarded as a region having the highest yield of rice production. An experiment on the effect of N fertilizer amounts applied was conducted in this area (Cui, *et al.*, 1998). Some physical and chemical properties of the experimented soil were as follows: 78.28 mg kg^{-1} of available N, 21.44 mg kg^{-1} of available P_2O_5, 148.08 mg kg^{-1} of available K_2O, and 27.4 g kg^{-1} of organic matter. The results of yield increment, and N uptake by rice applied with different amounts of N are given in Table 2.

Table 2. Effect of the amount of N applied on rice yield and N uptake by rice planted in Taihu Lake area

Treatment	N applied (kg ha^{-1})	Yield (kg ha^{-1})	N uptake (kg ha^{-1})	N efficiency
Control	0	5326.0 a*	59.45	-
N 1	150	6958.3 b	110.63	0.35
N 2	250	7232.8 b	125.06	0.25
N 3	350	6912.0 b	154.64	0.27

*Different letters denote significant difference in yield at 5% level.

Source: Cui *et al.* (1998)

From Table 2, it evident that N application greatly increased rice yield. When 250 kg ha^{-1} of N was used, the yield was the highest, although no significant difference was found among N treatments. Therefore, when the amounts of P and K applied were 100 kg ha^{-1} of P_2O_5 and 155 kg ha^{-1} of K_2O in this experiment, the economically corresponding N amount should be 150 kg ha^{-1}. From the data of N uptake by rice, it seemed that the reason of no significant yield increment with the increase of N input should be concerned with the luxury adsorption of N by rice. Such results also occurred in some other experiments conducted in Taihu Lake area (Song and Fan, 2003; Yan, *et al.*, 2005). The high input of N fertilizer has been one of the main problems for agricultural production in this area. Thus, the control of N input should be an important step in the balanced fertilization for high rice yield, for lessening environment pollution, and for saving resource, especially in high-yield area (Zhu, 2002).

For other regions, the complement of K seems more urgent. Most of the rice fields are located in South of China, but soil K is not rich in these regions because of weathering and deformation, especially in red soil area. From 1981-1991, a long-term field experiment was conducted in red soil in Hunan Province to explore the effect of K application on rice yield (Liu *et al.*, 1996). The data in Table 3 show that K application could increase the rice yield by 6.1% - 37.1%. Although the yield of rice varied with the change in varieties, the effect of K application was clearly observed in each year. The response of rice to K application seemed to be increasing with time.

Table 3. Effect of K application on rice yield (kg ha^{-1}) in red soil in Hunan Province

Treat-ment	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
NP	4950	4740	5550	3960	4245	5430	4515	4410	4440	4905	4650	3795
NPK	5250	5130	6930	5070	5820	6600	5295	5175	5565	6015	5325	4785
Yield increase (%)	6.1	8.2	24.9	28.0	37.1	21.5	17.3	17.3	25.3	22.6	14.5	26.1

Source: Liu *et al.* (1996)

The purple earth is a special type of soil in China, mainly distributed in Sichuan Basin. It was regarded as a K-rich soil for a long time (Xie and Li, 1987). On a purple soil with 88.2 mg kg^{-1} of readily available K_2O and 609.6 mg kg^{-1} of slowly available K_2O, 23.9 g kg^{-1} of organic matter and 4.3 mg kg^{-1} of available P, an experiment on K effect was conducted (Xiong *et al.*, 2000). The results showed that with no K application for 8 years, rice yield reduced from 6543.5 kg ha^{-1} in 1992 at the beginning of the experiment to 6021.0 kg ha^{-1} in 1999 (Table 4). Then, the increase in response to K fertilizer from 6.8 to 14.7% was observed, mainly due to the decline in soil K fertility. Even in such a "K-rich" soil, increase in rice yield with K application denoted that the input of K has been one of the factors or potential factors for high yields of rice.

Balanced fertilization of N, P, and K is the basic measure for high yields and maintenance of soil fertility. The facts demonstrated that economizing N, activating P, and supplementing K are the important preconditions for high rice yields in current China (Zhou *et al.*, 2004).

Table 4. Influence of K application on rice yield in purple paddy soil in Sichuan Province

Treatment	Fertilizers applied (kg ha^{-1})			Yield (1992)		Yield (1999)	
	N	P_2O_5	K_2O	(kg ha^{-1})	Increase (%)	(kg ha^{-1})	Increase (%)
NP	150	75	0	6543.5	-	6021	-
NPK	150	75	75	6991.5	6.8	6909	14.7

Source: Xiong *et al.* (2000)

Co-application of organic and inorganic fertilizers

In the long history of Chinese agricultural production, the chemical fertilizers have been extensively used for only about 50 years. Before it, organic manure played the dominating part on food crop production, feeding people and maintaining soil fertility. Therefore, the importance of organic fertilization in cropping is greatly known to most of the Chinese farmers. Even after having recognized the large effect of inorganic fertilizers in yield increase, co-application of organic fertilizers is still adopted and employed in the current agricultural production. Generally, organic fertilizers could be regarded as the source of N, P, K and micronutrients, and a kind of amendment material for soil structure. From 10 long-term rice-wheat experiments situated in South China for 10 years, it was found that for 7726.2 kg ha^{-1} of the average rice yield and 4575.8 kg ha^{-1} of the average wheat yield, on an average the K contributed by organic sources was 89 kg ha^{-1}, but only 38 kg ha^{-1} by inorganic fertilizers (Wang *et al.*, 2002). According to the statistics, K from organic manure accounted for more than 70% of the total K taken up by crops in 1990 (Lin, 1998).

A study was carried out in a red soil on the effect of the application of organic and inorganic fertilizers on rice yield and NH_3 volatilization (Li *et al.*, 2005). In this study, 3 treatments were tested as NPK, manure, 1/2 NPK + 1/2 manure. The amounts of N, P, and K were exactly the same in all the treatments, except for PK (with only P and K, no N applied). The results showed that both the applications of NPK and 1/2 NPK + 1/2 manure resulted in about 70% increase in rice yield, much larger than that in the solo manure treatment (Table 5). But the ratio of NH_3 volatilization to total N applied was 37.9% in the treatment with only NPK applied, much higher than the other treatments with manure applied or co-applied. It revealed that the effect of co-application of organic and inorganic fertilizers was more than that of the solo application of organic manure on the increase in rice yield. The loss of N was higher with the application of inorganic fertilizer, though it could result in the similar benefit on rice yield increment, compared with the co-application of organic and inorganic fertilizers. Similar results were observed in some other studies (Xie *et al.*, 2004). The less loss of N implied that the more N was left in soil and the more remainder N in soil can be beneficially available for the maintenance or enhancement of soil N fertility (Zhu and Wen, 1992), implying the role of organic manure as buffer and reserve for nutrients. Therefore, it could be said that co-application of organic and inorganic fertilizers is the basic of the current high yield and the insurance for the high yield in the future.

Table 5. Effect of organic and inorganic fertilizers application on rice yield and NH_3 volatilization

Treatment	Yield		NH_3 volatilization	
	(kg ha^{-1})	Increase (%)	(kg ha^{-1})	% of N applied
Control	3360±405 a	-	2.20±0.17	-
NPK	5690±315 c	69.3	59.10±8.65	37.9
M*	4510±323 b	34.2	3.76±0.64	1.0
1/2NPK+1/2M	5780±154 c	72.0	12.95±4.59	7.2

*M: the abbreviation of manure

Source: Li *et al.* (2005)

Rational distribution of fertilizers in the crop rotation

For very limited arable land area and big population, Chinese farmers always use the soils intensively. The crop rotations, such as 2 crops per year, 3 crops every 2 years and 3 crops per year are very common in China (Wang and Li, 2003). Among these, rice-wheat and rice-rice systems are the primary rotations and are widely practised in the southern provinces of Jiangsu, Zhejiang, Hubei, Guizhou, Yunnan, Sichuan and Anhui (The Science and Technology Bureau of Ministry of Agriculture, 1991; Timsina and Connor, 2001).

An outstanding feature of the rice-wheat rotation system is the alternate annual conversion of soil from aerobic to anaerobic (Bijay Singh *et al.*, 2004), which implied that there is a posibility of change in fertilizer efficiency for different crops. It had been said that the influence of K fertilization on wheat or late rice was always higher than that on rice or early rice, which was concerned with soil K status in the plant growth period (Xie *et al.*, 1992). Experiments carried in Guangdong, Hunan, and Jiangxi provinces (Table 6) showed that more benefit was gained when K fertilizer was applied in late rice than in early rice in Guangdong and Hunan provinces, but the reverse result was also observed in the experiment conducted in Jiangxi Province (The Science and Technology Bureau of Ministry of Agriculture, 1991). Different results of K distribution influence on wheat and rice were also reported by Chen *et al.* (2003). When the total amount of K was applied in rice season, better K efficiency was observed than in wheat season in the experiments conducted in Aquept and Aqualf paddy soils in Jiangsu Province. The conflicting results indicated that the distribution of K fertilizer should be properly operated according to different soil conditions to get the high use efficiency and high crop yields.

Table 6. Effect of K application on rice yield in early-late rice rotation experiments conducted in Guangdong, Hunan and Jiangxi provinces

Treatment	Guangdong Province (1980-1984)					Hunan Province (1981-1985)					Jiangxi Province (1984-1987)				
	Fertilizers ($kg\ ha^{-1}$)			Yield ($t\ ha^{-1}$)		Fertilizers ($kg\ ha^{-1}$)			Yield ($t\ ha^{-1}$)		Fertilizers ($kg\ ha^{-1}$)			Yield ($t\ ha^{-1}$)	
	N	P_2O_5	K_2O	Early rice	Late rice	N	P_2O_5	K_2O	Early rice	Late rice	N	P_2O_5	K_2O	Early rice	Late rice
NP	300	150	0	5.8	4.9	330	180	0	5.4	3.7	330	120	0	4.7	5.1
NPK	300	150	300	6.3	5.6	330	180	240	6.1	5.0	330	120	180	5.7	5.9
Yield increase (%)				9.0	15.7				13.1	34.8				20.8	16.6

Source: The Science and Technology Bureau of Ministry of Agriculture (1991)

Similarly, P fertilizer was also recommended to be applied in wheat in preference to rice in the rice-wheat rotation (Jiang, 1992). It was demonstrated that if all the P fertilizer was only used in wheat field, the effect of soil remainder P on rice yield was similar to that when another same amount of P fertilizer was applied to rice, which meant that the remainder P from wheat season was enough for the normal growth of rice (Jiang, 1992). Therefore, rational distribution of fertilizers is advantageous for gaining high yields of all the crops in the whole cropping system and saving resources.

Effect of fertilization patterns on high yields of rice

In China, there are normally several times of fertilization in the short growth period of rice, such as basal, at tillering and ear head. Basal and tillering fertilizers are used to provide sufficient soil N for valid tillering. After tillering stage, the concentration of soil N should be lowered to reduce the invalid tillering. Sometimes, basal and tillering fertilizers are merged in one stage fertilizer, i.e. basal fertilizer, for convenience in agricultural practice. Zhao *et al.* (1997) presented that the combined application of basal and ear fertilizers, splitting from the total N fertilizer, could bring a 13.3% of higher yield increment than the one-off application of basal fertilizer (Table 7). In addition, different ratios of basal and ear fertilizers can also have effect on rice yield and efficiency of N fertilizer (Ling *et al.*, 2002). The data in Table 8 showed that more than 1000 kg ha^{-1} of the yield difference could result from different ratios of basal and ear fertilizers.

Table 7. Effect of basal and basal-ear fertilizers application on rice yield

Treatment	Fertilizer applied (kg ha^{-1})			Yield	
	Basal Fertilizer	Ear Fertilizer	Total	(kg ha^{-1})	Increase (%)
Control	0	0	0	3466 a	-
Basal Fert.	180	0	180	7500 b	116.4
Basal-ear Fert.	126	54	180	8500 c	145.2

Source: Zhao *et al.* (1997)

Table 8. Effect of ratio of basal and ear fertilization on rice yield and efficiency of N fertilizer

Ratio of basal and ear fertilizers	Yield (kg ha^{-1})	Efficiency of N fertilizer(%)
2:8	8493	35.5
3:7	8764	41.0
4:6	9897	44.5
5:5	9883	41.1
6:4	9189	37.6
7:3	9083	33.6

Source: Ling *et al.* (2002)

The high yields from the distribution of N fertilizer at different growth stages should be concerned with the high N use efficiency. A study was made on the influence of the time and amount of N applied on NH_3 volatilization (Song *et al.*, 2004). The results presented in Table 9 showed that the rate of N loss was obviously varied with different application time and the loss amount was much larger with high level of N applied than with low level. The optimal pattern for N fertilization was recommended as: 40% of the total N applied should be used as basal fertilizer and 20% and another 40% as tillering and ear fertilizers, respectively. With this pattern, an objective rice yield of 9000 kg ha^{-1} could be achieved in soils with basic yield of 6000 kg ha^{-1} in Taihu Lake region (Wang, 2004).

Table 9. NH_3 volatilization loss after N applied at different periods of rice growth

Treatment	Total N applied	NH_3 volatilization loss			Total NH_3 loss (kg ha^{-1})
		Basal dressing	Tillering dressing	Ear dressing	
Low N	135	10.3 (25.4*)	20.9 (38.7)	7.5 (18.6)	38.7 (28.7)
High N	270	23.1 (28.5)	39.8 (36.8)	17.9 (22.1)	80.8 (29.9)

* The numbers in parentheses meant the percentage of the amount of N fertilizer applied

Source: Song *et al.* (2004)

Conclusions

China has a long history in rice cultivation and accumulated abundant experiences in high yield production. Combined traditional experiences and modern fertilization techniques, the fertilization measures for high yields of rice include: balanced input of N, P and K; co-application of organic and inorganic fertilizers; rational distribution of fertilizers in the rotation crops and adjustment of fertilizer use rate at different growth stages. With these measures, some optimized fertilization patterns were used in different areas and rotations to gain stable high yield of crops and minimum negative effects on environment. Recently, a large number of researches showed that as an artificial wetland, Chinese rice field ecosystem had done a lot of contribution on environmental protection: greatly reduced the removal of P and N from soil to water, helped the degradation of organic environmental pollutants with the alternant oxidation-reduction process, retarded the process of warming in the Earth as the store of CO_2, and decreased flooding risk. These contributions are surely related with the characteristics of the paddy soil and certainly concerned with the balanced fertilization measures.

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Potassium Imbalances and Sustainability of the Rice-Wheat Cropping Systems in South Asia

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Abstract

Due to large yield responses to application of nitrogen fertilizers and heavy subsidies, there exists a continued imbalance in the use of N, P and K fertilizers in both rice and wheat. Farmers in the Indo-Gangetic plains apply very small amount of K fertilizers to rice-wheat cropping systems. Responses of rice and wheat to applied K are generally small due to presence of illite as the dominant clay mineral in the soil. However, responses to K increase with time. On a long-term basis, rate of yield decline is more in soils receiving an imbalanced supply of N, P and K rather than where these are supplied in a balanced proportion. Total annual K removal by rice-wheat system exceeds 200 kg K ha^{-1}. Leaching of substantial amounts of K may further add to exhaustion of K in soil-plant system. Little or no additions of fertilizer K to soil under rice-wheat cropping system, generally leads to depletion of soil K supply. Continuous negative K balances (applied through fertilizers minus removal by crops) means soil K mining and ultimately loss in soil fertility. Possibly, in the near future, it may become difficult to maintain the present production levels of the rice-wheat system. Enhanced release of K from micas due to continuous removal of the reaction products by rice-wheat farming is accelerating the transformation of micas to expansible 2:1 layer silicates and other similar weathering products. Rice-wheat farming without application of adequate amounts of potassium fertilizers in the Indo-Gangetic plain may therefore soon lead to a point of no return posing a great threat to the sustainability of the system itself. Only the fertilizer management strategies leading to balanced supply of nutrients achieved through exogenous K supply based on supplies from soil and crop demand can ensure high and stable overall productivity with optimum economic return from the rice-wheat cropping system on long-term basis.

Keywords: Rice, wheat, south Asia, potassium imbalance, sustainability

With increasing population and wealth, the challenge for agriculture over the coming decades will be to meet the continuously rising demand for food in a sustainable way. Declining soil fertility and mismanagement of plant nutrients have made this task more difficult, particularly in the rice-wheat cropping system in the Indo-Gangetic plain of South Asia. This system occupies around 13.5 million ha in the Indo-Gangetic plains of Bangladesh, India, Nepal, and Pakistan (Ladha *et al.*, 2000). Due to introduction of high yielding varieties responsive to chemical fertilizers, the system witnessed a dramatic rise in productivity during the 1970s and 1980s. Afterwards rice and wheat yields have either remained stagnant or declined (ICAR, 1988; Duxbury *et al.*, 2000; Ladha *et al.*, 2003; Pathak *et al.*, 2003). Studies by Bhandari *et al.* (2002) and Regmi *et al.* (2002) attributed the reduced productivity of the rice-wheat system to declining soil organic matter, decreased soil fertility, occurrence of nutrient imbalances and inappropriate fertilizer practices.

In the rice-wheat system in South Asia, potassium imbalances emerge because of removal of large amount of K by aboveground plant parts and losses through leaching far exceeds the small additions through fertilizers and manures and it should have serious implications on the sustainability of the system on a long-term basis. Balanced application of N, P and K means replenishing the soil K reserves, which are being continuously mined by following high intensity rice-wheat cropping sequence. Depletion of soil K seemed to be a general cause of yield decline in 33 rice-wheat long-term experiments in the Indo-Gangetic plains investigated by Ladha *et al.* (2003). As exhaustion of K influences mineralogical transformations in soils, K nutrition of rice-wheat cropping systems is also important in terms of defining quality of the soil to be transferred to the future generations.

Application of Potassium vis-à-vis Nitrogen and Phosphorus

Rice occupies an area of 44.7 million ha and it accounted for 31.8 % (5.34 million t) of total fertilizer consumption in India during 2003/04 (Table 1). Fertilizer use on irrigated rice (155 kg ha^{-1}) is almost double that on rainfed rice (77.6 kg ha^{-1}). The average per-hectare use of fertilizer on rice was 119.1 kg (81.7 kg ha^{-1} N, 24.3 kg ha^{-1} P_2O_5 and 13.1 kg ha^{-1} K_2O). Wheat, grown largely under irrigated conditions accounts for 20.5 percent (3.44 million t) of total fertilizer consumption in India. Fertilizer use per hectare in 2003/04 was: 137 kg (100 kg ha^{-1} N, 30 kg ha^{-1} P_2O_5 and 7 kg ha^{-1} K_2O). Fertilizer use on irrigated wheat (144.9 kg ha^{-1}) is almost double that on rainfed wheat with the same trend for all the nutrients. Although the data for the two crops do not necessarily pertain to when these are sequentially grown in an annual rotation, yet these provide a fairly good idea of the extent of K fertilization vis-à-vis N and P. Although, rice-wheat cropping system in the Indo-Gangetic plain in India is practiced in various environments and on different soil types, the general recommendation for applying K to rice grown in rotation with wheat in the Indo-Gangetic plain in India is to apply 25 kg K ha^{-1} in Punjab (trans-Gangetic plains) and up to 50 kg K ha^{-1} in the middle- and lower-Gangetic Plains (Uttar Pradesh and West Bengal). For wheat, the range is 21 to 58 kg K ha^{-1} (Tiwari, 2000). Diagnostic surveys (Yadav *et al.* 2000b) have indicated that rice-wheat farmers in the Indo-Gangetic plain seldom adopt recommended fertilizer doses and K fertilizers are rarely used. While fertilizer N remained heavily subsidized, reduction in subsidies of phosphate and potash in India adversely affected their consumption. Per-hectare fertilizer use under rice-wheat cropping system in the Indo-Gangetic plain during 2002 is estimated at 334 kg (Sharma *et al.* 2004). It varies from 258 kg in the lower Gangetic Plain region to 444 kg in the Trans-Gangetic Plain (Haryana) region (Table 2). Interestingly, in the trans-Gangetic plain where highest amount of fertilizers are being applied to rice-wheat system, no K is being applied. On an average, farmers in the Indo-Gangetic plain apply 117.3 kg ha^{-1} N, 35.2 kg ha^{-1} P_2O_5 and 11.8 kg ha^{-1} K_2O on rice and 120.3 kg ha^{-1} N, 38.2 kg ha^{-1} P_2O_5 and 11.1 kg ha^{-1} K_2O on wheat. These figures reveal the extent of imbalance in applying fertilizer K vis-à-vis N and P is being made in rice-wheat cropping system in the Indo-Gangetic plains.

Table 1. Fertilizer use in rice and wheat in India

Crop	Gross cropped area (million ha)	Share in fertilizer consumption (%)	Fertilizer consumption (kg ha^{-1})			
			N	P_2O_5	K_2O	Total
Rice-irrigated	24.0	22.2	103.4	32.8	18.8	155.0
Rice-rainfed	20.7	9.6	56.6	14.5	6.5	77.6
Wheat-irrigated	22.8	19.7	105.6	32.1	7.3	144.9
Wheat-rainfed	2.9	1.3	55.7	15.9	4.3	75.9

Source: FAO (2005)

Table 2. Fertilizer use pattern under the rice-wheat cropping system in the Indo-Gangetic plain in India

Region	Crop	Fertilizer consumption (kg ha^{-1})			
		N	P_2O_5	K_2O	Total
Upper Gangetic plain	Rice	108.3	44.6	2.2	155.1
	Wheat	109.8	52.2	2.1	164.1
Trans-Gangetic plain (Punjab)	Rice	141.3	58.5	0	199.8
	Wheat	143.2	58.7	0	201.9
Trans-Gangetic plain (Haryana)	Rice	163.2	52.8	0	216.0
	Wheat	171.3	56.9	0	228.2
Middle Gangetic plain	Rice	111.9	36.4	9.8	158.1
	Wheat	111.6	42.4	11.6	165.6
Lower Gangetic plain	Rice	85.9	9.9	32.8	128.5
	Wheat	95.5	6.5	27.6	129.6
Indo-Gangetic plain	Rice	117.3	35.2	11.8	164.2
	Wheat	120.3	38.2	11.1	169.7
	Rice + Wheat	237.6	73.4	22.9	333.9

Source: Sharma *et al.* (2004)

A look at $N:K_2O$ ratios for nutrients consumed in states in the Indo-Gangetic plain (Table 3) reveals that in 2004 it was wider in northwestern states of Punjab (30.8) and Haryana (48.2) consuming the highest amount of fertilizer per unit area as compared to that in the eastern states (2.5 in West Bengal) of the Indo-Gangetic plain (Fertiliser Association of India, 2005). This trend is continuing since 1990s. Thus, although the fertilizer consumption is the highest in the intensively cultivated northwestern states yet the $N:P_2O_5:K_2O$ ratio has always been far from the ideal ratio of 4:2:1 (Table 1). Fertilizers are thus not being applied in a balanced way; there has been always a bias towards application of large doses of N vis-à-vis P and K.

Table 3. Fertilizer nutrient consumption per ha of cropped area in different states of the Indo-Gangetic plain and ratios of $N:P_2O_5:K_2O$

State	1991-92		1997-98		2003-04	
	$N:P_2O_5:K_2O$	$N+P_2O_5+K_2O$ (kg ha^{-1})	$N:P_2O_5:K_2O$	$N+P_2O_5+K_2O$ (kg ha^{-1})	$N:P_2O_5:K_2O$	$N+P_2O_5+K_2O$ (kg ha^{-1})
Punjab	51.5:17.7:1	168.4	45.2:12.9:1	170.9	30.8:8.8:1	193.2
Haryana	62.6:31.8:1	112.8	171.0:47.8:1	140.1	48.2:14.9:1	161.7
Uttar Pradesh	16.8:4.4:1	88.7	26.0:6.3:1	117.7	15.5:5.05:1	127.6
Bihar	9.1:2.8:1	57.9	11.5:2.9:1	87.2	24.3:1.8:1	88.0
West Bengal	2.5:1.3:1	90.5	3.2:1.5:1	112.0	2.5:1.3:1	114.1

Source: Fertilizer Association of India (2005)

Potassium Imbalance Effects on Yield of Rice and Wheat

Response of rice-wheat cropping systems to applied potassium

Studies carried out on a large number of on-farm locations in India showed that application of 60 kg K ha^{-1} (40 kg K ha^{-1} in case of rainfed rice) produced a grain yield response of 290 and 240 kg ha^{-1} in wheat and rice, respectively (Randhawa and Tandon, 1982). Percent yield increases over control (Table 4) with application of N, NP and NPK clearly exhibit the role of balanced application of fertilizer nutrients to both rice and wheat. In a large number of field experiments conducted on cultivators' fields in alluvial tracts of Uttar Pradesh, positive responses to K up to 50 kg ha^{-1} for rice and wheat under irrigated conditions were observed. The yield response was 3.6 to 8.6 kg grain kg^{-1} K in rice and wheat (Yadav *et al.*, 1993). Grain yield of rice and wheat increased with increasing levels of K up to 70 kg K ha^{-1} in calcareous soils (Prasad, 1993). In a two-year field experiment, response of two varieties of wheat HD 1941 and UP 301 were tested with four rates of K application on sandy loam (pH 7.6) alluvial soil of Varanasi. Application of 42 kg K ha^{-1} significantly increased the grain and straw yields, the response being 4.8 kg grain kg^{-1} K applied (Singh *et al.*, 1993). In studies carried out in Punjab, Haryana and Uttar Pradesh in the trans-Indo-Gangetic plains, response of rice to 25-50 kg K ha^{-1} ranged from 210-370 kg grain ha^{-1} (Meelu *et al.* 1992). Dobermann *et al.* (1995) observed significant yield increase of 12% to K application in rice at Pantnagar. In a 5-year field study on a sandy loam soil (ammonium acetate extractable K, 123 kg ha^{-1}), application of 25 kg ha^{-1} resulted in a mean increase in yield of rice and wheat by 280 and 160 kg grain ha^{-1}, respectively (Meelu *et al.*, 1995). In a number of long-term experiments on rice-wheat system located all over the Indo-Gangetic plain (Table 5), average response to application of 33 kg K ha^{-1} over 120 kg N and 35 kg P ha^{-1} to each crop ranged from 0 to 0.5 t ha^{-1} in rice and 0 to 1.3 t ha^{-1} in wheat.

Table 4. Effect of balanced nutrition on yield of rice and wheat in on-farm experiments in India

Crop	Number of experi-ments	Nutrients $N-P_2O_5-K_2O$	No-fertilizer control (t ha^{-1})	Yield increase over control (%)		
				N	NP	NPK
Rainfed rice	380	120-60-40	2.42	49	74	99
Irrigated rice	9634	120-60-60	2.96	27	51	56
Irrigated wheat	10133	120-60-60	1.55	59	95	114

Source: Randhawa and Tandon (1982)

Table 5. Response of sequentially grown rice and wheat to application of potassium in long-term experiments in the Indo-Gangetic Plains of India

Location	Years	Crop	Grain yield (t ha^{-1})			
			No-NPK	N	NP	NPK
Barrackpore†	1972-97	Rice	1.6	3.5	3.9	4.0
		Wheat	0.8	2.1	2.3	2.4
Pantnagar†	1972-96	Rice	3.4	5.0	5.0	5.4
		Wheat	1.6	3.8	3.8	3.9
R.S. Pura	1981-90	Rice	2.1	4.2	4.8	4.8
		Wheat	1.1	1.9	3.1	3.5
Palampur	1978-89	Rice	2.3	4.1	4.0	4.5
		Wheat	1.2	1.3	2.4	3.7
Faizabad	1977-90	Rice	1.0	3.9	4.7	4.8
		Wheat	0.8	3.6	4.5	5.5
Kanpur	1977-87	Rice	1.7	3.5	4.2	4.4
		Wheat	1.2	3.5	4.1	4.2
Pantnagar	1977-90	Rice	2.3	4.0	4.2	4.4
		Wheat	1.4	3.5	3.5	3.5
Varanasi	1977-88	Rice	2.1	4.1	3.7	3.8
		Wheat	1.3	3.1	3.5	3.6
Rewa	1978-90	Rice	2.0	3.9	4.1	4.2
		Wheat	1.0	1.5	2.7	2.9

Source: Swarup (1998)†; Hegde and Sarkar (1992)

Using time series analyses, Bhargava *et al.* (1985) showed that response to K has been increasing with time. The response of wheat to K in different agro-ecological regions was in the range of 6.7-12.7 kg grain kg^{-1} K during 1977-1982 as against 2.0-5.0 kg grain kg^{-1} K during 1969-1971. The corresponding values for rice were 6.5-10.7 kg and 1.8-8.0 kg grain kg^{-1} K (Table 6). Kumar and Yadav (2001) studied the effect of applying graded doses of NPK to rice-wheat system on yield trends and changes in response functions in a 20-year long-term experiment. The highest rate of yield decline in both rice and wheat was found when 120 kg ha^{-1} N was applied alone (Table 7). On the other hand, the lowest rate of decline was observed when all three nutrients (N, P and K) were applied, at 40, 35 and 33 kg ha^{-1} for N, P and K, respectively, followed by 120, 35 and 33 kg ha^{-1} (the recommended levels). The yield response of rice and wheat to N fertilizer declined over the 20 years, with a higher rate of decline in wheat. In contrast, the response to applied P and K increased with time in both crops, with a higher response rate in wheat. Kumar and Yadav (2001) further observed that rice and wheat crops did not respond greatly to applied K during the initial 10 years (Fig 1). Thereafter, the responses to K increased in both rice and wheat. In the 20^{th} year the incremental response of rice and wheat to K fertilizer reached 6.4 and 8.3 kg grain kg^{-1} K, respectively. Balance between different nutrient elements is necessary for sustainability over time. Data in Fig 2 clearly shows that wheat yields become uneconomical after 5 years when only N fertilizer is applied (Saxena, 1995). Even annual field applications of NP fertilizers are insufficient to sustain yields over the long term. The increasing trend in response to K over the years suggests the need for its application in intensive rice-wheat cropping system.

Table 6. Response of rice and wheat over different periods to applied potassium in different agro-ecological regions in India

Region	Response to 50 kg K ha^{-1} (kg grain kg^{-1}K)			
	Rice		Wheat	
	1969-71	1977-1982	1969-71	1977-82
Humid, Western Himalayan Subhumid, Satluj-Ganga Alluvial Plain	8.0	10.7	5.0	12.7
Subhumid to humid	4.8	7.0	3.4	7.8
Eastern Uplands	4.4	9.8	2.0	7.1
Arid western Plains	1.8	6.5	2.6	6.7

Source: Bhargava *et al.* (1985)

Table 7. Rate of decline (kg ha^{-1} year^{-1}) in grain yields of rice and wheat in a continuous rice-wheat system from 1977 to 1996 under different NPK fertilizer treatments

Fertilizer treatment (kg ha^{-1})			Yield decline rate over 20 years (kg ha^{-1} year^{-1})	
N	P	K	Rice	Wheat
0	0	0	36	29
40	35	33	30	60
80	35	33	37	93
120	35	33	38	102
120	0	0	105	197
120	35	0	45	113
120	0	33	85	196
L.S.D. (5%)			18	21

Source: Kumar and Yadav (2001)

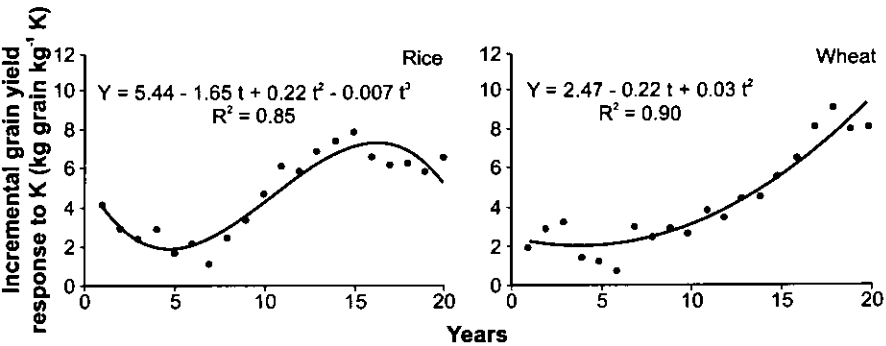

Fig 1. Incremental grain yield response of rice and wheat to K application at 33 kg ha^{-1} over 20 years in a continuous rice-wheat cropping system (Adapted from Kumar and Yadav, 2001)

A large proportion of area (about 2.8 million ha) in the Indo-Gangetic plain is highly alkaline (pH >8.5) and contains excessive concentration of soluble salts, high exchangeable sodium percentage (> 15%) and $CaCO_3$. In salt affected soils of Kanpur, application of 25 kg K ha^{-1} to both crops produced additional grain yield of 0.50 and 0.61 t ha^{-1} of rice and wheat, respectively (Tiwari *et al.*, 1998). However, Swarup and Singh (1989) found that application of fertilizer K did not significantly increase crop yields in rice-wheat rotation on reclaimed sodic soils in Haryana even after continuous cropping for 12 years.

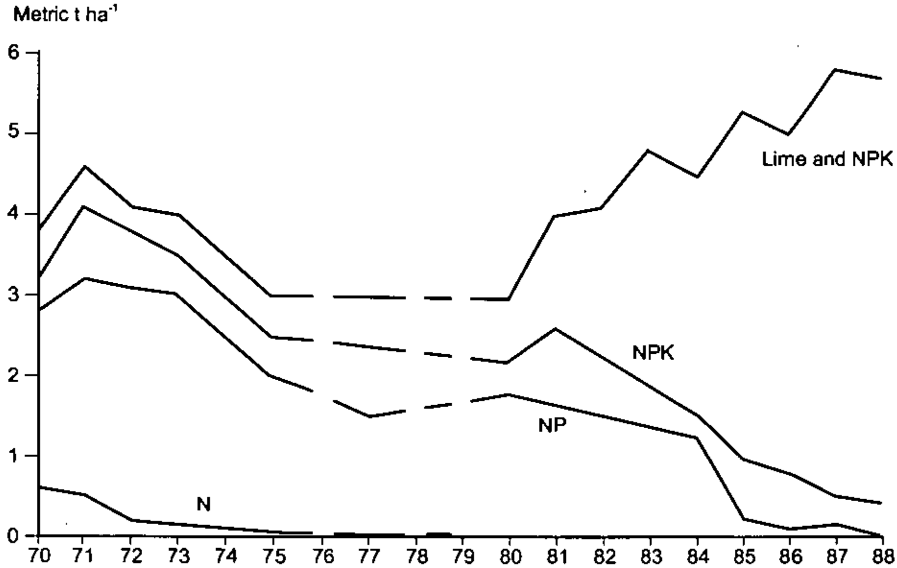

Fig 2. Long-term (1970-88) effect of balanced fertilization on wheat yield (adapted from Saxena, 1995)

Effect of potassium fertility status of soils on response to potassium

Responses of rice and wheat to K application are expected to be high on soils testing low in 1*M* ammonium acetate-extractable K than on high K soils. Significant responses of wheat to applied K were observed up to 25 kg K ha^{-1} on soils testing low in available K in Punjab, but no significant increase in wheat yield was observed on soils testing medium and high in available K (Sharma *et al.*, 1978, Stillwell *et al.*, 1975, Yadvinder-Singh and Khera, 1998). Rana *et al.* (1985) observed that rice responded to 50 kg K ha^{-1} on soils testing low and medium in available K, but no significant response to applied K was observed on soils testing high in available K. Experiments carried out by Kapur *et al.* (1984) revealed that wheat responded up to a dose of 75 kg K ha^{-1} on low K soils and up to 50 kg K ha^{-1} on medium and high K soils. On the same lines, Azad *et al.* (1993) observed that whereas wheat yield increased significantly up to 75 kg K ha^{-1} on soils testing low in available K, significant increase in wheat yield was observed only at 25 kg K ha^{-1} on soils testing medium as well as high in available K. Tandon and Sekhon (1988) concluded that response of high yielding varieties of rice and wheat to K application in soils rated medium in available K were only marginally lower than responses in low K soils. Such results emphasize the need for fresh look at soil fertility limits used for categorizing soils into low, medium and high with respect to available K, particularly for highly productive rice-wheat cropping system.

In a long-term experiment on rice-wheat system initiated in 1977-78 at Faizabad in the middle Indo-Gangetic plains, both the crops did not respond to applied K in the first 10 years. Thereafter, responses to applied K started increasing; higher response was observed in wheat (Yadav *et al.*, 2002). The release of K from non-exchangeable pool was responsible for the lack of response during initial years. Field experiments conducted at different locations in the Indian Punjab showed that rice responded more to applied K in north-eastern districts (Gurdaspur, Amritsar, Kapurthala and Hoshiarpur) than in central and south-western districts (Ludhiana, Bathinda, Sangrur, Ferozepur) (Singh and Bhandari, 1995). The values of available K in soil ranged from 150-180 kg K ha^{-1} in northwestern districts and 112-165 kg K ha^{-1} in central and southwestern districts. A 6-year study conducted at two locations in northwestern India showed that both rice and wheat responded significantly to K application up to 50 kg K ha^{-1} on a loamy soil at Gurdaspur, whereas no significant increase in rice yields was observed on a sandy loam soil at Ludhiana (Yadvinder-Singh *et al.* 2002). Wheat started responding to K application at Ludhiana two years after the initiation of the experiment. Although soils at both the locations tested low in ammonium acetate extractable K, higher response at Gurdaspur was due to high K-fixation capacity and slow K-release rate of the loamy soil. These results suggest that K supplying capacity of different soils is governed by pools of K other than water soluble plus exchangeable K.

It has been established that crop yield, profit, plant nutrient uptake, and nutrient use efficiencies can be significantly increased by applying fertilizers on a field-specific and cropping season specific basis. Fertilizer K rates predicted by the QUEFTS model (Janssen *et al.* 1990) to achieve the target yields and maintain the soil indigenous K supply were, on average, higher than the amounts currently applied by the farmers. Potassium rates in site-specific nutrient management plots ranged from 50-66 kg K ha^{-1} per crop, while the average farmer fertilizer K rate was 30 kg K ha^{-1}. Estimated K requirement (kg t^{-1} grain yield) using QUEFTS model ranged from 14.5-15.7 kg for rice (Witt *et al.*, 1999) and 28.5-32.0 kg for wheat (Pathak *et al.* 2003).

Potassium Balance in Rice-Wheat Cropping Systems

Potassium uptake by rice-wheat cropping systems

The removal of K depends on the production level, soil type and whether crop residues are removed or recycled in the soil. When crop residues are retained in the field, large amounts of K are recycled. Field crops generally absorb K faster than they absorb N or P or build up dry matter. Optimum application of N increased K uptake by 57% over control plots and N and P application increased K uptake by 145% (Tandon and Sekhon, 1988). The amount of K removed by rice-wheat cropping system from the soil can be as high as 325 K kg ha^{-1} in the Indo-Gangetic plains (Table 8). Grains of wheat contain more K than those of rice; opposite is true for straw. Based on published data from field experiments conducted during the years 1970 to 1998 across wheat growing environments in the Indo-Gangetic plains in India, Pathak *et al.* (2003) observed a relationship ($R^2 = 0.82$) between K uptake in no-K plots, a real measure of soil K supply and exchangeable soil K. Experiments carried out in the Indo-Gangetic plains (Tiwari *et al.*, 1992) suggest that contribution of non-exchangeable K fraction to the nutrition of rice and wheat was 89 % when no K was applied and 56 % when fertilizer K was applied at 50 kg K ha^{-1} to both rice and wheat.

Table 8. Potassium Removal by rice-wheat cropping systems in the Indo-Gangetic Plains

Cropping system	Total productivity (t ha^{-1})	K uptake (kg ha^{-1})	Reference
Rice-wheat-green gram	8.2	232	Yadav *et al.* (1998)
Rice-wheat	13.2	287	Kanwar and Mudahar (1986)
Rice-wheat-cowpea	9.6+3.9 (dry)	324	Nambiar and Ghosh (1984)
Rice-wheat-jute	6.9+2.3 (fibre)	212	
Rice-wheat	8.8	280	Sharma and Prasad (1980)
Rice-wheat-mungbean	11.2	279	Meelu *et al.* (1979)
Rice-wheat	10.7	238	Bhandari *et al.* (2002)

Potassium balance in the soil-plant system

Long-term studies have shown that K balance in rice-wheat system is highly negative even when recommended doses of K are applied to rice-wheat cropping system. Data obtained from a long-term experiment at Ludhiana in western India (Table 9) shows that highly negative K balance in NPK treatments was substantially improved by returning wheat residues. In Fig 3, K balances are shown from two long-term experiments in middle and lower Gangetic plains in which treatments consisted of increasing levels of NPK (Nambiar and Ghosh, 1984). Interestingly at Barrackpore in West Bengal, higher K levels applied due to smectitic nature of clay minerals resulted in K balance ranging from 0 to -75 kg K ha^{-1}. In sharp contrast, K balances in illitic soils in Pantnagar were highly negative even under 150% NPK treatment as removal of K by rice and wheat was high even at low K application levels (Fig 3). In a long-term experiment at Ludhiana, net negative K balance of more than 200 kg K ha^{-1} $year^{-1}$ was observed when no K was applied to rice or wheat. Application of fertilizer K to rice, wheat or both resulted in less negative K balance. Removal of all the straw from the fields leads to K mining at alarming rates because 80-85% of the K absorbed by rice and wheat crops is in the straw.

Table 9. Annual potassium balance in a long-term experiment progressing at Ludhiana (1988-2000)

Treatment	Input (kg K ha^{-1} year^{-1})				Output (kg K ha^{-1} year^{-1})		Balance (kg K ha^{-1} year^{-1})
	Manure/ Fertilizer	Irrigation	Rain	Seed	Crop removal	Leaching loss	
NPK	50	100	5.0	2.7	285	19	-151
Wheat straw +NPK	111	100	5.0	2.7	281	28	-90
FYM +NPK	131	100	5.0	2.7	271	31	-63

Source: Yadvinder-Singh *et al.* (2004)

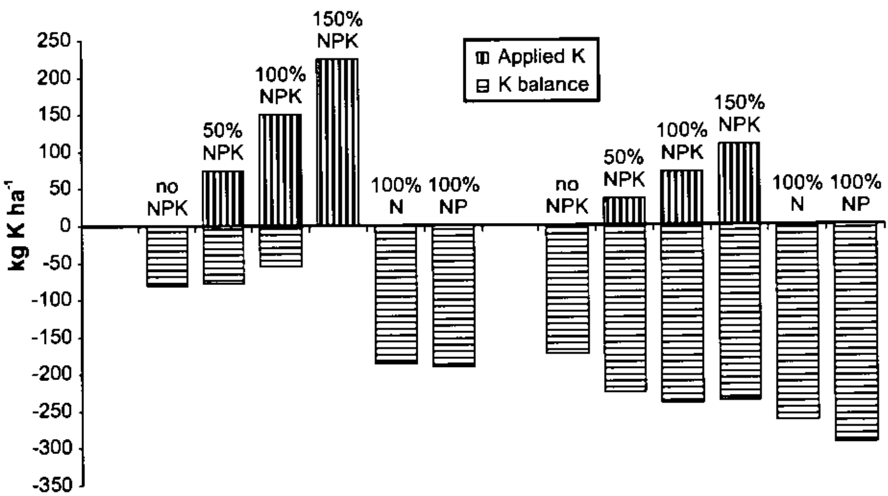

Fig 3. Potassium balance (applied minus removed by rice and wheat) in different treatments in long-term experiments at Barrackpore and Pantnagar (Adapted from Nambiar and Ghosh, 1984)

Ladha *et al.* (2003) analyzed 33 rice-wheat long-term experiments in the Indo-Gangetic plains of South Asia, non-Indo-Gangetic plains in India and in China to monitor yield trends, and identify possible causes of such yield trends. In treatments where recommended rates of N, P and K were applied, yields of rice and wheat stagnated in 72 and 85% of the long-term experiments, respectively, while 22 and 6% of the long-term experiments showed a significant ($P<0.05$) declining trend for rice and wheat yields, respectively. In over 90% of the long-term experiments, the fertilizer K rates used were not sufficient to sustain a neutral K input-output balance (Fig 4). All the long-term experiments with a significant yield decline had large negative balances of K.

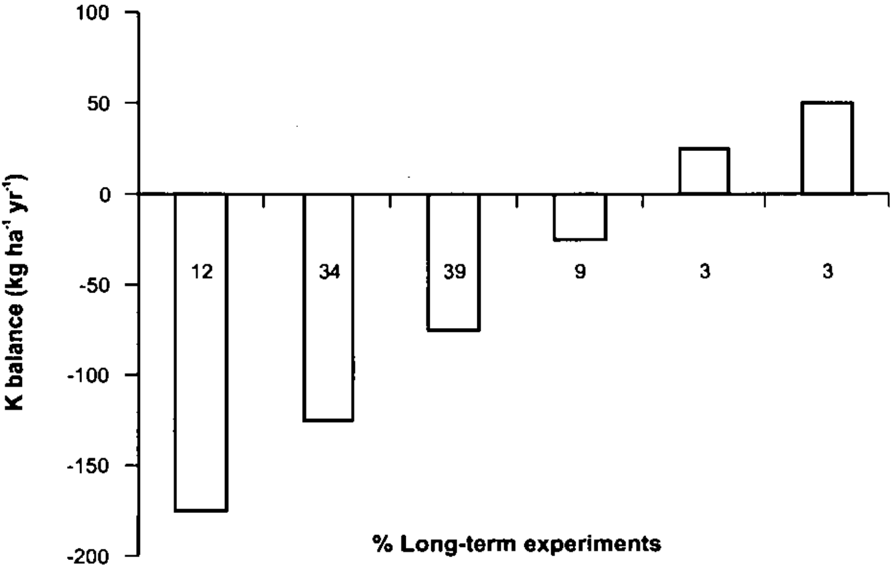

Fig 4. Apparent K balances in rice-wheat cropping system long-term experiments in Asia (adapted from Ladha et al., 2003)

The negative K balance means that it will be impossible to maintain the present production levels of the rice-wheat system. Long-term studies suggest that application of farmyard manure and recycling of crop residues can help improve the K balance in the rice-wheat cropping system. There is, however, a need to work out long-term K balances in the rice-wheat system based on precise data on K removal from a field or region through straw, K inputs from irrigation or rainwater besides the well defined inputs and outputs such as fertilizers, manures and grains. Straw management can strongly influence K budgets and can help in efficient management of K for a sustainable rice-wheat system in the Indo-Gangetic plain.

Effect of Negative Potassium Balance on Mineralogy and Fertility of the Soil

Mineralogy of soil potassium

Potassium feldspars and micas are the K minerals present in the soils of Indo-Gangetic alluvial plains in India (Sidhu, 1984). Potassium feldspar species present in these soils are microcline and orthoclase. Mica minerals present are muscovite and biotite in the coarser fractions and illite in the finer fractions. Illite, a mixed layer mica-monmorillonite, is partially weathered muscovite mica with layer charges less than for muscovite; part of its charge originates in the octahedral layer, unlike the muscovite. The salt affected alluvial soils in the Indo-Gangetic plain were found to contain smectite-mica and chlorite-vermiculite interstratified minerals. In the lower Gangetic basin, illite or smectite are the dominant minerals in the soils. Mishra *et al.* (1996) found that whereas smectite-illite-chlorite is the most common clay mineral phase in the terraces, soil clays of flood plains are dominated by illite-smectite-chlorite phase in the middle and lower Gangetic plains. Sekhon *et al.* (1992) carried out a systematic study of mineralogical composition of silt and clay fractions in soil samples collected from 8 soil series in the rice-wheat regions in the Indo-Gangetic plain in India. The results of this study revealed that except in two series from lower Gangetic plains in West Bengal, illite is the dominant clay mineral in the 6 soil series spread over states of Punjab, Uttar Pradesh, and Bihar. Dominant minerals in the silt fraction in the entire Indo-Gangetic plain are quartz-feldspar, quartz-mica or quartz alone.

Minerals continue to weather and proton exchange constitutes an important means for K release from micas. The degraded micas thus formed acquire inter-layer space from which more K can be released in time. However, if application of K fertilizer increases the concentration of K in soil solution, K^+ may get into expanded interlayer space and become fixed by reversing the weathering process. Since hydrated form of Ca^{2+}, the dominant cation in the solution of most soils under rice-wheat system in the Indo-Gangetic plain, is bigger in size than K^+, it enlarges the interlayer space releasing more K^+ in the process. When plant roots remove K from the soil solution, more K continues to be released from the clay minerals by cation (including proton) exchange. The gradual release of K from positions in the mica lattice results in the formation of hydrous mica (6-8 % K) or illite (4-6 % K). Further release of K due to weathering including excessive mining by rice-wheat cropping system converts illite to transitionary clay minerals (2-3 % K) such as expanding illites and interstratified minerals and ultimately lead to formation of montmorillonite/vermiculite (< 1% K).

The negative K-balance has serious implications on mineralogy of K in soils under rice-wheat cropping system in the Indo-Gangetic plains. Due to incorporation of K through canal and tube well water containing substantial amounts of K, weathering of K containing minerals, particularly illite is minimal. Mukhopadhyaya *et al.* (1992) observed formation of edge-wedge sites in K bearing minerals when K^+ was removed through 18 successive crops. After 28 crops, there was about 1% conversion of illite to vermiculite. The X-ray diffractograms of 1.0 nm peaks showed broadening towards low angle suggesting loss of interlayer K^+. A co-occurrence of illite and vermiculite indicated that in spite of K incorporation through irrigation, crop residues and fertilizers, the minerals exist under K^+-loss domain. The scenario is alarming in view of advancement of weathering front in illite-vermiculite or illite-vermiculite-smectite phases.

Potassium fertility of soil

Depletion of soil K reserves is a matter of deep concern from the point of view of sustainability of rice-wheat system. It is important to analyze the data from long-term experiments so as to plan efficient management of both K fertilizers and soil K reserves. In six out of 8 benchmark soil series in the Indo-Gangetic plain studied by Sekhon *et al.* (1992) for detailed characterization of K, measurements were made again after 10 years to assess changes in K fertility of soils. The data pertaining to changes in ammonium acetate and HNO_3 extractable K are listed in Table 10. Both the indices show considerable decrease in availability of K in a span of 10 years thereby suggesting that crops may start responding to K fertilizer in course of time. Tiwari (1985) observed a decline in available K and non-exchangeable by 17% and 2.8% after two cropping cycles measured on 14 fields at Kanpur (middle Indo-Gangetic plains). In long-term experiments progressing at different locations in the Indo-Gangetic plain, a decrease in available K have been observed at all sites in treatments where no K has been applied during 13 to 14 year period (Table 11). Except at Ludhiana, a decrease in available K content of soil was noticed even in treatments receiving K for both wheat and rice. These data suggests that fertilizer doses considered as optimum can still result in K depletion from the soil at high productivity levels and in the process become sub-optimal doses.

Table 10. Changes in potassium fertility in some soil series in rice-wheat growing regions of the Indo-Gangetic Plains

Soil series and location	Ammonium acetate-K ($mg\ kg^{-1}$)		HNO_3 - K ($mg\ kg^{-1}$)	
	First sampling	After 10 years	First sampling	After 10 years
Nabha, Ludhiana, Punjab	104±54	63±41	965±255	875±230
Akbarpur, Etah, Uttar Pradesh	125±41	71±23	1448±203	1231±188
Rarha, Kanpur, Uttar Pradesh	95±33	79±20	1531±353	1497±180
Hanrgram, Bardhaman, West Bengal	132±53	93±16	425±160	400±191
Kharbona, Birbhum, West Bengal	42±17	29±16	119±34	109±26

Source: Sekhon (1999)

Table 11. Changes in available potassium in soils in different treatments (no NPK, 50% NPK, 100% NPK†, 50% NPK + FYM, 50% NPK + crop residues, 50% NPK + green manure) in long-term fertility experiments on rice-wheat system at various locations in the Indo-Gangetic plains

Location	Duration of the experiment	1*M* ammonium acetate extractable K (mg kg^{-1})	
		At beginning	After 12 to 15 years
Ludhiana	1983-84 to 1997-98	46	4-17% increase (except in no NPK treatment)
Pantnagar	1983-84 to 1997-98	65	17-34% decrease
Kanpur	1985-86 to 1997-98	82	10-22% decrease
Faizabad	1984-85 to 1997-98	161	10-30% decrease
Sabour	1984-85 to 1997-98	58	7-14% decrease except in 50% NPK + FYM treatment

†100% NPK = 120 kg N + 26 kg P + 33 kg K ha^{-1}

Source: Yadav *et al.* (2000a)

Warning signals are already emanating from present K management practices with respect to sustainability of the rice-wheat system as soil deterioration with respect to K supplying power is being largely overlooked (Bijay Singh *et al.*, 2004). About a quarter century ago, Singh and Brar (1977) could show that continuous cropping without K dressing decreased 1*M* ammonium acetate extractable K in a soil from trans-Gangetic plains in North West India from 165 to 85 kg ha^{-1}. Still there was no response of crops to K application; obviously 90 % of K demand was met by release of K from non-exchangeable pool. In a 8-year experiment on a Vertisol, Singh *et al.* (2002) applied 33 kg K ha^{-1} to both rice as well as wheat and in view of a large negative K balance found sustainability of the system at threat as a distinct depletion of K from the sum of changes in HNO_3+$HClO_4$ extractable K after 8 years (16 crops) in 0-15, 16-30, and 31-45 cm layers was observed. In no N treatment, the total depletion of K was 54 kg K ha^{-1} year^{-1}, and it increased to 102 and 145 kg ha^{-1} year^{-1} on application of 90 and 180 kg N ha^{-1} to rice.

Potassium Imbalance and Nitrate Pollution of Ground Water

Nutrient imbalances always lead to low nutrient use efficiencies. Application of inadequate amounts of potassium fertilizers to crops like rice and wheat result in decreased nitrogen use efficiency which in turn leads to increasing amounts of unutilized mineral N in the soil. In irrigated agriculture, nitrate-N accumulated in the soil profile can leach beyond the root zone of crops during subsequent irrigation events and eventually reach ground water bodies and pollute these. In Fig 5 data have been plotted from two experiments (Bijay-Singh and Sekhon, 1976). When N, P and K were not applied in a balanced way to wheat (like in treatment $N_{120} P_0 K_0$), a large amount of nitrate-N was found to be present in the profile for subsequent leaching beyond. On the other hand, in the second experiment when N,P and K are applied in a balanced way but total amount of nutrients is increased from no-NPK to 150% of the recommended dose of NPK it always leads to negligible amounts of nitrate-N in the profile. It suggests that when nutrients are applied in a balanced way, these are absorbed by plants vigorously even in quantities more than that required for optimum economic yield.

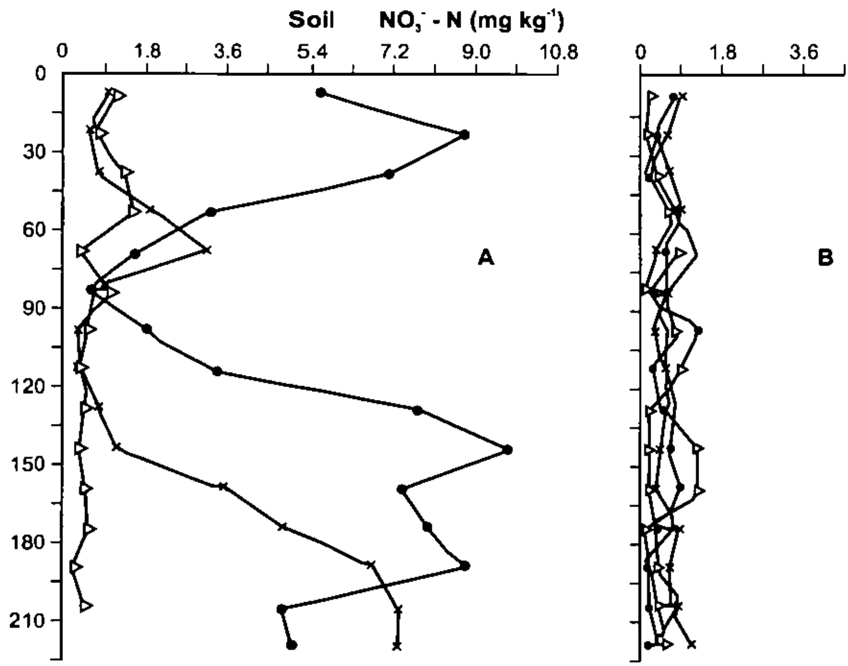

Fig. 5 Accumulation of nitrate-N in soil profiles as influenced by balanced application of N, P and K in wheat. Legend: A,•-----•$N_{120}P_0K_0$, ×-----× $N_{120}P_{13}K_{25}$, Δ-----Δ $N_{120}P_{26}K_{25}$. B,•-----•150% NPK, ×-----× 100% NPK, Δ-----Δ 50% NPK,□-----□no-NPK control (Adapted from Bijay-Singh and Sekhon, 1976)

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Efficiency of Potash Fertilizer Application in Rice-Rice and Rice-Wheat Cropping Systems in Bangladesh

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Abstract

Research trials and farmers' field demonstrations were conducted in the Central part and Northwestern (NW) region of Bangladesh to study the effect of potassium fertilizer on rice and wheat yields and find out the appropriate dose of potassium fertilizer for these crops under rice-rice and rice-wheat cropping pattern. Potassium fertilization significantly increased the production of rice-rice and rice-wheat cropping system. In the complete fertilized plot, the yearly grain yield of rice was roughly consistent within the range of 9-10 t ha^{-1} while in the -K plots the grain yield production decreased sharply with time from about 10 t ha^{-1} in 1985 to 6.2 t ha^{-1} in 2000. The initial rice yield decreased due to omission of K was not significant but the yield gap between the balanced treatment and the -K treatment widened sharply and significantly with time. In the reverse treatment i.e., the application of K to the plots not receiving K for the last 16 years, a dramatic yield increase by 2 t ha^{-1} was observed. The estimated nutrient balance after 16 years indicated a severe depletion of K from experimental soil. The rate of K mining from fertilized plot was 141 kg $ha^{-1}yr^{-1}$ and from K omitted plot was 132 kg $ha^{-1}yr^{-1}$.

Potassium fertilization @ 50 kg K ha^{-1} appeared to be sufficient and economically most viable to produce optimum grain yield of rice in both dry and wet season in clay loam soil at Gazipur and 66 kg K ha^{-1} for T. Aman rice and wheat in sandy loam soil in Northwestern region of Bangladesh. Crop residues incorporation @ 4.5 t ha^{-1} substantially increased the rice and wheat yield, which was comparable to that of 33 kg K ha^{-1} and farmers K dose. The effect of applied K was more prominent in light textured soil than in heavy textured soil. On the other hand, wheat crop utilized the applied K more efficiently than rice crops. In research trials K fertilization increased rice grain up to 14% over control plot in clay loam soil while 30% of rice and 53% of wheat grain in sandy loam soil. Application of K fertilizer on soil test based (STB) increased grain yield of rice up to 20% in T. Aman and 22% in Boro season in the farmer's field demonstration at Gazipur while in NW region, the application of K fertilizer on STB in farmer's field increased grain yield of wheat by 86% and T. Aman rice by 25% over K control plot. Response of K fertilizer to the grain yield of rice and wheat was found more prominent in farmer's field demonstration than that of research trial in experimental field.

Keywords: Rice, wheat, potassium, crop residue, fertilizer efficiency

Potassium (K) is a major plant nutrient and its requirement for rice is quite high, even greater than that of nitrogen (N). The K reserve of any soil is certainly limited, and no soil can supply K to crops adequately for an indefinite period of time. Studies on K buffering capacity, K-depletion, K release pattern and Q/1 relationships of some soils indicated that there is a difference in soils in immediate and long term availability of K (Progress Report, 1991). Intensive cropping and use of modern rice varieties for high yield caused heavy depletion of K in soils particularly in the absence of K application (Tiwari, 1985). Mohanty and Mondal (1989) reported a negative K balance in rice systems at many sites in India. A negative K balance even upto 60 kg ha^{-1} applied K level with diminishing magnitude was observed in a recent study at Bangladesh Rice Research Institute (BRRI) and suggested that an amount of about 60 kg K ha^{-1} would be required to sustain soil native K for rice cropping (Ahsan *et al.*, 1997). Recent study indicated that about 60% cultivable land of Bangladesh is deficient in N, P and K. Most of the area of the north western part of the country is deficient in K. Light-textured soils of these areas have low exchangeable K and farmers also use low amount of K fertilizer (Miah, 2005). As the pressure to grow more food from the same piece of land increases, the soils come under the threat of nutrient depletion. Nutrient balance studies indicated a negative balance for N and K and the mining of K from Bangladesh soils is now in an alarming situation. The value varied between 0 to 50 kg ha^{-1} yr^{-1} for N and -100 to - 25 kg ha^{-1}yr^{-1} for K (Rijmpa and Islam, 2002). Rice is the staple food of Bangladeshi people. Wheat is relatively a new crop and growing wheat in a rice-wheat cropping pattern has been getting importance as a promising system for increasing food production in the country. Rice-wheat cropping system draws a lot of potassium from the soil and taking in to consideration inadequate potash fertilizer inputs, soils are often single supplier of K to plants in the Indo Gengetic plains. As recently reviewed by Bijay Singh *et al.* (2004), K removal by rice wheat cropping system in the Indo Gengetic plains and in China ranges from 132 to 324 kg ha^{-1} depending upon the cropping system and the productivity.

Long-term on-farm experiments conducted in different Asian countries indicated that initial rice yield increase due to K application was not significant (Witt *et al.* 2004). However, yield increase was consistent and become larger over time. Over 16-year period, the omission of K fertilizer significantly decreased the yield of rice and the yield gap between the balanced treatment and the -K treatment widen sharply with time (BRRI, 2001). Diba *et al.* (2005) reported a positive effect of K fertilizer use on rice yield contributing parameters. The response to K fertilizer on cereal crops like wheat was reported by Saha *et al.* (2001) and rice by Ahsan *et al.* (1997). Timsina and Connor (2001) reported that intensive rice-based cropping system including wheat may cause heavy depletion of soil K. Potassium deficiency in wetland rice has so far received limited attention. The general recommended dose of K fertilizer for MV rice in Bangladesh is ~ 35 kg ha^{-1} while an average crop of rice yielding 4.0 t ha^{-1} removes at least 70 kg K ha^{-1} from the soil. The present K fertilizer management practice may not be enough for sustaining a favourable K fertility status of the soil in the long run. There is a tremendous scope of K fertilizer application for increasing cereal crop production in Bangladesh. Considering these points, studies were conducted at different locations with a view to develop appropriate K-fertilizer management practices for sustainable improvement of soil health and crop production of rice-rice and rice-wheat cropping system.

Materials and Methods

Research trials and farmers' field demonstrations were conducted with varying combination of nutrient treatments under Boro-Fallow-T. Aman and Wheat-Fallow-T. Aman cropping pattern at different locations in Bangladesh during 2003-2006. Research trials were conducted at Bangladesh Rice Research Institute (BRRI) farm Gazipur (AEZ 28, Modhupur tract, medium highland) and at Hajee Danesh Science and Technology University (HSTU) experimental farm, Dinajpur (AEZ 1, Old Himalayan Piedmont Plain, medium highland). Farmers' field demonstrations were conducted at Gazipur (AEZ 28), and Dinajpur, Thakurgaon and Panchagar (AEZ 1). The Gazipur soils are clay loam in texture, low in fertility and very strongly acidic to slightly acidic in reaction (Table 1). The soils of the experimental fields in north western region are sandy loam in texture, very strongly acidic to strongly acidic in nature, very low in total nitrogen, exchangeable K and S, very low to optimum in P and low to optimum in Zn content (Table 2). Tested cropping patterns were Boro-Fallow-T. Aman in Gazipur and Wheat-Fallow-T. Aman in NW region. The rice varieties used for Boro were BR3, BRRI dhan28 and BRRI dhan29 and, in T. Aman BR11, BRRI dhan31, BRRI dhan39 and BRRI dhan41. The wheat variety used was Shatabdi.

Table1. Initial soil characteristics of the experimental sites at Gazipur

Soil properties	Location	
	BRRI Farm, Gazipur	Farmers' field
pH	6.10	4.10 - 5.70
Organic matter (%)	2.02 (M)	1.23 (L) - 2.56 (M)
Total N (%)	0.07 (VL)	0.08 (VL) - 0.13 (L)
Available P (mg kg^{-1})	10.14 (L)	2.30 (VL) - 5.02 (VL)
Exchangeable K (me q 100^{-1} g soil)	0.17 (M)	0.08 (L) - 0.21 (M)
Available S (mg kg^{-1})	6.10 (VL)	3.20 (VL) -12.90 (L)
Available Zn (mg kg^{-1})	2.80 (VH)	0.47 (L) - 2.80 (VH)
Textural class	Clay loam	Clay loam

VL = Very low, L= Low, M= Medium, Opt = Optimum, H = High, VH = Very high

Table 2. Initial soil characteristics of the experimental sites at NW region* of Bangladesh

Soil properties	Locations	
	HSTU Farm, Dinajpur	Farmers' field*
pH	4.70	3.60 - 4.05
Organic matter (%)	1.13 (L)	1.17 (L) - 1.52 (L)
Total N (%)	0.06 (VL)	0.06 (VL) - 0.08 (L)
Available P (mg kg^{-1})	17.80 (M)	4.53 (VL) -28.16 (Opt)
Exchangeable K (me q 100^{-1} g soil)	0.05 (VL)	0.03 (VL) - 0.09 (L)
Available S (mg kg^{-1})	4.50 (VL)	2.20 (VL) - 6.10 (L)
Available Zn (mg kg^{-1})	1.21 (Opt)	0.40 (L) - 1.40 (Opt)
Textural class	Sandy loam	Sandy loam

VL = Very low, L= Low, M= Medium, Opt = Optimum, H = High, VH = Very high

* Dinajpur, Thakurgaon & Panchagarh districts.

The continuous omission of a fertilizer nutrient was investigated in a long-term soil fertility experiment at BRRI farm Gazipur. The experiment was initiated in 1985 and has been continued to date. There was a "complete" treatment consisting of the application of recommended N, P, K, S and Zn fertilizer and other treatments "missing" the nutrient elements such as -N, -P, -K, -S and -Zn. In the research trials, six potassium treatments with varying doses viz. K control (K_0), recycling of crop residues but no K fertilizer (K_{0+CR}), 33 kg K ha^{-1} (K_{33}), 50 kg K ha^{-1} (K_{50}), 66 kg K ha^{-1} (K_{66}) and farmers' fertilizer doses (K_{FP}) were tested in randomized block design (RBD) with 4 replications. Farmers' field demonstrations were established with three doses of K fertilizer viz. K control (K_0), farmer's practice of K (K_{FP}) and soil test based K dose (K_{STB}). The soil test based flat doses of NPS and Zn was applied in all the plots. Nitrogen fertilizer was applied into 3 splits for rice and two splits for wheat. All other fertilizers (PKS and Zn) were applied at land preparation. In K_{0+CR} treatment, residues of previous crop were incorporated into soil through ploughing at 10-15 days before transplanting/sowing. Two to three rice seedling/hill were transplanted at 20 x 20 cm spacing and wheat was sown in rows. The crop was harvested from 5 m^2 area at the center of each plot and rice grain weight was adjusted to 14% and wheat grain to 12% moisture content. Soil and plant samples were analyzed using standard analytical procedure (Black, 1965; Jackson, 1962; Olsen *et al.*, 1954; Page *et al.*, 1982; Yoshida *et al.*, 1972). The data were statistically analyzed using IRRISTAT version 4.1 (IRRI, 1998).

Results and Discussion

Boro-Fallow-T. Aman Rice Cropping System

The continuous omission of K fertilizer was tested in a long-term soil fertility experiment at BRRI farm, Gazipur. Over a 16-year period, the problem of K in the -K plots intensified with time. While the total yearly grain yield (BR3, Boro + BR11, T. Aman) with the "Complete" treatment was generally within the range of 9-10 t ha^{-1}, the total yield in the -K plots dropped sharply from about 10 t ha^{-1} in 1985 to 6.2 t ha^{-1} in 2000 (Fig 1). The rice yield decrease during initial years due to omission of K was not significant. The yield gap between the balanced fertilizer treatment and the -K treatment widened sharply and significantly ($p=0.05$) with time. In Boro 2000 the K plots were split to accommodate a reverse treatment i.e. the application of K (+K, 60 kg K ha^{-1}) to the plots not receiving K for the last 16 years. The K "reverse" treatment resulted in a yield increase by 2 t ha^{-1} (Fig 2). Nutrient balance estimate indicated that about 141 kg $K^{-1}ha^{-1}yr^{-1}$ (2255 kg ha^{-1} in 16 years) was removed in excess of K added as fertilizer (66 kg K $ha^{-1}yr^{-1}$) by two modern variety (MV) rice crops giving a grain yield of around 10 t ha^{-1} yr^{-1}. On the other hand about 132 kg $K^{-1}ha^{-1}yr^{-1}$ (2117 kg ha^{-1} in 16 years) was removed from the soil where K was not added as fertilizer (K omission plot) by two MV rice crops giving a grain yield of 6.2 t ha^{-1} (Fig 3). Higher biomass production and K concentration in plant tissue in K fertilized plot compared to -K plot may explain the excess mining of K from the K addition plot. These results indicated the need for modifying the recommended K fertilizer doses for the MV rice-rice crop production system in flood free land where yearly K replenishment due to alluvial deposition does not occur.

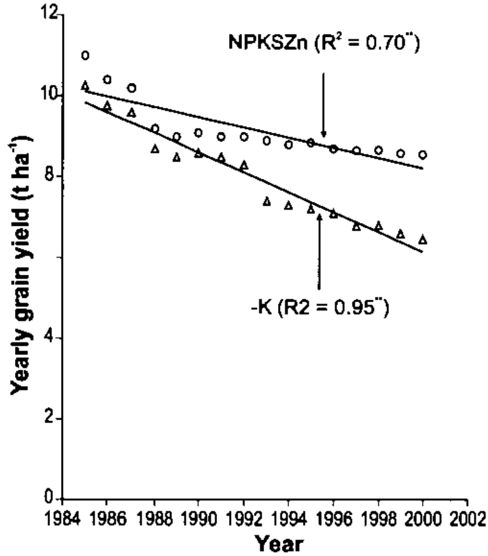

Fig 1. Total yearly grain yield of wetland MV rice under balanced and K missing fertilizer, BRRI farm, Gazipur, 1985-2000

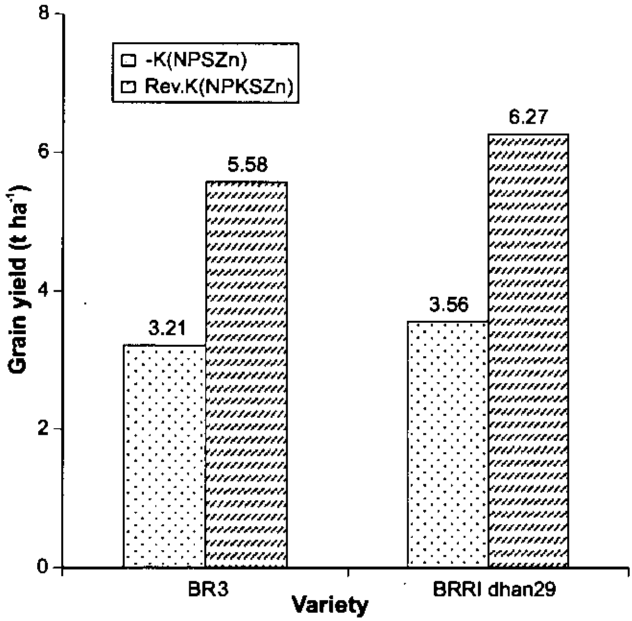

Fig 2. Potassium response of MV rice (Boro 2000) to K fertilization in plots receiving no K fertilizer for 16 years

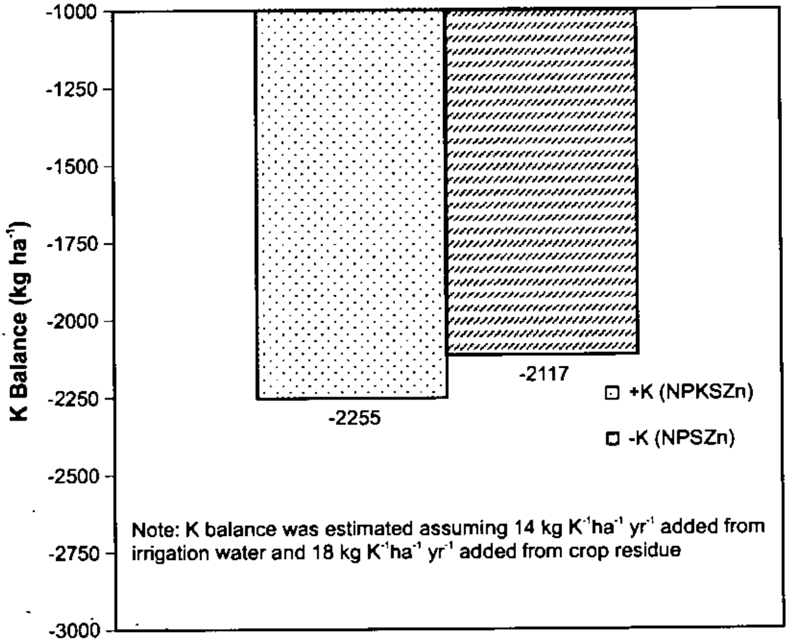

Fig 3. Long term ommission effect of K on the K balance after 16 years of the wetland MV rice under Boro-Fallow-T. Aman cropping pattern, BRRI, Gazipur, 1985-2000

It is apparent from the research trial conducted at BRRI farm Gazipur that the application of potassium fertilizer increased grain yield of rice in any season. The increase of grain yield due to application of K fertilizer was not significant in the first crop (T. Aman 2003) while in the subsequent T. Aman and Boro seasons significantly higher grain yield was found with K-fertilization either from crop residues or from chemical fertilizer over control. The grain yield increased with the increase in applied-K dose up to 50 kg ha^{-1} in both T. Aman and Boro seasons and above this K-level, no appreciable influence in yield was observed. Incorporation of crop residue (rice straw) into soil @ 4.5 t ha^{-1} contributed significantly to produce comparable grain yield of rice in successive crop growing seasons as was produced with chemical K-fertilizer (Table 3). The average grain yield of three T. Aman and three Boro seasons indicates that the grain yield of rice increased from 6 to 13% in T. Aman and 7 to 16% in Boro season due to different doses of K application either through chemical fertilizer or crop residues. The yearly average production of rice grain increased from 6% with farmers' fertilization practice to 14% by applying 50 kg K ha^{-1} over K control (Table 3).

Table 3. Influence of K fertilizer on the grain yield (t ha^{-1}) of rice grown in Boro - Fallow - T. Aman cropping pattern, BRRI farm, Gazipur, 2003-2006

Treat-ment	T. Aman					Boro					Yearly	
	2003 1st crop	2004 3rd crop	2005 5th crop	Mean Yield	% Yield increase	2004 2nd crop	2005 4th crop	2006 6th crop	Mean Yield	% Yield increase	Mean Yield	% Yield increase
K_0	3.09	3.62	3.28	3.33	-	4.82	5.11	5.18	5.04	-	4.19	-
K_{33}	3.25	3.93	3.56	3.58	7.51	5.41	5.6	5.67	5.56	10.32	4.57	9.07
K_{50}	3.22	4.16	3.70	3.69	10.81	5.65	6.08	5.77	5.83	15.68	4.76	13.60
K_{66}	3.19	4.43	3.64	3.75	12.61	5.33	5.97	5.89	5.73	13.69	4.74	13.13
K_{FP}*	3.20	3.84	3.54	3.53	6.01	5.12	5.54	5.46	5.37	6.55	4.45	6.21
K_{0+CR}**	3.10	3.88	3.66	3.55	6.61	5.62	5.82	6.04	5.83	15.68	4.69	11.93
L.S.D. (0.05)	NS	0.29	0.22			0.19	0.38	0.56				
CV(%)	3.6	4.8	4.1			2.3	4.4			6.5		

*FP = Farmers practice only for K based on the average of 25 local farmers (K_{18} in T. Aman & K_{37} in Boro)

**CR = Crop residues.

Flat dose for T. Aman : N-P-S-Zn @ 97-14-13-0 kg ha^{-1}, respectively

Flat dose for Boro : N-P-S-Zn @ 145-23-23-0 kg ha^{-1}, respectively

In farmers' field demonstrations, K-fertilization positively influenced the grain yield of rice in both the seasons. Potassium application on soil test basis (K_{STB}) produced the highest grain yield of rice followed by K_{FP} and K-control in both T. Aman and Boro seasons. The performance of K_{STB} appeared to be superior in terms of seasonal and yearly average yield of rice grain over K_{FP}. The percent increase in yearly rice grain production estimated from K_{STB} plot was almost double (22%) than estimated from farmers' fertilized plot (10%) over K control plot (Table 4). The response of rice to added K was more prominent in dry season than that in wet season.

Wheat - Fallow - T. Aman Cropping System

The results of research trial conducted at Hajee Danesh Science and Technology University experimental farm indicated that the use of K fertilizer in sandy loam soil of NW region of Bangladesh positively enhanced the grain yield of rice and wheat. The recycling of crop residues significantly increased the grain yield over K_0 and produced statistically similar grain yield to those of K_{33} and K_{FP} of both T. Aman and wheat crops. Application of K @ 66 kg K ha^{-1} produced the highest grain yield of both rice and wheat in all the seasons (Table 5). Soil test based K fertilization (K_{STB}) significantly increased the grain yield of both T. Aman rice and wheat over farmers K-fertilization practice (K_{FP}) and K control in farmers' field demonstrations (Table 6). The contribution of K-fertilizer to grain yield production was prominent in wheat than that in T. Aman rice (Table 6).

Table 4. Influence of K fertilizer on the grain yield (t ha^{-1}) of rice at farmers* field grown in Boro - Fallow – T. Aman cropping pattern, Gazipur, 2003-2006

Treat-ment	T. Aman					Boro					Yearly	
	2003 1st crop	2004 3rd crop	2005 5th crop	Mean	% Yield increase	2004 2nd crop	2005 4th crop	2006 6th crop	Mean Yield	% Yield increase	Mean Yield	% Yield increase
K_0	3.59	3.05	3.41	3.55	-	4.25	4.21	4.56	4.34	-	3.95	-
K_{FP}	3.72	3.47	3.90	3.70	10.45	4.85	5.23	5.05	5.04	16.13	4.37	10.36
K_{STB}**	3.95	3.70	4.40	4.02	20.00	5.20	5.95	5.73	5.63	29.72	4.83	22.28

*Average for five farmers fields per season

*FP = Farmers practice only for K based on the average of 25 local farmers (K_{18} in T. Aman & K_{35} in Boro)

**STB = Soil Test Basis (K_{22-53} (av. K_{41}) in T.Aman and K_{34-82} (av. K_{67}) in Boro season.) Flat dose of N-P-S-Zn on STB

T. Aman Varieties: BRRI dhan31 & BR11; Boro varieties: BRRI dhan28 & BRRI dhan29

Table 5. Influence of K fertilizer on the grain yield (t ha^{-1}) of rice and wheat grown in Wheat - Fallow - T. Aman cropping pattern, HSTU, Dinajpur, 2003-2005

Treat	T. Aman					Wheat				
	2003 1st crop	2004 3rd crop	2005 5th crop	Mean	% Yield increase	2004 2nd crop	2005 4th crop	2006 6th crop	Mean	% Yield increase
K_0	1.97	2.32	4.64	2.98	-	2.64	1.99	2.33	2.32	-
K_{33}	2.46	2.96	5.60	3.67	23.15	3.58	2.52	2.81	2.97	28.02
K_{50}	2.73	3.13	5.41	3.76	26.17	3.84	3.09	3.06	3.33	43.55
K_{66}	3.07	3.41	5.17	3.88	30.20	3.92	3.43	3.31	3.55	53.02
K_{FP}	2.44	2.77	5.12	3.44	15.44	3.43	2.57	2.63	2.88	24.14
K_{0+CR}**	2.50	2.90	5.34	3.58	20.13	3.20	2.60	2.63	2.81	21.12
L.S.D. (0.05)	0.35	0.31	0.23			0.47	0.22	0.36		
CV (%)	9.3	7.1	2.9			9.1	5.5	8.6		

*FP = Farmers practice only for K based on the average of 25 local farmers (K_{25} in T. Aman & K_{30} in Wheat)

**CR = Crop residues

Flat dose for T. Aman: N-P-S-Zn @ 100-5.5-14-0.5 kg ha^{-1}, respectively

Flat dose for Wheat: N-P-S-Zn @ 133-18-31-0.5 kg ha^{-1}, respectively

The average grain yield of both T. Aman rice and wheat increased with the increase in applied K-dose up to 66 kg ha^{-1}. Crop residues incorporation or chemical fertilizer application as a source of K increased about 15- 30 % grain yield of rice and 21-53 % wheat grain in research trial (Table 5). On the other hand, the use of K-fertilizer in farmers' field demonstrations produced about 14-25% higher rice yield and 41-86% wheat grain (Table 6). The influence of K fertilizer to increase grain yield was found more prominent in wheat than that in rice (Table 5 and 6).

Table 6. Influence of K fertilizer on the grain yield (t ha^{-1}) of rice and wheat grown in Wheat - Fallow - T. Aman cropping pattern, NW region of Bangladesh, 2003-2005

Treat	T. Aman					Wheat				
	2003 1st crop	2004 3rd crop	2005 5th crop	Mean	% Yield increase	2004 2nd crop	2005 4th crop	2006 6th crop	Mean	% Yield increase
K_0	3.31	3.27	3.17	3.25	-	1.52	1.84	2.59	1.98	-
K_{FP*}	3.68	3.81	3.60	3.70	13.85	2.79	2.73	2.84	2.79	40.91
K_{STB**}	3.89	4.16	4.14	4.06	24.92	3.72	3.60	3.71	3.68	85.86

*Average for five farmers fields per season (Four fields in T Aman 2005, three fields in wheat 2005 season)

*FP = Farmers practice only for K based on the average of 25 local farmers (K_{24} in T. Aman & K_{31} in Wheat)

**STB = Soil Test Basis (K_{43-65} (av. K_{58}) in T. Aman and (K_{72-99} (av. K_{87}) in Wheat season)

Flat dose of N-P-S-Zn on STB

T. Aman Varieties: BRRI dhan31, BRRI dhan39 & BR11; Wheat varieties: Shatabdi

Agronomic Efficiency of Applied K Fertilizer

Table 7 illustrates the effect of different rates of K application on K use in wetland rice under Boro-Fallow-T. Aman cropping system. The T. Aman rice 2003 was the 1st crop of the experiment and the efficiency of applied K was found relatively lower in this crop as compared to the succeeding Boro and T. Aman crops. Fertilizer K application improved the agronomic efficiency of K up to 50 kg ha^{-1} and the efficiency declined with further increase in K application in both Boro and T. Aman season. The efficiency of K was found more pronounced in dry season rice than that in wet season rice. Better vegetative growth coupled with increased grain yield production in dry season than that in wet season in K fertilized plot might explain the results. The efficiency of K fertilizer under Wheat-Fallow-T. Aman cropping pattern is presented in Table 8. Similar to Gazipur site, the efficiency of K fertilizer was found relatively lower in the 1st crop than the succeeding crops. In the 1st T. Aman crop the efficiency of K fertilizer slightly increased with the increasing level of K up to 66 kg ha^{-1} while in the succeeding T. Aman crops, the highest efficiency was observed at 33 kg ha^{-1} and then it declined with increase in applied K level. The wheat crop utilized K fertilizer more efficiently than T. Aman rice. It is apparent from the mean efficiency data of three wheat crops that wheat utilized K fertilizer more efficiently when applied at the rate of 33-50 kg ha^{-1} in North western region of Bangladesh.

Table 7. Agronomic efficiency of K fertilizer use to rice (kg grain kg^{-1} K) in Boro - fallow - T. Aman cropping pattern, BRRI farm, Gazipur 2003-2006

Treat-	T. Aman				Boro			
ment	2003	2004	2005	Mean	2004	2005	2006	Mean
K_{33}	4.9	9.4	8.5	7.6	17.9	14.9	14.9	15.9
K_{50}	2.6	10.8	8.4	7.3	16.6	19.4	11.8	15.9
K_{66}	1.5	12.3	5.5	6.4	7.7	13.0	10.8	10.5

Table 8. Agronomic efficiency of K fertilizer use to rice (kg grain kg^{-1} K) in Wheat - fallow - T. Aman cropping pattern, HSTU, Dinajpur 2003-2006

Treat-	T. Aman				Boro			
ment	2003	2004	2005	Mean	2004	2005	2006	Mean
K_{33}	14.9	19.4	29.1	21.1	28.5	16.1	14.6	19.7
K_{50}	15.2	16.2	15.4	15.6	24.0	22.0	14.6	20.2
K_{66}	16.7	16.5	8.0	13.7	19.4	21.8	14.9	18.7

Economic Analysis

Economic analysis of the experiments was done with the mean data of 3 crops. The results are presented in Tables 9. In clay loam soil at Gazipur, potassium fertilizer applied @ 66 kg K ha^{-1} in T. Aman and @ 50 kg K ha^{-1} in Boro season appeared to be most economical in terms of additional income. While on the basis of marginal benefit cost ratio (MBCR), farmers' fertilization practice in T. Aman and 50 kg K ha^{-1} in Boro season was found most suitable. It is noted that the additional income earned due to K-fertilization was more in Boro rice than T. Aman rice (Table 9). In sandy loam soil of NW region of Bangladesh the maximum additional income in both T. Aman rice and wheat were obtained from the same treatment where K-fertilizer was applied @ 66 kg ha^{-1} (Table 9). Applied K from chemical sources resulted in higher benefit than that of crop residue incorporation in both rice and wheat production. The additional income earned due to K-fertilization was higher in wheat than rice (Table 9). In the case of farmers' field demonstrations, K application based on soil test always contributed higher additional benefit than that of farmers' fertilization practice in any season in both heavy and light textured soils (Table 9).

Table 9. Additional income (per ha) and marginal cost benefit ratio (MCBR) due to K fertilizer use at research station and farmer's field experiments (mean of 3 years, 2003-06)

Particulars	K Fertilizer (kg ha^{-1})											
	K_0	K_{33}	K_{50}	K_{66}	K_{FP}	K_{0+CR}	K_0	K_{33}	K_{50}	K_{66}	K_{FP}	K_{0+CR}
	T Aman						Boro					
Clay loam soils of BRRI Farm, Gazipur Additional income												
(Tk. ha^{-1}) due to K use	-	1843	2573	2670	1646	102	-	4188	6382	5015	2277	5647
MBCR	-	2.99	2.84	2.44	4.27	1.05	-	5.53	5.56	3.71	3.20	3.51
Farmers' field demonstrations in clay loam soil of Gazipur Sandy loam soils of HSTU Farm, Dinajpur Additional income												
(Tk. ha^{-1}) due to K use	-	6284	6765	7655	4125	3998	-	6699	10347	12350	5830	3460
MBCR	-	7.80	5.83	5.14	6.89	2.78	-	8.25	8.39	7.68	7.94	2.54
	K_0	K_{FP*}	K_{STB**}	K_0	K_{FP*}	K_{STB**}						
Farmers' field demonstrations in clay loam soils of Gazipur Additional income												
(Tk. ha^{-1}) due to K use	-	1278	4044	-	6091	11025						
MBCR	-	3.54	4.52		7.22	6.88						
Farmers fields demonstrations in sandy loam soils of northwest region of Bangladesh Additional income												
(Tk. ha^{-1}) due to K use	-	4173	6980	-	8307	17030						
MBCR	-	7.21	5.30	-	10.57	7.99						

FP = Farmers practice only for K based on the average of 25 local farmers (K_{18} in T. Aman & K_{37} in Boro) at BRRI farm Gazipur and K_{25} in T. Aman and K_{20} in wheat at HSTU farm Dinajpur)

CR = Crop residues. (@ 4.5 t ha^{-1} in both the seasons

**STB = Soil Test Basis (K_{22-53} (av.K_{41}) in T.Aman and K_{34-82} (av.K_{67}) in Boro season at Gazipur and (K_{43-65} (av.K_{58}) in T. Aman and (K_{72-99} (av.K_{87}) in wheat season in northwest region of Bangladesh

In all the treatments, the MBCR was more than the acceptable limit (MBCR=2) except the treatment K_{0+CR} (MBCR = 1.05) in T. Aman at Gazipur (Table 9) while in NW region of Bangladesh the MBCR value of this treatment K_{0+CR} was 2.78. But in Boro and wheat (dry) season, the treatment K_{0+CR} showed a reasonably higher MBCR (Table 9). Relatively higher MBCR was obtained in wheat in light-textured soils of NW region of Bangladesh.

Conclusions

Potassium fertilization significantly increased the production of rice-rice and rice-wheat cropping systems. Initially the decrease of yield of rice and wheat due to omission of K was not significant but the yield gap between the balanced fertilized and -K plot widened with time. The results indicated the need for increasing the present recommended K fertilizer dose for the MV rice-rice and wheat-rice crop production system in flood free land where yearly K replenishment due to alluvial deposition doses not occur.

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Development of Site-Specific Nutrient Management for Irrigated Rice-Wheat in North India

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Abstract

Rice-wheat cropping system is predominant in the Indo-Gangetic Plain (IGP) of north India. On-farm experiments were conducted near Pantnagar to develop and evaluate the site-specific nutrient management (SSNM) approach in irrigated rice-wheat system. Field- and crop-specific NPK recommendations were developed by accounting for the indigenous nutrient supply, yield targets, and nutrient demand as a function of the crop growth. Nitrogen applications were fine-tuned based on crop-specific rules and field-specific monitoring of crop N status using leaf color chart (LCC). The performance of SSNM was tested at 11 on-farm sites for two rice and one wheat crop. Compared with the current farmers' fertilizer practice (FFP), average grain yield of rice increased from 6.22 to 6.80 Mg ha^{-1} and wheat grain yield increased from 5.1 to 5.5 Mg ha^{-1}. The gross return over fertilizer cost was 11% greater with SSNM than with FFP in rice and about 9% greater in wheat. SSNM saved about 41 kg N ha^{-1} in rice and 32 kg N ha^{-1} in wheat but increased K application by 25 kg ha^{-1} in rice and 27 kg ha^{-1} in wheat. Balanced fertilization and improved timing and splitting of fertilizer N increased N recovery efficiency in rice from 0.43 kg kg^{-1} in FFP plots to 0.57 kg kg^{-1} in SSNM plots. In wheat SSNM increased N recovery from 0.54 kg kg^{-1} to 0.64 kg kg^{-1}. The agronomic N use efficiency (grain yield increase per kg fertilizer applied) was 59% greater with SSNM than with FFP in rice and 42% greater in wheat. The results of this study showed that SSNM has potential for improving yield and nutrient efficiency in irrigated rice-wheat system by providing balanced nutrition tailored to the dynamic crop demand in the season. However, there is a need to develop a more user-friendly method for extending this agro-technology to large areas with minimum crop monitoring.

Keywords: Site specific nutrient management, rice-wheat

In India more than 10 million ha of arable land is used for growing irrigated rice-wheat in the Indo-Gangetic Plain (IGP). Rice and wheat production increased rapidly from 1970 to 2000 mainly due to the widespread adoption of semi-dwarf varieties of these crops and an increase in fertilizer use. However, since 2000 the yield growth rates have slowed down. Current average yields of rice and wheat in most part of IGP are only about 50 to 60% of the estimated genetic and climatic yield potential (Mishra, 2001; Pathak *et al.*, 2003). Fertilizer prescriptions based on soil testing are either not available or even if available, such recommendations are not adopted by the farmers. Environmental pollution by nitrogen leaching or denitrification from rice fields has become another concern (Pathak *et al.*, 2004). Several on-farm studies have been conducted in India, which indicate low N use efficiency in irrigated rice. Fertilizer N use efficiency in wheat is slightly better than rice but not satisfactory by any standard. Trends similar to those in India have been observed in other irrigated rice-wheat regions of Asia (Ladha *et al.*, 2000). The important concern is how to accelerate the yield and productivity growth of these two important food grain crops in the future. Site-specific nutrient management (SSNM) offers a new approach to increase the crop yields, profit, plant nutrient uptake, and N use efficiencies from the fertilizer on farmers' field. SSNM has been defined as the dynamic, field-specific management of nutrients in a particular cropping season to optimize the supply and demand of nutrients according to their differences in cycling through soil-plant systems (Dobermann and White, 1999). The objective of the present study was to develop NPK recommendations for SSNM and compare its agronomic and economic performance with the current practice of fertilizer use in rice-wheat cropping system.

Materials and Methods

Site characteristics

The experimental domain is located near Pantnagar (29°'N, 79.3°7'E) in Uttaranchal, India and represents a typical rice-wheat growing area in IGP. Soils at the study site mainly include alluvial soils with high fertility (Hapludoll, Aquoll). The study site has a subtropical climate with annual average temperature of 23.4°C and 1486 mm rainfall. Rice-wheat is the main cropping system in this area. Rice is grown from June to October and wheat from November to April next year. Before rice transplanting, land preparation is done on wet soils with tractors. Canal and tube wells irrigate all the fields.

On-farm experiments

On-farm experiments were conducted from 2003 to 2004 to develop and test SSNM approach for rice-wheat. In a village near Pantnagar, 11 farms belonging to different farmers were selected to represent the range of socio-economic conditions and soil types in the whole domain. All farmers grew rice-wheat system. Treatments included: SSNM (Site-Specific Nutrient Management) and FFP (Farmers' Fertilizer Practice). All crop and fertilizer management in rice-wheat field was done by the farmer with no interference by the researcher. Ranges of farmers' fertilizer rates in 2003 were 137.5 to187.5, 40 to 57.5, and 0 to 46.5 kg ha^{-1} N, P_2O_5 and K_2O, respectively for rice and 141.5 to 179.0, 32.0 to 57.5 and 20.0 to 24.0 kg ha^{-1} N, P_2O_5 and K_2O, respectively for wheat. Most farmers applied 40-50% N and all P and K fertilizers as basal dressing before planting rice or wheat.

For estimating indigenous nutrient supply (INS, IPS, IKS) to the crop from soil, water (irrigation and rain), crop residues etc. nutrient omission plots in the farmers' field were established as described by Mishra *et al.* (2005). Small omission plots (25-50 m^2) of 0-N, 0-P and 0-K were embedded in the farmer's field (FFP) to ensure that macronutrients other than the one omitted in the plot did not limit plant uptake from indigenous sources. All rice fields received 25 kg zinc sulphate ha^{-1} as basal dressing to provide adequate zinc supply, which is commonly deficient in the area.

Site-specific nutrient management

Nutrient applications were prescribed to a larger plot (300-500 m^2) located within the farmer's field (FFP) on a field- and crop-specific basis following the SSNM approach described below. Ranges of fertilizer rates in 2003 and 2004 were 110 to 133, 48 and 54 kg ha^{-1} N, P_2O_5 and K_2O, respectively, applied to rice and 121.5 to 133, 48 and 54 kg ha^{-1} N, P_2O_5 and K_2O, respectively, applied to wheat.

Nutrient omission plots were rotated within the field after each crop to avoid residual effects. The SSNM plot was established with the 2003 rice crop and remained at the same location for two consecutive rice-wheat crop cycles grown in 2003 and 2004. Rice and wheat varieties were chosen by the farmers and were the same in both SSNM and FFP treatments. Farmers planted conventional modern varieties (6 different non-scented cultivars of rice and 5 cultivars of wheat). Wheat was planted at row spacing of 23 cm by seed drill. Farmers did all water management, weed control and pest control in both FFP and SSNM plots following the commonly adopted methods. Rice fields were kept flooded for most of the season until grain filling stage whereas irrigation in wheat was given at all the critical growth stages viz. crown root initiation (CRI), maximum tillering, late jointing, heading and milk stage. No severe incidence of pests in rice or wheat was observed during the experimental period.

Soil and plant measurements

Initial soil samples were collected in summer of 2003 to determine general soil properties in the 0.0- 0.15 m depth. Composite samples of 8-10 soil cores per field were analyzed following standard procedures. Grain yields were obtained from a central 5-m^2 harvest area in each sampling plot at harvestable maturity and rice grain yields are reported at a standard moisture content of 0.14 kg kg^{-1}. Straw yields were estimated from the oven-dry grain yield of the 5-m^2 harvest area and the grain/straw ratio of the 12-hill sample. Similarly, plant samples were drawn from wheat field. Leaf N status was measured by leaf color chart (LCC) using the uppermost fully expanded leaf in the SSNM and FFP treatments. In rice beginning at 20 DAT, 10 LCC readings per plot from randomly selected leaves were averaged, and measurements continued at 10-d interval until about 10 d after flowering. In wheat LCC readings were recorded at critical growth stages only.

Site-specific nutrient management approach

Details of the SSNM approach are provided elsewhere (Dobermann *et al.*, 2002). The SSNM approach applied in this study focused on managing the spatial variation in the indigenous N, P, and K supply among individual rice fields and the temporal variability in crop N demand occurring within a field during a growing season. The SSNM mainly involved prediction of field-specific optimal NPK fertilizer rates and development and implementation of a site-specific N management scheme that accounted for real-time variation in crop N demand at major growth stages of rice and wheat.

A simplified QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model (Janssen, 1998; Witt *et al.*, 1999) was used to work out field-specific fertilizer recommendations for rice and wheat at each farm at the beginning of each season. Information needed to estimate the total amount of N, P, and K to be applied included (i) yield goal (ii) grain yield in 0-N, 0-P and 0-K plots (iii) level of straw recycling of the preceding crop. The details of the simplified and improved procedure for providing NPK recommendations for rice using SSNM approach are given by Buresh *et al.* (2005) and for rice-wheat by Mishra *et al.* (2005).

In the FFP, many farmers typically applied all N in two splits of about 50% preplant and remaining 50% within 20 to 25 days after transplanting (DAT) in rice, and only few applied a third dose at later growth stages. In SSNM for rice, fertilizer N was applied in four splits-20% shortly before transplanting (incorporated), 20% top dressed at 14 DAT, 25% top dressed at maximum tillering stage and 35% top dressed at panicle initiation (PI). In wheat about 40% N was applied as basal, 25% at crown root initiation (CRI) and 35% at maximum tillering stage. Plant N status was monitored with LCC at the critical growth stages at which N must be applied (active tillering and panicle initiation in rice; crown root initiation and maximum tillering in wheat), but the amount of N applied varied based on the actual plant N status as measured by LCC.

Fertilizer sources used were urea (46% N), single superphosphate (7.1% P), and muriate of potash (50% K). All P fertilizer was incorporated into the soil before transplanting (100% basal). Potassium fertilizer was split into 44% basal plus 56% at panicle initiation. Nitrogen use efficiencies were estimated using the differences between N-fertilized treatments and the 0-F plots. Parameters of N use efficiency were agronomic efficiency of applied N (AE_N; kg grain yield increase kg^{-1} N applied), apparent recovery efficiency of applied N (RE_N; kg N taken up kg^{-1} N applied), and partial factor productivity of applied N (PFP_N; kg grain kg^{-1} N applied). Gross return above fertilizer cost (GRF) was calculated as the difference between the gross income from grain yield and the cost of fertilizer in the particular treatment viz. SSNM or FFP. The incremental profitability of SSNM (ΔGRF) was measured as the difference in GRF for SSNM and FFP.

Results and Discussions

Indigenous nutrient supply

Most farms had loam to silty clay loam soil texture, relatively high soil organic matter content, neutral to alkaline reaction (pH) and low to moderate cation exchange capacity (Table 1). Plant-available levels of soil P, K and Zn were highly variable among the fields (CVs 16.5-36.1%). Olsen-P content ranged from 18.2 to 37.0 mg P kg^{-1} soil, thus all farms had Olsen-P contents above the commonly proposed critical level of 10 mg P kg^{-1} soil. Potassium extracted by 1 *M* ammonium acetate ranged from 0.18 to 0.35 cmol kg^{-1} soil, thus most of the fields had greater than 0.2 cmol K kg^{-1} soil, a critical level often used for rice soils with little K fixation (Dobermann and Fairhurst, 2000). However, plant-based indicators of the IKS indicated greater available K reserves than suggested by extraction with 1 *M* ammonium acetate. In many fields, DTPA extractable Zn was low ranging from 0.3 to 2.1 mg kg^{-1} soil.

Table 1. General soil properties in rice-wheat fields near Pantnagar, Uttaranchal (n=11)

Soil property[a]	Mean	Min.	Max.	CV (%)
Clay (%)	17.00	12.60	24.30	16.30
Silt (%)	41.00	23.00	56.00	15.10
Sand (%)	40.20	17.00	63.00	21.50
Soil organic C (g kg^{-1})	11.00	7.50	14.50	16.60
Total soil N (g kg^{-1})	0.78	0.65	1.08	21.50
Soil pH (1:2 H_2O)	7.47	6.80	7.70	6.20
Cation exchange capacity ($cmol_c$ kg^{-1})	14.70	10.90	24.50	16.40
Exchangeable K ($cmol_c$ kg^{-1})[b]	0.25	0.18	0.35	16.50
Extractable P (mg kg^{-1})[c]	25.60	18.20	37.00	27.20
DTPA extractable Zn (mg kg^{-1})	0.65	0.30	2.10	36.10

[a] Measured on soil samples collected from 0-0.15 m depth before the rice season 2003

[b] 1 *M* ammonium acetate extraction at pH 7

[c] 0.5 *M* $NaHCO_3$ extraction (Olsen-P)

The averages of nutrient omission yields and INS, IPS, and IKS for rice were higher than for wheat (Table 2, 3). The INS in rice ranged from 47 to 57 kg N ha^{-1} and in wheat from 39 to 50 kg N ha^{-1}. IPS in rice ranged from about 10 to 13 kg P ha^{-1}, and in wheat from 9.8 to 12 kg P ha^{-1}. IKS in rice ranged from about 68 to 87 kg K ha^{-1} and in wheat from 63 to 75 kg K ha^{-1}.

Table 2. Grain yield of rice and wheat in nutrient omission plots at 11 farms near Pantnagar, Uttaranchal

Season	Mean	Min.	Max.	CV
	Grain Yield, Mg ha^{-1}			(%)
0-N plot				
2003 rice	3.03	2.82	3.23	4.7
2004 rice	3.59	3.29	3.76	4.5
2003-04 wheat	2.27	1.91	2.47	7.7
0-P plot				
2003 rice	6.24	5.81	6.43	3.5
2004 rice	6.64	6.53	6.81	1.4
2003-04 wheat	5.27	5.00	5.49	2.8
0-K plot				
2003 rice	6.00	5.48	6.34	5.0
2004 rice	6.11	5.76	6.29	2.9
2003-04 wheat	4.90	4.70	5.19	3.5

Table 3. Variation in indigenous nutrient supply to rice and wheat estimated by nutrient omission plot technique at 11 farms near Pantnagar, Uttaranchal

Season	Mean	Min.	Max	CV
	Nutrient uptake, kg ha^{-1}			(%)
INS				
2003 rice	47.4	40.2	50.6	15.7
2004 rice	52.4	47.2	56.8	14.5
2003-04 wheat	43.1	39.3	49.5	12.7
IPS				
2003 rice	11.5	10.1	12.3	9.5
2004 rice	12.3	11.2	13.0	10.4
2003-04 wheat	10.2	9.8	11.9	10.8
IKS				
2003 rice	72.6	68.6	81.2	15.0
2004 rice	78.8	73.6	86.9	12.9
2003-04 wheat	68.3	63.0	74.6	15.5

INS = indigenous N supply; IPS = indigenous P supply; IKS = indigenous K supply

Grain yield of rice and wheat

Compared with FFP, SSNM significantly increased grain yields in rice crop (Table 4). The average yield difference between SSNM and FFP for rice was 0.58 Mg ha^{-1}. Compared with FFP, SSNM significantly increased grain yields in wheat crop grown in 2003-04 (Table 4). The average yield difference between SSNM and FFP for wheat was 0.4 Mg ha^{-1}.

Table 4. Effect of site-specific nutrient management (SSNM) on grain yield and fertilizer use in rice-wheat at 11 farms near Pantnagar, Uttaranchal (2003-2004)

Particulars	Crops	SSNM	FFP[1]	Difference (SSNM-FFP)
Grain yield, Mg ha^{-1}	Rice	6.8	6.2	0.6
	Wheat	5.5	5.10	0.40
N Fertilizer, kg ha^{-1}	Rice	120.5	161.1	-40.6
	Wheat	127.8	159.5	-31.7
P Fertilizer, kg ha^{-1}	Rice	21.0	18.2	2.7
	Wheat	21.0	18.4	2.6
K Fertilizer, kg ha^{-1}	Rice	45.0	20.1	24.9
	Wheat	45.0	18.2	26.8

[1]FFP= farmers' fertilizer practice

Fertilizer use

Compared with other regions in India, fertilizer use in the FFP at this study site was relatively high. Farmers applied average rates of 161.1 kg N ha^{-1}, 18.2 kg P ha^{-1} and 20.1 kg K ha^{-1} to rice and 159.5 kg N ha^{-1}, 18.4 kg P ha^{-1} and 18.2 kg K ha^{-1} to wheat crop (Table 4). Use of K in the FFP was low in rice as well as wheat. However, most farmers had no means of adjusting their fertilizer rates according to the actual soil fertility status.

On average, 40.6 kg ha^{-1} less fertilizer N in rice and 31.7 kg ha^{-1} less fertilizer N in wheat was used in SSNM treatments than the amount used by farmers in FFP (Table 4). For the rice and wheat crops, about 3 kg ha^{-1} more P was applied in the SSNM treatment compared with FFP. K applications in SSNM in both the crops were significantly higher than in FFP (25 kg ha^{-1} greater in rice and 27 kg ha^{-1} greater in wheat). Lower fertilizer N rates in the SSNM treatment resulted from LCC-based adjustments that accurately accounted for plant N demand in the season.

Nitrogen use efficiency

Significant increase in N use efficiency was achieved through the field- and season-specific N management practiced in the SSNM treatment (Table 5). In general, compared with the FFP, less N fertilizer was applied and AE_N, RE_N, and PFP_N were significantly increased. On average, AE_N increased by 11.2 kg kg^{-1} in rice and 7.5 kg kg^{-1} in wheat, RE_N by 0.14 kg kg^{-1} in rice and 0.10 kg kg^{-1} in wheat, and PFP_N by 17.8 kg kg^{-1} in rice and 11 kg kg^{-1} in wheat. Significant differences in the impact of SSNM on N use efficiency between rice and wheat were observed. There was greater impact of SSNM in rice than in wheat.

Table 5. Effect of site-specific nutrient management (SSNM) on fertilizer N use efficiency, fertilizer cost, and gross return above fertilizer cost (GRF) in rice-wheat at 11 farms near Pantnagar, Uttaranchal (2003-2004)

Particulars	Crops	SSNM	FFP	Difference (SSNM-FFP)
AE_N,' kg grain kg^{-1} N	Rice	30.25	19.03	11.20
	Wheat	25.48	17.94	7.54
RE_N,§ kg N kg^{-1} N	Rice	0.57	0.43	0.14
	Wheat	0.64	0.54	0.10
PFP_N,¶ kg grain kg^{-1} N	Rice	56.47	38.64	17.83
	Wheat	43.00	32.00	11.00
TFC,## Rs. ha^{-1}	Rice	2641	2711	-70
	Wheat	2718	2684	34
GRF, *Rs. ha^{-1}	Rice	35761	32112	3650
	Wheat	31989	29388	2601

1 US$ = Rs. 45.00

' AE_N = agronomic efficiency of N

§ FFP = farmers' fertilizer practice

¶ PFP_N = partial productivity of N

TFC = total fertilizer cost

* GRF = gross return over fertilizer cost

Compared with the FFP, N applications in the SSNM treatment were uniform among farms, spread more evenly through the growing season, and avoided heavy single applications at early growth stages. In the SSNM treatment, preplant N application was much smaller than in the FFP treatment. The top dressed N application at 14 DAT in rice was also small (about 23 kg N ha^{-1}), but a third dose of 30 to 50 kg N ha^{-1} was applied between 45 and 50 DAT, with the date and amount depending on plant N status.

These results provide on-farm evidence that current N management practices in rice-wheat in north India are inconsistent with the physiological N requirements of the crops and lead to large N losses. Nitrogen supply appears to be excessive during early vegetative growth but deficient during grain filling. During early growth, LCC readings in the FFP plots were mostly larger than those in SSNM plots, but the reverse was true during reproductive growth stages. The importance of sufficient late-season N supply for achieving high rice yields has been highlighted by Peng and Cassman (1998). Other studies in India have shown that applying more N fertilizer during middle growth stages improved N use efficiency and increased N uptake and grain yields in rice (Dhyani, 1994).

Profitability of site-specific nutrient management

Site-specific nutrient management led to a reduction of the average fertilizer cost by Rs 70 ha^{-1} in rice crop but a small increase by Rs 34 ha^{-1} in wheat crop (Rs 45= 1 US$). However, there was an increase in GRF in both the crops: by Rs 3650 ha^{-1} in rice and Rs 2601 ha^{-1} in wheat (Table 5) compared with FFP. Increase in GRF was significantly larger for rice than for wheat. The calculation of ΔGRF implicitly assumes that the only difference in crop management between SSNM and FFP was different quantities of nutrients and different timing of nutrient applications while all other management practices and quantities of input use were held constant.

Conclusion

The SSNM approach significantly increased grain yield and nutrient uptake with less fertilizer N applied, resulting in large increases in N use efficiency and profit. Increases in N use efficiency and profit by SSNM were due to an improved N management schedule that included use of LCC for decision making in the timing and amount of N topdressing. However, average yields under SSNM were 85% of the yield goal in rice (8 Mg ha^{-1}) and 82% of the yield goal in wheat (6.5 Mg ha^{-1}). This unattained yield gap of 15% in rice and 18% in wheat was mainly caused by (i) climatic factors particularly in wheat, (ii) poor water management in rice, and (iii) insufficient planting density in rice due to labour shortages. These results of this study underscore the importance of knowledge-intensive nutrient management in rice-wheat cropping system, particularly with regard to the timing and amount of N and K applications. Further refinement in SSNM approach is needed to make it more user-friendly for extending this agro-technology to large areas with minimum crop monitoring.

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Balanced Fertilization for Crop Sustainability : The Neglect of Potassium

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Abstract

In ancient time, agriculture was more or less sustainable due to regular organic fertilization as indicated by Chinese traditional agriculture. Due to various economic constraints, farmers are forced to apply agrochemicals that give higher returns resulting in relatively high N input and a coincidental decrease of other nutrients including K. This situation is accompanied by negative K balance for many agricultural regions and indicates only a short-term consideration. A long-term neglect of K would result in a non-sustainable situation for crop productivity.

From the various physiological functions of K in crop production, particularly, in avoidance of various biotic and abiotic stresses, it can be concluded that the practice of imbalanced fertilization with the neglect of proper K fertilization will result in increasing problems, particularly, under stress-prone environments. Innovative K fertilization management strategies have to be developed to efficiently counteract the decline in crop sustainability due to an imbalanced fertilizer use. Therefore, fertilizer industry, farmers and scientists have to work in close cooperation for practical solutions and have to take these plant and soil health aspects as an actual challenge.

Keywords: Disease resistance, nutrient balance, rhizosphere, stress avoidance, water use efficiency, potassium

Farmers are being increasingly forced to improve productivity because of increasing demand of growing population, escalating costs of agrochemicals and simultaneously declining prices for agricultural products in the world market. Beside higher demand better quality in terms of higher mineral and vitamin content is required. Another requirement is a more environmental friendly production often induced by national recommendations or laws.

This pretentious demand for an improved crop production should also be sustainable to guarantee a long-term successful production for future generations. In this context crop sustainability means a long-term successful agricultural production in view of economy and natural science. This will require to sustain an adequate soil fertility, optimum soil organic matter content and balanced nutritional status.

In the past, Chinese agriculture has shown a sustainable crop production for more than 3000 years mainly based on organic fertilization (Tso, 1998). Thaer (1811), known for his 'Humus theorie', claimed in his book 'Grundsätze der Rationellen Landwirtschaft' that agricultural production has to be sustainable in an economic manner. He contended that an optimal humus content was the basis for an adequate soil fertility and thus sustainability. Later Justus v. Liebig (1803 - 1873), known for his 'Mineralstofftheorie', stressed in his last edition of 'Agriculturchemie' (1876), the importance of organic fertilization for the maintenance of an adequate nutrient supply to guarantee a high soil fertility and thus sustainability and to avoid soil degradation. According to Liebig, mineral fertilizers should only be used as a supplement if mineral nutrients are not adequately supplied thorough organic fertilizers including recycled organic municipal waste such as compost (Haller, 1989; Lewicki, 1989).

Mineral nutrients exist in different forms in soil and thus differ in their availability to plants. There are various methods available including soil and plant analysis for making fertilizer recommendations. In contrast to plant and soil analysis, the provision of nutrient budgeting for a field or a farm or region will show whether maintenance, accumulation or depletion status of nutrient of soil takes place on a medium time scale as a basis for crop sustainability. A nutrient surplus, often observed in industrialized countries with a high livestock production (Table 1), would mean a low fertilizer and also resource efficiency together with the risk of environmental pollution.

Table 1. Nutrient balance for N, P and S for different forms of conventionally-managed farms in Baden-Württemberg, Germany (1991-1995)

Production system	N	P	S
		(kg ha^{-1} yr^{-1})	
Crop	60	12	-6
Fodder	115	16	9
Livestock	126	25	9
Mean	104	16	6

Source: Horlacher *et al.* (1997)

Due to the high impact of nitrogen surplus in agriculture of industrialized countries for the environment, the main focus of local, national or European governments as well as of world agencies is on loss of nitrogen through nitrate leaching and gaseous losses as NH_3 or NO_2. Potassium (K) is an essential mineral element at a disadvantage behind nitrogen. This neglect of K, however does not mean that K leaching should be ignored for a farm under consideration for nutrient budgeting and thus for soil fertility and sustainability. As shown in Table 2 considerable amounts of K can be leached in a farm on a sandy soil of North-Germany with a humid climate.

Table 2. Average K leaching as affected by the rate of K application during the winter seasons 1989/1990 to 1994/1995 in sandy soils of North Germany

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

Source: Wulff *et al.* (1998)

On the other hand, a negative nutrient balance, also called nutrient mining, is wide-spread in developing countries, in East-European countries under economical constrain (Table 3) or in low-input systems like in organic farms (Table 4), can be recognized as a non-sustainable situation. Even a minor depletion of nutrients such as P or K as indicated by a negative nutrient balance (Table 3 and 4) can result in a fast decline in nutrient status and thus soil fertility and sustainability.

Table 3. K and P balance in agricultural soils of Bulgaria during 1986 to 2004

Year	1986	1989	1992	1998	2004
			(kg ha^{-1} yr^{-1})		
Potassium:					
Input	26	20	0	46	65
Output	65	55	57	44	64
Balance	-39	-35	-57	2	1
Phosphate:					
Input	51	44	6	2	6
Output	23	19	27	20	26
Balance	+28	+25	- 21	-18	-20

Source: Koutev *et al.* (2006)

Table 4. Yardgate balance sheet of three organic-managed farms in Baden-Württemberg, Germany estimated for 1989

	Input	Output	Balance	Remarks
Farm No.1				
Phosphate	6.5	3.4	+3.1	
Potassium	3.9	3.7	+0.2	
Magnesium	1.0	0.8	+0.2	
Farm No.2				
Phosphate	13.3	12.2	+1.1	(high production of
Potassium	3.6	22.0	- 18.4	K-rich potatoes, carrots
Magnesium	3.0	3.0	0.0	and cereals for the market)
Farm No.3				
Phosphate	9.1	6.5	+2.6	(high application rate of
Potassium	15.7	12.3	+3.4	Mg-containing rock meal)
Magnesium	24.5	1.7	+22.8	

Nutrient Balance Sheets as Criterion for Sustainability

As discussed above such a provision of nutrient balance sheets can give important information on the sustainability of a farm. Although in industrial countries, the balance sheet for N often shows, as a rule, a positive balance (Table 1), due to import of feed for the intensive livestock production and overuse of mineral N fertilizer, the use of K fertilizer has remarkably declined. This has resulted in a negative K balance of numerous European farms, particularly after 1990 in East European countries, such as Czech Republic or Bulgaria (Table 3).

Usually such nutrient balance sheets of a farm are calculated on the basis of a yard gate balance as shown in Table 5A for an organically managed farm. The calculated negative K balance however is higher for the same farm if the field balance is taken as basis (Table 5B). This distinctive higher K losses of 1195 kg versus 239 kg K per farm per annum within the farm is probably mainly due to K leaching from stored manure at the field margin before spreading resulting in about one ton K loss (1195-239 kg) per year.

This measured and calculated K losses in such an organically-managed farm appear rather small as compared to the total stock of K in the top layer of the clay-rich soil of this farm (Mayer, 1997). Model calculation as shown in table 6, considering the negative K balance of the various balance sheets (Table 5A and B), indicates a relatively fast K depletion of K-poor sandy soils with consequences in a predictable decreased yield and soil degradation. Following a comparable calculation for P with the assumption of 0.01-0.07% P in the top layer of different soils and an often determined annual negative balance of 2-10 kg P ha^{-1} in organic farms the time periods for the assumed depletion are even worse with 114 and 15 years, respectively which emphasize the non-sustainable situation in case of nutrient mining.

Table 5. K balance sheet of an organic-managed farm (33.5ha) at Stuttgart-Ruit, Germany, estimated on farm level (yard gate balance) and on field level (field balance) for 1993/94

	A. Yardgate balance		B. Field balance	
	kg a^{-1}	kg ha^{-1} a^{-1}	kg a^{-1}	kg ha^{-1} a^{-1}
Input	233	7	3910	117
Output	472	14	5105	152
Balance	-239*	-7	-1195*	-36

* Farm internal losses: 1195-239 = 956 kg K a^{-1}

Source: Mayer (1997)

Table 6. Time required for K depletion of a top soil assuming a negative balance sheet (nutrient mining): a model calculation

K content in top soil

0.1 - 3.3% = 7 000 - 228800 kg K ha^{-1}

Required years for assumed depletion

Normal scenario:

Balance - 5 kg K ha^{-1} a^{-1}; 50% depletion of top soil with 3.3% K

$$\frac{228800 \times 50}{5 \times 100} = 22800 \text{ years}$$

Worst case scenario:

Balance - 40 kg K ha^{-1} a^{-1}; 25% depletion of top soil with 0.1% K

$$\frac{7000 \times 25}{40 \times 100} = 44 \text{ years}$$

Interestingly, K deficiency symptoms can be observed in dicotyledonous plant species even on such clay-rich soils with high K reserves under summer drought spells (Mayer, 1997). This can result in an increasing suppression of legumes with a low capability in K acquisition on a pasture after repeated drought spells. In principle, this can be explained by a restricted spatial availability due to limited transport of available K and P to the root surface through diffusion (Table 7). This restricted spatial availability of K and P is further limited by a drought-induced inhibition of diffusion and particularly of root growth (Table 8).

Table 7. Effect of restricted root growth expressed as root length density in a sandy top soil on spatial availability of K and P for maize plants

Root length density ($cm \cdot cm^{-3}$ soil)	Proportion of soil volume delivering chemical available K and P to the root surface	
	K	P
>> 2	50%	20%
< 2	12%	5%

Source: Fusseder and Kraus (1986)

Table 8. Possible causes for inhibited K and P uptake by maize roots induced by low soil water content simulated by a model for various soils

Change in soil water content (volumetric water content)	Percentage of decreased nutrient uptake under drought due to:	
	Effective diffusion coefficient	Root growth (including root hairs)
27% → 22%	27 - 32% for P	50 - 56% for P
(medium) (low)	11 - 27% for K	46 - 69% for K

Source: Marckay and Barber (1985)

Thus in conclusion, besides the nutrient balance sheet, the nutritional status of a soil together with root growth data such as root length density often observed under adverse soil conditions such as compaction, low temperature or low soil water content has to be considered for the aspect of crop sustainability. This is particularly important for mineral nutrients transported through diffusion to the active uptake sites of roots, such as P or K. From the data above it got also obvious that even a K-rich clay soil requires a regular K fertilization particularly under frequently occurring adverse soil conditions with inhibited replenishment and acquisition of K. However, the following questions remain to be answered: Which crop in a rotation should preferentially be fertilized with K and when K should be applied during the season, in which form (e.g. as chloride or sulfate) and whether as soil or foliar application? In order to answer these questions adequately we should recall the general and specific functions of K in crop growth, yield formation and stress avoidance. This will help to develop effective and innovative strategies for K fertilization to achieve a better crop performance, which is nowadays in the line of fertilizer industry that likes to sell packages or strategies for fertilization instead of only fertilizer.

Management of K

On the basis of the various functions of K in plant metabolism it is possible to develop adaptive strategies for K fertilization including the various K fertilizer types and fertilization techniques. Such innovative fertilization strategies will help to achieve a better crop performance and crop sustainability.

Late stage foliar K application

Following the main functions of K in photosynthesis, phloem loading and phloem transport of photo assimilates (e.g. sucrose) it might be worthwhile to improve the K status of source leaves of a plant in a developing stage with already beginning senescence. This will guarantee the utilization of the potential of source leaves for a sustained source function for a longer period.

This prolonging of the seed/fruit development could be particularly important under frequent drought spells often occurring during the seed filling stage with strongly inhibited K acquisition by roots. This is mainly caused by a low carbohydrate content in roots as energy resource and a low spatial availability of K in the dried out top soil (low diffusion coefficient and inhibited root growth; (Table 8). The effectiveness of such a late application has been shown for N, in particular, to increase the N content in grains of cereals, but also for P. This information shows that a decrease in root activities during reproductive stage with a decline in cytokinine export from roots to shoots can be compensated partially by a preferential foliar spray containing the limited mineral nutrients. This late stage application, thus, will prolong photosynthesis and supply of carbohydrates for sustaining root activities with the consequence of an increase of leaf area duration or delayed senescence (Batten and Wardlaw, 1987).

Such a late stage foliar application of K and presumably also Mg (Marschner and Cakmak, 1989) will guarantee optimal photosynthetic activity and low formation of oxygen radicals, particularly at high light intensity and temperature (Cakmak, 2005). This will ensure reduced heat stress, a problem in many agricultural areas. It has to be stressed that such a recommended foliar supply of K will matter only relative small rates compared with the regular annual soil application rates. Therefore, this measure could be considered as a very effective strategy for a better crop performance.

Seed dressing with K

It is well-known that high quality seeds can improve early stage performance of plants and often final yield also (Harris, 1996). Depending on sites for seed production, content and concentration of distinct mineral nutrients such as micronutrients or P can be critical for a high germination rate and early seedling establishment (Ajouri *et al.*, 2004; Yilmaz *et al.*, 1998). Such a requested adequate content of mineral nutrients in seeds for an optimal early plant development will be particularly important for seedling growth at sites with various biotic (e.g. disease and pests) and abiotic stress conditions (e.g. drought, submergence, adverse temperature, high light intensity, salinity).

All these various stress factors have, as a common consequence, an enhanced production of reactive oxygen species (ROS, various oxygen radicals), which are toxic to plants by impairment of cellular functions and thus, resulting in a declined crop productivity (Cakmak, 2005). For detoxification of such reactive oxygen species distinct micronutrients such as Zn, Mn and Cu are involved and have to be, thus, adequately available for plants and particularly, during early seedling establishment. However, because seedlings at this sensitive early stage are primarily depending on mineral nutrients stored in seeds, production of seeds under conditions with a better nutrient supply or seed dressing or coating with such limiting mineral nutrients gets interesting for seed producers. Such improved stocks of mineral nutrients in or on seeds will not be adequate, of course, to build up the final biomass at harvest but will guarantee vigor seedlings with a pronounced root system which will enable an effective nutrient acquisition in the following growth stages.

Up to now, most reports on nutrient dressing or mining regard distinct micronutrients (e.g. Mn, Zn, Mo, B) and P as a macronutrient (Table 9; Ajouri *et al.*, 2004). Although K is known to be important in alleviating detrimental effects of abiotic stresses in plants (Cakmak, 2005). There are nearly no reports on an improved seed quality by K priming or dressing of seeds. This might be due to the general finding of relatively high K contents in seeds. But this would also be valid for P, although for P and improved seedling growth by nutrient priming with P salts has been shown by Ajouri *et al.* (2004) and Ros *et al.* (2000).

Table 9. Effect of nutrient priming on growth and nutrient content of 2 week old barley seedlings grown in potted soil without drought stress

Priming treatment	Shoot D.M. (mg plant $^{-1}$)	Root D.M. (mg plant $^{-1}$)	Shoot content (μg plant $^{-1}$)	
			P	Zn
Water (ctr.)	15.7	19.4	10.7	1.4
P	20.5	24.6	20.7	1.3
Zn	19.6	21.5	11.4	2.1
P + Zn	22.4	23.2	23.1	2.0

Source: Ajouri *et al.* (2004)

Therefore, it seems reasonable, particularly considering the wide-spread negative K balance sheets for many agricultural regions (Table 3), to test seed dressing or coating seeds with K to improve early crop establishment with a better root growth. This better establishment can further be translated into an increased final yield via a better uptake of the limited nutrient by the strengthen root system as observed for chickpeas (Mussa *et al.*, 1999) and other corps (Ajouri *et al.*, 2004). Such a nutrient priming with K will be particularly of interest for an investigation for drought-prone or saline environments (Kaya *et al.*, 2001). It has been observed that such an improved K and P nutrition will also improve water-use-efficiency (Matar *et al.*, 1992; Ros *et al.*, 2000), which is of high importance for semi-arid regions. Further experiments under field conditions have to prove these theoretical considerations on K priming as an effective measure for farmers' practice.

K fertilizer for rhizosphere management

The rhizosphere is defined as the soil compartment in the immediate vicinity of roots, affected by root activities and plays a decisive role in processes such as weathering of K minerals, nutrient availability and control of root infections by soil-born pathogens such as *Gaeumannomyces graminis* as fungus of take-all disease (Römheld, 2005; Römheld and Neumann, 2006). Plant roots are the driving force for the rhizosphere conditions by depletion or accumulation of nutrients, release of protons and exudates which will affect microbial activities (Römheld, 1990). Supply of N in the various forms (NH_4 versus NO_3) will exert big changes in rhizosphere pH, particularly if ammonium is stabilized by a nitrification inhibitor (Thomson *et al.*, 1993).

However, K fertilizer can affect rhizosphere processes, mainly indirectly by an improved assimilate partitioning between shoots and roots, improved root exudation and Fe-deficiency-induced proton release (Römheld, 2005). Iron nutrition can also be improved via a preferential use of K_2SO_4 instead of KCl (Table 10), which will result in a lower rhizosphere pH (Römheld, 1986; 2005). An improved K supply can also promote infections with arbuscular mycorrhizae fungus with a subsequent suppression of replant disease (Waschkies *et al.*, 1994). These few examples might indicate that an appropriate rhizosphere management with K fertilizers can be a suitable tool for a better nutrient acquisition and microbial activities.

Table 10. Dry matter production and chlorophyll concentration of peanuts grown on a high calcareous soil affected by source of K fertilizer (K_2SO_4 versus KCl)

Treatments	Yield (g pot^{-1})	Chlorophyll (mg cm^{-2})
- Fe (control)	4.4	0.64
Fe SO_4 + KCl	8.8	3.89
$FeSO_4$ + K_2SO_4	14.3	5.93
FeEDDHA	11.8	5.79

Source: Mortvedt (1991)

K fertilizer for suppression of diseases

Take-all is a wide-spread fungal disease in cereals with no effective fungicides in the market to control this fungus. As a consequence crop management strategies have been developed over decades to suppress this specific disease. One of the most common practices in areas with a high percentage of cereals is to decrease the rhizosphere pH via stabilized ammonium (Römheld, 1990). It is well-established that the fungus of take-all disease cannot invade roots of wheat at low rhizosphere pH, which is achieved by combination of ammonium fertilizer and the nitrification inhibitor N-serve used in the USA (Römheld,1990; 2005).

In addition, there are various observations that KCl, but not K_2SO_4 together with ammonium fertilizer can suppress take-all disease in farmers' fields (Table 11). There are various speculative theories for this chloride effect from which the function of chloride at higher concentrations as nitrification inhibitor might be most realistic explanation. This has also been confirmed by preliminary incubation studies

Table 11. Effect of KCl on incidence of take-all (*Gaeumannomyces graminis*) in wheat applied with ammonium-N in autumn or spring

Cl treatment as KCl ($kg\ Cl\ ha^{-1}$)		Infected roots	Grain yield
autumn	spring	(%)	($t\ ha^{-1}$)
0	0	45	5.3
56	0	34	5.7
56	185	11	6.5

Source: Christensen *et al.* (1981)

Beside this direct low pH effect on pathogens activities in the rhizosphere, there is also an indirect rhizosphere effect via an enhanced plant availability of Mn, which can be applied for suppression of other diseases similar to take-all (Huber and McCay-Buys, 1993; Römheld and Neumann, 2006). These plant health aspects, affected by rhizosphere management will attract, without doubt, increasing interest in future.

Outlook and Prospects

In modern agriculture it gets more and more important to use mineral fertilizer such as K not only for basic fertilization but also to guarantee a balanced nutrient situation and crop sustainability. Increasing costs, economic conditions and environmental instructions require a more efficient and function-based use of distinct mineral fertilizers. It has been shown that from the specific functions of K in cell extension growth, photosynthesis, photoassimilate transport and stress avoidance, distinct and much directed K fertilization strategies can be concluded. These possible strategies require further consideration and practical evaluation by applied science and fertilizer industry for the farmers well being. The innovative management strategies such as late stage foliar application of K or seed priming or coating with K might allow a more efficient use of K resources for a better crop performance than the traditional annual basic K fertilization. Therefore, this further development and evaluation of innovative K fertilization strategies for farmers will be a great challenge which should be taken to improve plant and soil health and thus, the requested crop sustainability.

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Balanced Use of Fertilizers with Emphasis on Potash in Pakistan

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Abstract

Balanced use of fertilizers, including K besides NP, is essential for obtaining better and higher crop yields, besides increasing the efficiency of fertilizer, particularly N. Data have been presented to show that more than 100 per cent increase in yield can be achieved with balanced use of NPK fertilizers. The contribution of K to increase in crop yields is about 20-30 per cent. Both sources of K (SOP and MOP) have their place: SOP particularly for tobacco. However, some saline - alkali and waterlogged soils need be avoided for the use of MOP. The present strategy to promote N and P alone need a change towards emphasis on P and K. Fertilizer blends are an important means to promote the balanced use of fertilizers.

Keywords: Balanced fertilization, potash

Pakistan soils are generally deficient in nitrogen (N) and phosphorous (P) and medium in potash (K) availability. About one third of soils are considered requiring the use of K. It was with the ushering of Green Revolution in the 70s when fertilizer use really started taking off with the introduction of semi dwarf high yielding cereal crops. The use of nutrients during 2005-06 was 3804 thousand tonnes of N (2927), P_2O_5 (851) and K_2O (27), making up a ratio of 1:0.29:0.009. In terms of nutrients the use rate was 169 kg ha^{-1} of N, P_2O_5 and K_2O (130.0 for N, 37.8 for P_2O_5 and 1.2 for K_2O kg ha^{-1}) (GOP, 2006).

Land area and crop use data indicate that of the total land area of 79.6 million hectare (mha) in Pakistan, the cultivated area during 2005-06 was 22.15 mha, (27.8 %). However, the total cropped area, considering some areas fallow and some sown more than once, was 22.51 mha, of which about 80 per cent is irrigated. Land holdings are generally small: 64 per cent up to 5 ha, 20 per cent up to 10 ha and 15 per cent more than 10 ha. Major crops from the point of view of fertilizer use are wheat, cotton, rice, sugarcane and maize which constitute about 93.5 per cent of fertilizer off take (wheat 52, rice 7, cotton 25, sugarcane 8, maize 1.5 per cent) (GOP, 2006). Besides these crops, potato and onion among vegetables are high users (2.5 per cent) of fertilizer (GOP, 2005). Crops yields are generally low; wheat 2613, cotton 731, rice 2116, sugarcane 49230 and maize 3458 kg ha^{-1} (for the year 2005-06). Wheat, cotton, rice, maize and sugarcane yields registered an average growth rate of 2.0, 3.3, 2.1, 7.1 and 0.2 per cent, respectively for the ten-year period 1996-2005; sugarcane yield is almost stagnant (GOP, 2006).

There are seven main cropping patterns in Pakistan (FAO, 2006). They include irrigated and non-irrigated (rainfed) areas. The main cropping patterns are: Cotton-wheat (5.50 mha in Punjab and 1.60 in Sindh), Rice-wheat (2.80 mha in Punjab, 1.10 in Sindh and 0.35 in Balochistan), Mixed crops (4.10 mha in Punjab, 1.30 in Sindh, 0.53 in NWFP and 0.40 in Balochistan), Pulses-wheat (1.90 mha in Punjab and 0.36 in NWFP) Maize-wheat / oilseeds (1.20 mha in Punjab), Maize-wheat (0.90 in NWFP) and Orchard /vegetables-wheat (0.30 in Balochistan). These cropping patterns depend on: land type, microclimate, availability of irrigation water, transport infrastructure and cultural aspects. Most farms are mixed as farmers try to produce most of the crops and to maintain some livestock.

Pakistan soils are generally alkaline, pH range of 7.9-8.2 and calcareous in nature. The Indus plains are of alluvial origin. The soil forming parent materials are generally derived from rocks: mainly limestone, calcareous shales and sandstones, besides some igneous granitic material and some patches of volcanic rocks. Five major landforms have been recognized throughout the country: river terraces, loess plains, piedmont plains, rock plains and mountains (Akhtar *et al.*, 2003).

The use of fertilizer in Pakistan is far from being balanced, especially for K. After nitrogen the main emphasis, both by the government policy and fertilizer industry, is on promoting P. And possibly this is one of the reasons of low fertilizer use efficiency and low crop yields. This paper reviews briefly the situation.

Status of NPK use

Commercial use of fertilizer in Pakistan started in 1952 with 1000 tonnes of N. Phosphate was introduced in 1959-60 with 1000 tonnes and K in 1966-67 with 100 tonnes. The historical fertilizer off take data for selected years are given in Table 1.

Table 1. Historical data of fertilizer off take for selected years

(000 tonnes)

Year	Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)	NPK
1952-53	1.0	-	-	1.0
1959-60	19.3	0.1	-	19.4
1966-67	112.8	3.9	0.1	116.8
1969-70	274.0	36.6	1.3	311.9
1979-80	806.0	228.5	9.6	1004.1
1989-90	1467.9	382.5	40.1	1890.4
1999-00	2217.8	597.2	18.5	2833.4
2005-06	2927.0	851.0	27.0	3805.0
Demand forecast by NFDC*				
2009-10	3321.0	1213.0	53.0	4587.0
2014-15	3850.0	1406.0	78.0	5334.0

* Source: FAO (2006a)

While the consumption of N and P has increased progressively, the use of K has suffered a set back: it was 45.12 thousand tonnes in 1987-88, which has progressively deteriorated and only lately started recovering with the present use of 27 thousand tonnes. The primary reason for this deterioration was that initially fertilizers were subsidized and the use of K was primarily as potassium sulphate (SOP). With the elimination of subsidy the price of SOP sharply increased and the off take declined. However, with the introduction of muriate of potash (MOP) during 1996 the use of K has started picking up slowly. Private sector during 2005-06 imported 76,599 tonnes of potassic fertilizers (42,499 tonnes MOP and 34,100 tonnes SOP) making up a total of 42,500 tonnes K_2O. This is a very significant development especially with respect to the import and use of MOP in the country.

The ratio among N, P_2O_5 and K_2O during 2005-06 in Pakistan was 1.000: 0.291: 0.009 which was even worse than in 1979-80 (Table 2). It is not heartening to see projected ratio in 2014 – 15 as 1.000 : 0.365 : 0.020 compared to 1.000 : 0.261 : 0.027 achieved in 1989 – 90 with respect to N, nevertheless, the ratio in respect of P is progressively improving.

Table 2. NPK ratios during different periods of time

Year	Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)
1979-80	1.000	0.283	0.012
1989-90	1.000	0.261	0.027
1999-00	1.000	0.269	0.008
2005-06	1.000	0.291	0.009
2009-10*	1.000	0.365	0.016
2014-15*	1.000	0.365	0.020

* projected

The government expression of balanced fertilizer use is in terms of N and P only. The ratio thus, worked out is shown in Table 3. The figures show a decreasing trend in N and increasing trend of K. Nevertheless, the use of K compared to N as shown in Table 2 would hardly improve even in the 2014-15. This is a matter of serious concern for policy planners.

Table 3. NPK ratios with phosphate as base

Year	Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)
1979-80	3.527	1.000	0.042
1989-90	3.838	1.000	0.027
1999-00	3.542	1.000	0.031
2005-06	3.439	1.000	0.032
2009-10	2.738	1.000	0.044
2014-15	2.738	1.000	0.055

Source: GOP (2006)

Realizing the fact that the use of K was neglected as borne out by the data presented in Table 1, the government of Pakistan explored the use of potassium chloride (MOP) as source of K. Traditionally K has been used as SOP, which was heavily subsidized and thus affordable by the farmers. The elimination of subsidy in the 80s adversely affected the use of K, which led to the formulation of research and development of project on use of K, with special emphasis on the K sources (Akhtar *et al.*, 2003). The main objectives of the project included the evaluation of MOP vs SOP; areas where MOP can be used safely and soil / cropping condition where it should not be used, besides investigating harmful effects of chloride in MOP on soils and crops if any; studying the benefit of potash fertilization on yield and quality of major crops; and help developing appropriate ways of introducing MOP into Pakistan fertilizers market system (a dry bulk blending facility to be used to promote NPKs).

Field and laboratory studies were undertaken to compare SOP and MOP and the long-term effects of the use of K sources on soil quality. Experiments on the response of different crops (cereals, oilseeds, sugar crops and cotton), vegetables and fruits to K fertilizations were conducted during 1993-1998, further extended by another two years.

Results

Response of crops to K

Summary of crop responses to K and its sources for the period 1993-1998 is given in Table 4. The data were collected by a large number of organizations involved in the implementation of the project and have paved a way for the introduction of MOP along side SOP to meet the varying requirements of crops and soils in the country.

The yield increase due to K application was 25-30 per cent in cereals, 10-15 per cent in cotton, sugarcane, sugar beet and groundnut and more than 40 per cent in canola. Since, these are mean data and the site differences are not reflected. The effect of K sources was similar. However, MOP being cheaper its economic benefits will be more than SOP.

Response of canola to K

A replicated experiment on canola was also conducted to study the effect of sources of K on its yield and oil quality (Table 5). Data show a significant response of increasing levels of potash on canola yield: application of 50 kg per hectare increased yield by 34 per cent in case of MOP and 9 per cent in case of SOP; however, the additional increment of 50 kg did not increase yield in case of MOP but the yield increased for SOP by 24 per cent. Although the incremental rates of

Table 4. Summary of crops response to potash and its sources during 1993-98

		Control	NP	NPK (SOP)	NPK (MOP)	NPK (Mean)
Wheat (kg ha^{-1})						
Mean	212 *	1751	3558	3983	4034	4009
Yield increase over control	kg ha^{-1}	-	1807	2232	2283	2258
	%	-	103	127	130	129
Rice (kg ha^{-1})						
Mean	62 *	2544	3759	4456	4514	4485
Yield increase over control	kg ha^{-1}	-	1215	1912	1970	1941
	%	-	48	75	77	76
Maize (kg ha^{-1})						
Mean	20 *	1382	2903	3306	3350	3328
Yield increase over control	kg ha^{-1}	-	1521	1924	1968	1946
	%	-	110	139	142	141
Cotton (kg seed cotton ha^{-1})						
Mean	72 *	1343	2048	2144	2214	2179
Yield increase over control	kg ha^{-1}	-	705	801	871	836
	%	-	52	60	65	62
Sugarcane (t ha^{-1})						
Mean	4 *	38.1	63.0	68.2	66.5	66.4
Yield increase over control	t ha^{-1}	-	24.9	28.1	28.4	28.3
	%	-	65	73	75	74
Sugarbeet (t ha^{-1})						
Mean	4 *	38.7	50.5	58.5	55.9	57.3
Yield increase over control	t ha^{-1}	-	11.8	19.9	17.2	18.6
	%	-	30	51	44	48
Rapeseed (Canola) (kg ha^{-1})						
Mean	5 *	1000	1875	2312	2316	2314
Yield increase over control	kg ha^{-1}	-	875	1312	1316	1314
	%	-	88	131	132	131
Groundnut (kg ha^{-1})						
Mean	27 *	1840	2313	2568	2576	2572
Yield increase over control	kg ha^{-1}	-	472	728	736	732
	%	-	26	40	40	40

* Number of trials / experiments conducted

SOP resulted in significant increases over NP, the magnitude of increase in yield was more for MOP at the initial level and increasing rates did not add to the yield. It was concluded that K increased canola yield by about 30 per cent and the sources of K behaved alike.

As to the effect on canola quality, it was seen that all contents and fatty acid profile remained unaffected; however, glucosinolates were higher in seed where higher rates of K were applied as SOP (Table 6). For further details see Akhtar *et al.* (2002a).

Table 5. Comparative effect of MOP and SOP on canola yield (1993-94)

Treatment (kg ha^{-1})	Seed yield (kg ha^{-1})	
	MOP	SOP
N_{100} P_{60} K_0	2224 C	2441 BC
N_{100} P_{60} K_{50}	2982 AB	2653 ABC
N_{100} P_{60} K_{100}	2891 AB	3021 A
N_{100} P_{60} K_{150}	2824 AB	2869 AB
N_{100} P_{60} K_{200}	2836 AB	2750 ABC
Mean	2744	2747
L.S.D.	198	198

Table 6. Effect of MOP and SOP on oil content and glucosinolate of canola

Treatments	Oil contents (%)		Glucosinolate (µm g^{-1} seed)	
(kg ha^{-1})	MOP	SOP	MOP	SOP
N_{100} P_{60} K_0	47.1	47.1	25.1	19.1
N_{100} P_{60} K_{50}	47.0	47.7	24.8	24.5
N_{100} P_{60} K_{100}	47.4	47.2	24.1	24.1
N_{100} P_{60} K_{150}	47.5	47.9	22.8	26.2
N_{100} P_{60} K_{200}	48.0	47.2	21.1	27.3
Mean	47.4	47.4	23.6	24.3
L.S.D.	NS	NS	NS	6.8

Response of onion to K

Onion response to potash was studied on five varieties and three bulb sizes. Data presented in Table 7 indicate that K increased onion yield by 21 to 27 per cent on varietal mean basis. However, individual varieties varied considerably in yield and response to K. Further trials (Akhtar *et al.*, 2002) and demonstrations on onions in Potohar area have shown a very high response to K.

Table 7. Onion response to K based on bulb size and variety

Fertilizer treatment (N-P-K, kg ha^{-1})	Yield (t ha^{-1})		
	Bulb size 10-15 (mm)	Bulb size 15-20 (mm)	Bulb size 20-25 (mm)
	Mean yield (t ha^{-1})*		
150-100-00	30.2	38.3	32.4
150-100-200	38.0	46.1	38.9
	Variety: Swat 1 (mean yield 17.3)		
150-100-00	14.8	16.7	12.0
150-100-200	19.4	23.6	17.1
	Variety: White Creole (mean yield 28.8)		
150-100-00	17.6	31.5	26.8
150-100-200	23.6	38.0	35.2
	Variety: Burgundy (mean yield 34.7)		
150-100-00	30.6	40.7	20.4
150-100-200	42.1	48.6	25.5
	Variety: Texas E. Grano (mean yield 51.1)		
150-100-00	42.2	50.0	48.2
150-100-200	49.5	59.3	57.0
	Variety: Phulkara (mean yield 54.8)		
150-100-00	45.4	52.8	54.6
150-100-200	55.1	61.1	59.7

* Average of five varieties: Phulkara, Burgundy, White Creole, Swat 1, Texas E. Grano

Source: Akhtar *et al.* (2002)

Response of tomato to K

Trials were carried out on potatoes and tomatoes. Potash increased significantly the yield and quality, particularly of tomatoes (Table 8). Further, higher percentage of marketable tomatoes was obtained from K treatments as compared to control and MOP source gave better results than SOP. Potassium levels and sources had no effect on acidity of tomato pulp. Potassium application decreased the sugar contents of tomato pulp and this effect was more pronounced in SOP treated fruits. Potash as MOP had a positive effect on vitamin C, whereas it decreased with SOP application. Results indicated that plants treated with potash had less disease and insect attack incidence.

Table 8. Effect of K as SOP and MOP on the yield and quality of tomato

Treatments	Yield (kg ha^{-1})	Acidity	Sugar (%)	Vit C (mg kg^{-1})
250 – 150 – 000	12581 [b]	1.50	4.21 [a]	231.3
250 – 150 – 125 (SOP)	15437 [b]	1.33	3.15 [ab]	188.1
250 – 150 – 125 (MOP)	24796 [a]	1.30	3.18 [ab]	259.9
250 – 150 – 250 (SOP)	16464 [b]	1.29	2.45 [b]	187.7
250 – 150 – 250 (MOP)	19158 [ab]	1.35	3.47 [ab]	252.4
LSD	6253	NS	1.40	61.3

Source: Akhtar *et al.*, 2003

General crop response trends

- Fertilizer contributed up to 40 per cent in enhancing crop productivity where K fertilizers were also applied along with N and P.
- The response to K was generally very high in vegetables, especially potatoes, onions and fruits. The use of K generally increased sugar content and MOP source of K enhanced vitamin C contents compared to SOP.
- The application of P and K fertilizers on cotton improved the N use efficiency and both sources of K fertilizer i.e. SOP and MOP had similar effects on crop yields (Akhtar *et al*, 2003).

IMPHOS trials on balanced fertilization of crops

World Phosphate Institute (IMPHOS) and FAO supported NFDC in implementing a project on the promotion of balanced fertilization of crops in three phases: 1987-1990, 1996-2000 and 2002-2005. The work was undertaken in collaboration with provincial soils fertility organizations (FAO, 2006a). The treatments in the demonstration included: Control, N, NP and NPK. In 712 trials conducted on seven crops: wheat (412 trials), rice (159), cotton (57), maize (54), sugarcane (9), oilseed (11) and onion (10) in four provinces of Pakistan: Punjab (366 trials), Sindh (152), North West Frontier Province (137) and Balochistan (57). The experimental sites with similar characteristics (general physical features, cropping systems, etc.) were grouped in 15 crop production regions (CPRs).

On overall basis, the wheat yield in control was 1371 kg ha^{-1}, for the fertilizer treatments it was 2168 kg ha^{-1} for N, and 3284 kg ha^{-1} for NP. The wheat yield increase per unit of nutrient applied was 6.6 kg for N, 12.4 kg for P and 9.1 kg for NP. Based on Annex 2 of the report, some data have been summarized and presented in Table 9. The data indicate that the average increase in cereal yields due to N alone was 37 percent while with NP and NPK, the increases were 87 and 104 per cent, respectively. It means another increase over N alone of 50 per cent was due to NP (the response to P over N being 36.8 per cent) and 67 per cent due to NPK (the response to K over N being 49 per cent and over NP being 19 per cent). These data generated by NFDC strongly support the foregoing responses of crops to applied K.

Table 9. Main data of three phases for selected crops (kg ha^{-1})

Crop	Province	Crop rotation	Control	N	NP	NPK
Wheat	Punjab	Cotton – wheat	2051	2076	3270	3540
		Rice – wheat	2271	2653	3982	4187
		Rainfed	1931	2495	3275	3467
	Sindh	Rice – wheat	1015	2033	2760	3073
		Mixed crops	1579	2511	4016	4305
	NWFP	Maize – wheat	1747	3000	4073	4580
		Pulses – wheat	1371	2295	2980	3538
		Mixed crops	2142	2939	3932	4135
		Rainfed	1652	2275	3090	3745
	Balochistan	Mixed crops	1727	2483	3427	3750
Maize	Punjab	Mixed crops	3429	3745	5792	6506
Rice (Basmati)	Punjab	Rice – wheat	2836	3714	4480	4582
Rice (IRRI)		Rice – wheat	2914	3727	4531	4673
Rice	Sindh	Rice – wheat	2686	3346	4877	5225
		Cotton – wheat	2230	3680	4755	5220
Rice (JP-5)	NWFP	Mixed crops	3406	4065	5164	5792
Rice (KS-282)		Mixed crops	2712	3465	4703	5341
Rice (Basmati)		Mixed crops	1587	2670	3583	3716
Rice	Balochistan	Rice – wheat	2876	4592	6303	6697
Cotton	Punjab	Mixed crops	776	1077	1645	1898
Sugarcane	Sindh	Mixed crops	29867	59083	109167	126334
Oilseeds (Raya L-18)	Punjab	Cotton – wheat	923	1281	1662	1838
Average*			2219	3040	4158	4530
Per cent increase over control			-	37.0	87.4	104.1

* Except cotton, sugarcane and oilseeds

Source: FAO, 2006

Long-term effect of MOP on chloride content in soil

Nineteen long-term experiments, comparing the use of SOP and MOP in different agro-ecological conditions, were conducted in four provinces of the country (Akhtar *et al.*, 2003). The soil profiles for about one meter at all the sites were monitored for electrical conductivity and chloride contents. No chloride accumulation was observed for five years period at any place in Pakistan except in Sindh (Table 10) where more studies covering crops such as rice, sugarcane and banana are warranted.

Table 10. Results of long term trials at Faisalabad, Tarnab and Tandojam

Sites	Year		K_2O level	Chloride content (mg L^{-1}) treatments		
	Initial	Last	(kg ha^{-1})	Control	NPK (SOP)	NPK (MOP)
ARI, Faisalabld	1985	1997	60	2.4	2.4	2.4
SFI, Lahore	1991	1997	100	3.4	4.0	4.0
ARI, Tarnab	1993	1997	100	1.3	1.4	1.2
NIFA, Tarnab	1993	1997	75	4.7	4.7	4.9
ARI, Tandojam	1993	1997	75	4.8	4.8	5.3
AU, Tandojam	1993	1997	75	1.3	1.9	2.8
AEARC, Tandojam	1993	1998	100	1.4	1.3	2.6

Further, results of long term trial at Faisalabad on chloride dynamics for 12 years have shown that no chloride accumulation has occurred with the application of MOP; the over all mean for SOP and MOP for the last years i.e. 1995-97, were 3.7 and 4.0 me L^{-1} respectively (Table 11).

Table 11. Results of long term experiment at Faisalabad on chloride content (me L^{-1})

Treatments	1985-96	1996-97	Mean 1985-96 (Initial 10 yrs)	Mean 1994-97 (last 3 yrs)
Control	4.4	2.4	3.9	3.5
NP	4.3	2.5	4.1	3.3
NPK (SOP)	4.0	2.4	4.1	3.7
NPK (MOP)	4.3	2.4	4.7	4.0

Chloride tolerance limits of crops

Results of pot experiments conducted at the Department of Soil Science, University of Agricultural, Faisalabad, indicated that wheat, maize and rice have a high degree of tolerance to chloride: yield gradually increased up to 400-600 mg Cl L^{-1}, the higher levels up to 1000 mg Cl L^{-1} depressed yield in wheat, however, it was still equal or higher than control in rice (Akhtar *et al.*, 2003).

Crop response to K on soils varying in clay mineralogy

A pot trial conducted by NFML tested response to four levels of K (0, 125, 250, 375 kg ha^{-1}) at constant N (250 kg ha^{-1}) and P (125 kg ha^{-1}) rates in wheat (Rabi 1994-95) on three soils varying in clay mineralogy under rice-wheat rotation (Akhtar *et al*, 2003). Three soils (Tarnab, Shahdara, Nandipur series) represented three major soil series, one each in Punjab, Sindh and NWFP province under rice-wheat cropping system. Texturally Tarnab and Shahdara series were silt loam and Nandipur, clay loam; all the three soils were low in P but adequate in K. Clay mineralogy of three soils was different (Table 12).

Table 12. Clay mineralogy of soils

Soil	Sm	Vm	SC	HM	KK
Tarnab	-	4	2	3	2
Shahdara	-	-	4	3	3
Nandipur	4	3	-	3	-

Sm - Semetite, Vm - Vermiculite, SC - Chlorite, HM - Hydrous mica, KK - Kaolinite; Numbers denote: 4 - Dominant, 3 - Major, 2 - Minor
Source: Akhtar *et al.*, 2003

The grain yield (g pot^{-1}) showed that the three soils responded differentially to NP as well as K. Wheat response progressively increased with NP and NPK levels: it was more significant in Nandipur followed by Shahdara and Tarnab (Table 13). However, more data are required to be generated on this important aspect, which seems to be ignored.

Table 13. Wheat grain yield (g pot^{-1}) on three soils

Treatments	Soils series					
N - P_2O_5 - K_2O ha^{-1}	Tarnab	% incr.	Shahdara	% incr.	Nandipur	% incr.
0 – 0 – 0	0.963	-	0.975	-	1.000	-
250 – 125 – 0	1.375	41.2	1.150	17.5	1.175	17.5
250 – 125 – 125	1.525	56.2	1.225	25.0	1.325	32.5
250 – 125 – 250	1.625	66.2	1.400	42.5	1.675	67.5

Source: Akhtar *et al.* (2003)

Soil mining of K

Some recent data generated by Soil Fertility Survey and Soil Testing Institute, Lahore (Punjab), indicated that soil K had considerably decreased during 1990 to 2001 (Table 14). The soil mining of K is very high if we consider the application of nutrients and their removal by crops.

Table 14. Changes in status of soil K (kg ha^{-1}) in the Punjab over a period of 11 years

Zone	1990		2001		%	No. of
	Mean	SD	Mean	SD	Decrease	Samples
Rainfed	114	34	106	21	7	3,014
Rice	176	71	132	90	33	3,816
Central	295	153	198	83	49	5,583
Cotton	210	5	165	32	27	4,012

Source: *Dr. Khalid Hussain Gill, Director General, Ayub Agriculture Research Institute, Faisalabad, 2006*

Potash status of Pakistan soils

Soils samples were collected from the demonstration trial fields and analysed for organic matter (Walkley & Black method), available P (Olsen's method) and available K (NH_4OAC & AB-DTBA methods). The limits used for P and K were: P: low <10, medium 10-15 and adequate >15; K: low <60, medium 60-120 and adequate >120 mg kg^{-1} (FAO, 2006a).

Summarized data (weighted averages) presented in Table 15 show that soils with adequate P level in the country range between 2.8 (Punjab) and 6.4 (NWFP) per cent, Sindh having 5.8 per cent soils. Adequate level of K the provinces of Punjab and Sindh was 43.7 and 52.9 per cent respectively, while in NWFP it was 50.0 per cent. Figure for soils collected from farmers' fields in Balochistan is 16.9 per cent; however, this needs further investigation.

In the low category, there were 14.2 and 28.3 per cent samples in Punjab and Sindh respectively, while in the medium category the figures were 42.1 and 18.8 per cent. This clearly shows that almost 60.0 per cent soils in Punjab and 47.0 per cent in Sindh are below the adequate levels and require the application of K for obtaining optimal crop yields. The picture for NWFP is similar i.e. 50.0 per cent. In fact the soil sample for NWFP represent only the Peshawar valley; in lighter soils of Kohat, Bannu and Karak besides sub-mountainous areas such as Swat, Abbottabad and Mansehra are far too low in K status compared to Peshawar valley.

Table 15. Soil P and K status in Pakistan

Parameter	No. of samples 000'	Per cent of total samples		
		Low	Medium	Adequate
P - Punjab	650	77.2	20.0	2.8
- Sindh	48	88.4	5.8	5.8
- NWFP	10	52.6	41.0	6.4
- Balochistan	0.36	8.6	85.8	5.6
K - Punjab	142	14.2	42.1	43.7
- Sindh	48	28.3	18.8	52.9
- NWFP	10	16.9	33.1	50.0
- Balochistan	0.36	0.3	82.8	16.9

Soil analysis data reveal very interesting status of P and K: the adequate levels of soils for P are only about 6.0 per cent and about 50.0 per cent for K. This underlines the importance of applying K to soils where the availability levels are low or medium, depending on the nature of crop and soil.

Bulk blending

Bulk blending can be seen as a rough and ready method of applying several nutrients to the soil, originated in the USA in 1940s. However, it took off in 1960s with the production of granular products. The bulk blender provided the services of blending and spreading to his customers in the area within a radius of 15 to 50 km of the plant. The process had a provision for the addition of micronutrient and herbicides. The technology is cheap, simple and small-scale, giving an edge over the chemically compounded fertilizers on account of their low cost and flexibility. Materials are selected with known chemical analysis, which closely match in particle size. The plant is designed to perform basically the functions of movement of material from storage to a mixing location, proportioning of the materials by weight and delivery into a mixer, mixing and movement of finished blend to a holding bin, or to a bagging machine.

Various blends were prepared by NFML and tested in farmers' fields on various crops. The blended fertilizer use resulted in better germination, less disease incidence; higher crop yields and comparable efficiency of both MOP and SOP. Farmers' response to the use of blends was very positive. As a result of the introduction of NPK blends, a keen demand for fertilizer blends was created amongst the farmers.

The recommendations of PPIC-PARC project on potash

Potash should be given proper emphasis in balanced fertilization of crops, especially in the following situations (Akhtar, *et al* , 2003): low and medium soil - K; high yield intensive agriculture; high - K requiring crops (banana, potato, tobacco, etc.); crops with quality concern (sugarcane, sugarbeet, tobacco, vegetables (especially potato, tomato and onion), fruits (especially citrus and mangoes).

MOP is a good source of potash as SOP for all crops except tobacco. Some scientists have expressed their concern on the advisability of application of MOP on some fruit and vegetable crops. However, there are no data generated in Pakistan to substantiate their concern. Long-term research should continue to monitor the effect on chloride on soils and crops. Based on the available data MOP is specially recommended for the following situations: Light textured (sandy to loam) soils; rolling and slopping terrains, hilly and sub-hilly rainfall areas. In the province of Sindh, however, SOP should be preferred for chloride-dominant salinity and waterlogged areas.

Bulk blending technology tested under the project proved a success. Therefore, fertilizer blends are a preferred strategy to promote balanced use of fertilizer.

Specialized unit for potash research and development is necessary to follow-up the promotion of balanced use of fertilizers, including K, and besides generating data to disseminate educational material on the subject.

Potassium in Human Nutrition

Potassium content of crops is affected by K content in the soil. Soils poor in K produce crop products low in K and the applied K to crops from fertilizers improves the K content. Only scanty data are available and there is need to generate data on this important aspect.

Potassium is important in complex biological functions and its RDA value is easily attained through a high daily intake of certain vegetables and fruits. The daily requirement of K is 2,000 mg (2g). An adult body weighing 60 kilogrammes contains 210 grams of potassium, a mineral that naturally balances adverse sodium reactions. Since the body absorbs most of the dietary intake of potassium, deficiency is not common. The ratio of sodium to potassium in the body is essential because it maintains the water level and the acid-alkaline balance of the body, resulting in optimal nervous and muscular stability. Green vegetables, grains, fruits, herbs and potatoes keep the sodium potassium balance normal. Potassium has the following benefits:

- Potassium is extensively effective in lowering blood pressure. For those with hypertension about 3,500 mg is recommended daily.
- It maintains the flow of all body fluids, the smooth performance of nerve transmission and muscle contractions.
- High K intake prevents heart diseases and stroke. Studies have shown that by including just one extra serving of any potassium rich food containing 400 mg reduces the risk of stroke by 40 per cent.
- Potassium neutralizes acids in the body.

A deficiency of K can lead to serious health problems:

- Hypokalemia, which can be potentially fatal, is caused by excessive loss of fluid caused by vomiting and diarrhea, and in the case of athletes excessive sweating: sports people require high levels of K (6000 mg daily).
- Poor reflexes and response to muscle relaxation.
- Cells contain up to 95 per cent K and its loss from cells is the root cause for many chronic diseases such as oedema, hypertension, enzyme dysfunction, and impaired electrical potential.
- A diet low in potassium can cause a jump in blood pressure by four points i.e. from 90-130 to 94-134.

Food sources of potassium

Some of the important sources are give in Table 16. It may be observed that there is a great variation in K content of vegetables and fruits. Generalized figures in Table 16 may vary for different varietal and soil situations.

Table 16. Potassium content in foods

Item	Amount	mg
Squash	1 cup	1040
Kidney beans (C)	1 cup	710
Potato (C)	1 medium	610
Raisins	½ cup	600
Chicken (C)	1 piece	580
Watermelon	1 cup	570
Carrot (R)	1 cup	500
Cantaloupe	1 cup	490
Fish	4 oz	479
Orange juice	1 cup	470
Banana	1 medium	470
Zucchinl (C)	1 cup	450
Skim milk	1 cup	418
Sweet potato	1 medium	400
Lima bean	½ cup	370
Pomegranate	1 cup	340
Spinach (R)	1 cup	310
Dates	5 dried	270
Grapefruit	1 medium	214
Lentil soup	1 cup	170

C = Cooked, R = Raw

Source: *Rashida Ali (2006) Potassium - A Nutritional Star, Pakistan Times, 9th July, 2006*

Need to Promote the Balanced Use of Fertilizers

Needless to say that the balanced use of NPK is vital for obtaining maximum economic yields of high quality, besides addressing environmental concerns (Akhtar *et al.*, 1997). However, the definition of balanced fertilization of crops is, unfortunately, restricted to the use of N and P only, and K hardly figures in government policy originations both at federal and provincial levels. The situation needs to be remedied and K has to be an important component of balanced use of fertilizers. In fact, most of official recommendations do improve the application of K along with NP.

It is recognized that wheat and rice at high yield levels, sugarcane, maize (hybrid), potato, onion and tomato essentially require the application of K ,besides NP. The application of K not only helps to increase crop yields in balanced application of nutrients but also improves crop quality, storage and transportability, besides imparting resistance against lodging and certain pests and diseases.

Fertilizer blends are the best ways to promote balanced NPK application. Crops specific blends can be prepared. Engro Chemical Pakistan Ltd. is presently promoting this strategy. However, more needs to be done.

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Trends and Changes of K-fertilizer Use in Iran in the Past Ten Years : Achievements and Challenges

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Abstract

The trend of mineral fertilizers consumption in Iran during the 1980s and the 1st half of the 1990s brought with it unbalanced use of primary nutrients to the country's fertilizer scene. Phosphorus application rates were in excess of crop needs, resulting in the accumulation of P in major farming areas and causing the precipitation of valuable micronutrients present in the soil, especially zinc and iron. K-fertilizer application rates did not match the releasing power of the soil or the plant uptake needs, and the use of the much-needed micronutrients was generally overlooked. In fact, the average of N-P_2O_5-K_2O use ratios for the entire period of 1980/94 were almost 100:85:05+0.0% micronutrients, indicative of the imbalanced use of different nutrient carriers. From 1995, Soil and Water Research Institute (SWRI), the main research body in Iran responsible for the improved management of the country's soil and water resources, took up the task of adjusting the fertilizer application rates to the levels of the soil nutrients and crop needs/uptakes. In the past decade more than 2500 different experiments were carried-out for different crops, vegetables and orchards all over the country. The results generally revealed that K-fertilizers increased yield as well as crop quality. SOP did better in vegetables and orchards especially under salinity stresses. In contrast, in the depleted soils with higher percentage of clay, where the K-fertilizers are expensive, or the farmers use K-fertilizers in a small quantity (50-100 kg ha^{-1}), or areas were under continuous cultivation of cereals (e.g., wheat, corn, rice, sugarcane, oilseed plants, sugar beet, potato), split application of potassium chloride (MOP), KNO_3 or Solu Potasse were recommended. The results have been a tangible improvement of the N-P_2O_5-K_2O + micronutrients ratios to 100: 45: 23+ 1.5% micronutrients. The main goal will be to achieve ratios of 100: 45: 35 for primary nutrients, improve the use of up to 800,000 tons of sulphur and increase in the consumption of micronutrients up to 4% of the total national fertilizer use level (5 million tons per year). This trend in the balanced use of different mineral fertilizers have been instrumental in improving the soil fertility of major farming areas to such an extent that, despite persistent droughts of the past decade, a sustainable farming is now becoming evident in some main regions and the average yields per unit area of the major crops have improved to the extent of 25 to 30 percent in the past five years, bringing about increased economic return from mineral fertilizer use to the country's farmers.

Keywords: Potassium (K), split application, soil test, K-fertilizers, critical level, optimum level, crops yield and quality

Potassium (K) is an essential element for all living organisms. It is the most important cation in term of its abundance in plant tissues as well as physiological and biochemical functions. Potassium occupies a vital role in regulating crop yield and quality. Potassium as an essential macro element plays an important role on the quality and quantity of crop production. Potassium in soil may occur as soluble, exchangeable, non-exchangeable and structural forms. It has been indicated that there is a dynamic equilibrium among these forms of K. Availability of K to plant roots depends on the dynamics existing among the various K-bearing phases. When a K fertilizer is added to a soil, a fraction of the added K will increase soluble K, a fraction will be adsorbed onto exchange sites and a fraction may be fixed into non-exchangeable forms that will not rapidly equilibrate with soluble K. Distribution of added K among these three fractions specially fixed K, plays a significant role in the soil-plant system influencing effectiveness of fertilization and is also one of the important factors from soil fertility and plant nutrition point of view. So, availability of applied K as a fertilizer to plants is influenced by soil mineralogy, environmental factors and rates of K application.

Today the question of food quality is of the greatest interest with research objectives everywhere especially with respect to the type and rates of chemical fertilizers. Potassium (K) is ranked only second to nitrogen and is highly required by every plant because it activates nearly 60 plant enzymes which determine the yield and quality of agricultural crops. Potassium is involved in the synthesis of starch and protein, also in photosynthetic process, in regulating osmotic pressure, cellular growth, operations of stomata cells, and of plants water regime; it participates in the translocation of carbohydrates from leaves to other plant parts, and acts as a counter ion. It is very mobile within plants, often translocations from old to younger tissues, and functions in producing a stable pH which is necessary for vital cellular enzymatic activities. K-fertilizers, particularly potassium sulphates (SOP), is considered to be a quality fertilizer since it improves the color, skin quality, taste, sugar and vitamin C content of vegetables and fruits. It also improves plants' tolerance against water and salt stresses. The yield and quality of many vegetables such as tomato, spinach, lettuce and celery depends to a large extent on K supplies either by SOP or by potassium chloride (MOP) (Malakouti, 1992; Malakouti, 1996; Tisdale *et al.*, 2003; Malakouti *et al.*, 2005; Soil and Water Research Institute, 2002-06).

Different crops require a considerable amount of potassium for proper growth. Sufficient amounts of potassium is an effective fertilizer for improving the yield and quality of different crops because of its effect on photosynthesis, and water use efficiency as well as the plants tolerance to diseases, and for making a balance between protein and carbohydrates. To evaluate these effects on different crops (e.g. wheat, corn, potato, onion, oilseed plants, beans, citrus and grape and apple orchards) in all over the country in different years in randomized complete block experiments with four replications were carried out in various farms and orchards starting from the Fall of 1995.

Materials and Methods

To evaluate the effect of different forms of potassium fertilizers on the yield of different crops, a randomized complete block experiment was carried out in various orchards and farms starting from 1995, using almost the following treatments: T_1 = Application of all the required nutrients including micronutrient fertilizers except for potassium on the basis of soil tests; $T_2 = T_1$ + potassium as MOP on the basis of soil tests; $T_3 = T_1$ + potassium as SOP on the basis of soil tests; $T_4 = T_1$ + potassium as MOP at 50% more than the rate required by soil tests; $T_5 = T_1$ + potassium as SOP at 50% more than the rate required by soil tests; $T_6 = T_1$ + potassium as MOP at twice the rate required by soil tests; $T_7 = T_1$ + potassium as SOP at twice the rate required by soil tests; $T_8 = T_1$ +1.5 times K-fertilizer as MOP and the other 1.5 times as SOP through top-dressing; $T_9 = T_1$ + 100% of K-fertilizer as MOP and the other 100% as SOP through top-dressing; $T_{10} = T_1$ + 3 times K- fertilizer as MOP; $T_{11} = T_1$ + 3 times K-fertilizer SOP; $T_{12} = T_{10}$ + micronutrients; $T_{13} + T_{11}$ + micronutrients and C = application of only N and P.

Results and Discussions

The analysis of variance results indicated significant treatment effects on the growths and yields at 1% or 5% level. A comparison between the average values for grain yields by Duncan test revealed significant effects of treatments on yields between different treatments as compared with the control plot. The highest yield was obtained with treatments in which K-fertilizers were applied on the basis of soil test with split application (Fig 1 and 2).

NP NPK NPKZn

Fig 1. Synergistic interaction between K and Zn on the yield increase of wheat (SWRI, 2006)

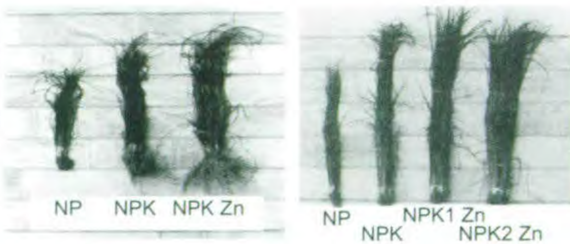

Fig 2. Synergistic interaction between K and Zn on the yield increase of rice (SWRI, 2006; Malakouti *et al.*, 2005)

Methods of K-application as well as potassium sources have their effects on the yield and quality of crops, and thus must be considered in formulating potassium rates. Side dressing of potassium, especially in the case of depleted soils, has been shown to be superior to pre-plant applications, particularly with respect to high K-demanding crops like corn, onion, potato, cotton, etc. Various investigations have shown that the yield response of agronomic as well as horticultural crops to K-fertilizers even under different soil and climatic regimes is determined by the availability of micronutrient fertilizers to a great extent. Figures 3 to 9 show that yield improvements for different crops that were only obtainable with K-split application and at rates that were 1.5 to 2 times the rates determined by soil tests.

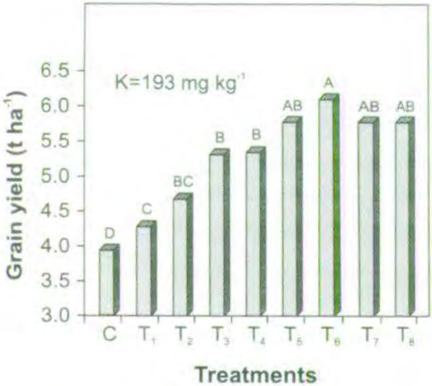

Fig 3. The role of sources and rates of K-fertilizers on the wheat grain yield in Fars (SWRI, 2006; Malakouti *et al.*, 2005)

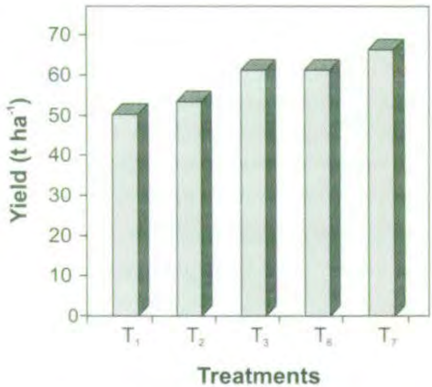

Fig 4. The role of sources and rates of K-fertilizers on the onion yield in East Azarbyjan (SWRI, 2006, Malakouti *et al.*, 2005)

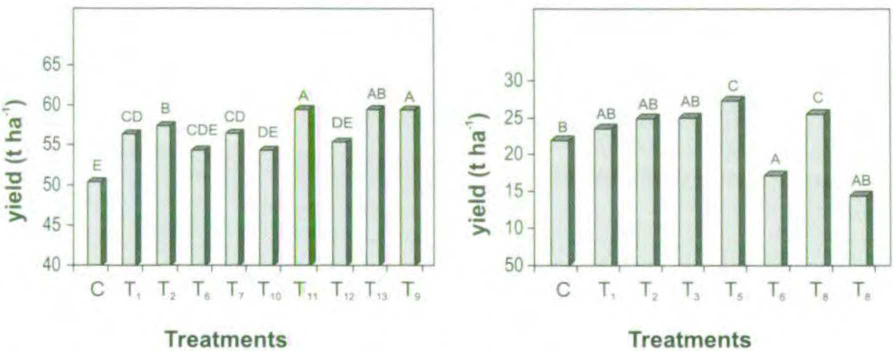

Fig 5. The role of sources and rates of K-fertilizers on the potato yield in different locations (SWRI, 2006; Malakouti *et al.*, 2005)

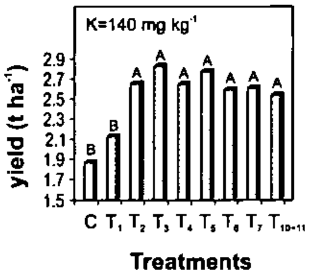

Fig 6. The role of sources and rates of K-fertilizers on the soybean yield (SWRI, 2006; Malakouti *et al.*, 2005)

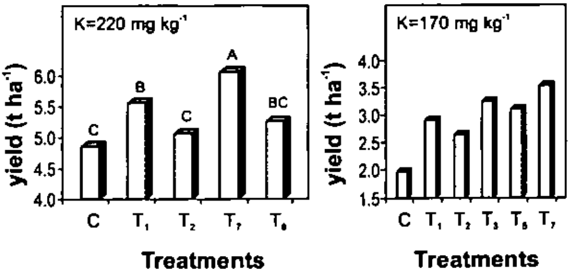

Fig 7. The role of sources and rates of K-fertilizers on the cotton and canola yield in different locations (SWRI, 2006; Malakouti *et al.*, 2005)

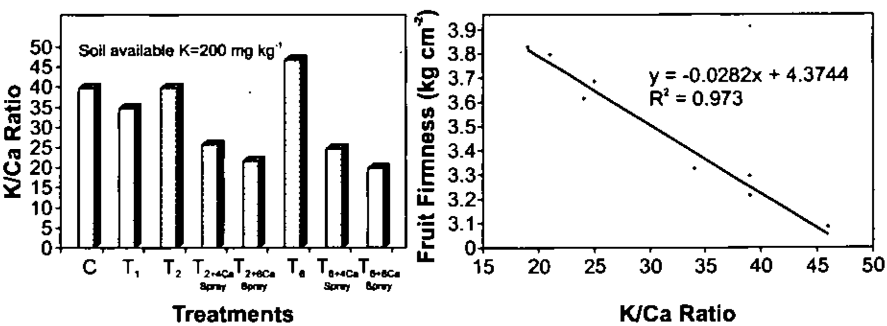

Fig 8. The role of sources and rates of K and Ca-fertilizers on the apple fruit firmness (Dilmaghani *et al.*, 2004)

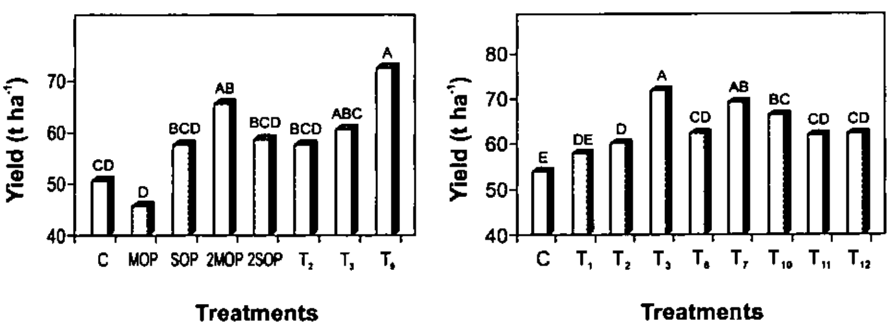

Fig 9. The role of sources and rates of K-fertilizers on the grape and citrus yield in different locations (SWRI, 2006; Malakouti *et al.*, 2005)

Potassium along with zinc also reduced the concentrations of pollutants such as nitrate (NO_3) and cadmium (Cd) in the edible parts of the plants (Fig 10 and 11).

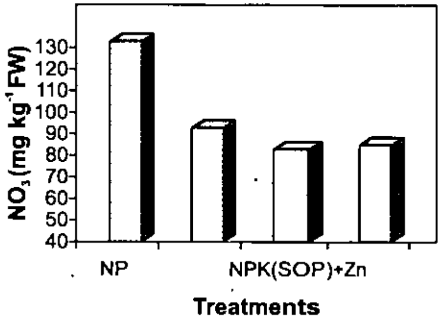

Fig 10. Effect of balanced fertilization in the reduction of nitrate (NO_3) in potato (SWRI, 2006; Malakouti *et al.*, 2005)

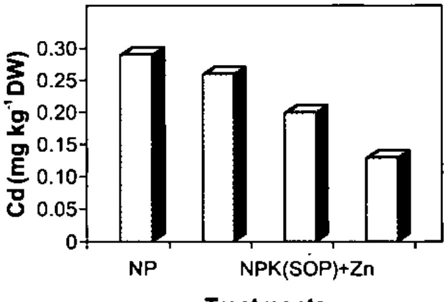

Fig 11. Effect of balanced fertilization in the reduction of cadmium (Cd) in potato (SWRI, 2006; Malakouti *et al.*, 2005)

These positive effects depend on the status of soil potassium and improving the yield and quality of agricultural products along with other information on the role of potassium in increasing the efficiency of N-fertilizers under growing conditions in Iran. These results also revealed some new research findings, especially with regard to potassium movement in the rhizosphere; and with the advantages of using optimum level instead of critical level as an index with regard to the yield increase objectives of the country's Development Plans. Additional information on the physiological roles of potassium in humans, especially in relation to regulating the ratio of K/Na and with regard to controlling blood pressure, are also need to be studied. In practical terms recommendations for potassium rates are commonly based on comparing the value of ammonium acetate extractable-K of a given soil with critical values which are experimentally determined. However, this approach is reliable only with soil potassium levels that are too high or too low but not for intermediate levels. In the case of intermediate soil-K levels, consideration of CEC, PBC, type of clay, and plant factors will improve the accuracy of recommendations.

Conclusions

To apply potassium critical values for calculating fertilizer rates detailed soil maps (1:25,000) which are currently unavailable is needed. The response of different crops to a given level of soil available potassium varies as was seen in the case of wheat, rice, corn etc. Plant analysis could also provide a basis for correcting potassium deficiencies. As a whole, the following conclusions were made from the experimental results:

- The research results prove that many of the agronomic as well as the horticultural crops tested here respond to potassium applications with improved yields and quality aspects. The plants that grew in soils with low levels of exchangeable potassium responded more favorably to the treatments even though a positive kind of response was not always the case for some of the crops. Therefore, it seems factors other than the level of soil exchangeable potassium should be involved and must be researched; in other words, we should try to find a more widely applicable index than soil exchangeable potassium to relate to various crops' yields and qualities.
- There were no significant differences observed between MOP and SOP for most of the agronomic crops. However, we recommend that SOP be applied to quality crops such as vegetables and used before planting and with high potassium demanding crops in light textured soils MOP be used as a side dress.
- There was not a definite correlation between leaf- K and potassium applications for some fruit trees. The highest yields were obtained with potassium levels applied based on soil tests for most of the crops tested in this investigation.
- In the case of high potassium demanding crops, such as onion, potato and cotton, rates of potassium application should definitely excced levels determined by the soil test.
- More experiments are needed to evaluate factors which are responsible for the differences in plant yield in different locations other than the potassium content of the soil.

Acknowledgment

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Nutrient Balances: EU Legislation and Status Quo in Selected European Countries

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Abstract

During the nineteen hundred seventies/eighties several regulations have been initiated in the EU legislation framework mainly focusing on the reduction of water pollution due to nutrient inputs. Especially the "Nitrate Directive" led to a number of measures in the EU member states (e.g., establishment of nitrate vulnerable zones, nitrate monitoring programs) which influenced farming practice. Specific action programs and codes of good agricultural practice were mainly targeting to regulate/restrict the amount of N applied to arable land and grassland. Although this has led to an overall reduction of N use in Europe, farmers need to decide on farm/field level on nutrient inputs to ensure sustainable production.

Keywords: EU legislation, nitrate vulnerable zones, nitrogen surplus, nutrient balances, water quality

In Europe, discussions on environmental issues related to nutrient use in agriculture started in the early nineteen hundred seventies. There had been several issues: (1) high nitrate concentrations in ground and drinking water, (2) eutrophication of lakes and rivers, (3) algae blooms in offshore waters and at the coast lines as well as (4) decreasing wild life diversity for plant and animal species. Society in general, interest groups and as a consequence politicians were involved in these debates and numerous research projects were initiated in EU member states.

Calculation of Nutrient Balances

One approach in this early phase of environmental discussion was the calculation of so-called "farm gate N balances" for each country. On a national level all available data on the inputs (e.g. imports via fertilizers, foodstuff, feeds, seeds, etc.) and also on the amount of nutrients exports were collected (Fig 1). The difference between input and output from these simple balance sheet calculations can be either assigned to changes in the stocks or is available for losses (volatile losses to the atmosphere or leaching into the groundwater, etc.). Thus the nutrient surplus can be used as an indicator for the risk of ecological damage for non-agricultural ecosystems.

One of the outcomes of such nutrient balance calculations was that excess use of nitrogen in agriculture was closely related to several of environmental problems. In a study based on datasets for Germany from 1970-1995, Bach and Frede (1998) calculated that the N surplus per unit area increased from 1970 with a rate of around 2 % per year. The maximum was reached in 1987 (166 kg N ha^{-1} $year^{-1}$). More detailed studies conducted in several European countries (e.g. France, Germany) revealed that within a country distinct differences between regions can occur. Regions with a high animal density have much higher N surplus than regions which are dominated by arable farming. According to Frede (2003) there is a close relationship between animal density in a region and the N surplus. A typical region in Germany where animal husbandry is most important is northwest Germany (Fig 2). The same pattern can be found in France: while in many regions in the south of the country no problems arise, in some regions the N surplus is quite high (e.g. in Brittany, northwest France; Pau Vall and Vidal, 2006).

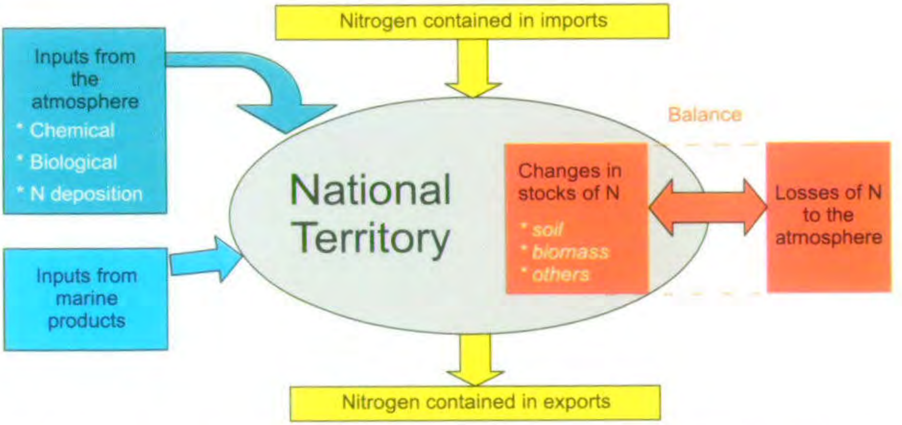

Fig 1. Schematic setup of a "farm gate nitrogen balance" at national level (Source: Pau Vall and Vidal, 2006; modified)

Data sets for 3 years (1990, 1993 and 1995, respectively) for the EU-15 countries reveal that there are obviously huge differences between the countries especially with regard to N inputs from manure (Fig 3). High N inputs via manure can be found in the Netherlands, Belgium, Ireland and Luxembourg. In many other countries the N input via manure is around 50 kg N per ha per year. However, even in those countries with an overall acceptable N input via organic fertilizers there might be regions with a high N surplus (Fig 2).

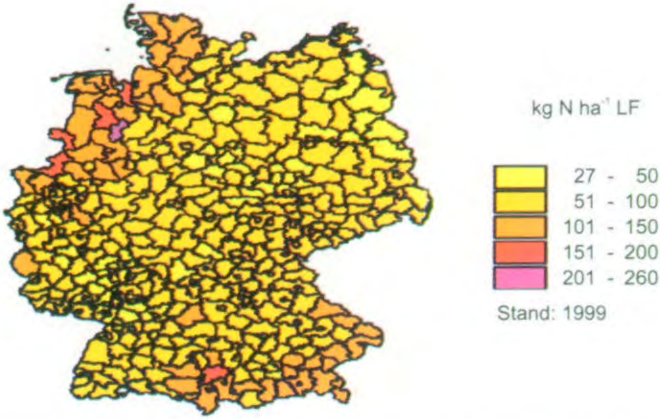

Fig 2. Regional nitrogen balance for Germany 1999 (Source: Frede, 2003)

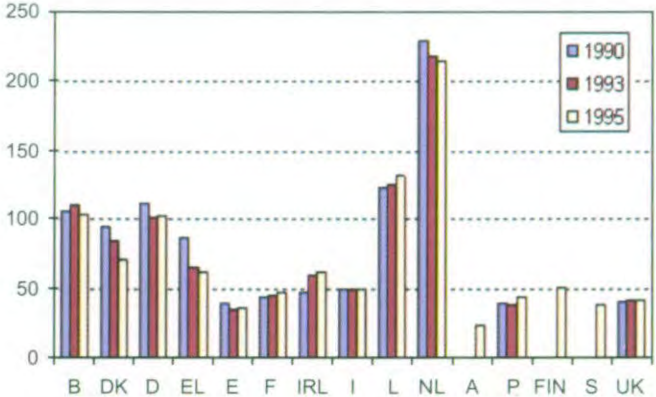

Fig 3. Nitrogen inputs from manure at national level for EU-15 countries in 1990, 1993 and 1995 (Source: Pau Vall and Vidal, 2006; modified)

European Frameworks for Water Protection

The EU commission started several initiatives to reduce water pollution and nowadays water is one of the most comprehensively regulated areas of EU environmental legislation. It started in 1975 with the "Surface Water Directive". In 1978 the "Fish Water Directive" was published. In 1980 the "Groundwater Directive" as well as the "Drinking Water Directive" were launched. With the "Sewage Sludge Directive" implemented in 1986 EU legislation switched to a more source oriented approach, i.e. the environmental damage should as a priority be rectified at the source. Finally in 1991 the "Urban Waste Water Treatment Directive" and the "Nitrates Directive" were launched.

For the agricultural sector the "Nitrates Directive" was the most important one as it was implemented to reduce and prevent nitrate pollution from agricultural sources (i.e. mineral fertilizers and livestock manure) to safeguard drinking water supplies as well as to protect fresh water and marine waters from eutrophication. During this period it became clearer that efficient water protection has to be based on emission limits as well as on quality standards for water. Furthermore it was generally agreed that the environmental conditions (soils, climate, cropping systems) in the various European regions have to be taken into consideration.

In the preamble of the "Nitrates Directive" the objective of this initiative is explicitly stated: ".. to reduce water pollution caused by nitrates from agricultural sources and prevent further such pollution" (Anonymous, 1991). Several measures were approved by the EU:

- Designation of "nitrate vulnerable zones" (NVZ)
- Start of monitoring programs for nitrate in ground and drinking waters
- Establishment of specific action programs
- Implementation of "Good Agricultural Practice" codes and promotion to the farmer community

Nitrate Vulnerable Zones

During the first implementation phase (starting in 1996) some EU member states decided to designate the whole area of the country as nitrate vulnerable zone (e.g. Austria, Denmark, Finland, Germany and The Netherlands). All other countries choose the option to assign only specific regions as NVZ (Fig 4). After the implementation of the NVZs the EU commission cross-checked what has happened in the different EU countries. England for example had designated only a very small portion of the total area as NVZ (Hanley, 2001). However, in 2002 this had to be corrected. Nowadays most of the area in England is within a NVZ (DEFRA, 2006). Furthermore certain rules concerning closed periods for spreading of manure, slurry and mineral fertilizers, limits for the amount of applied N ha^{-1}, instructions how much storage capacity has to be installed on a farm and rules regulating record keeping at farm level were implemented.

Monitoring Programs

One of the aims of monitoring programs was the compilation of datasets on the changes of nitrate concentrations in groundwaters. This should enable the decision takers to judge if a certain measure at national, regional or local scale was successful (or not) in respect to water quality. In Germany data sets from the early 90s are used as reference values. About 10 years later groundwater nitrate concentrations in many regions of Germany still are not acceptable, that means that the concentration of nitrate is higher than the EU threshold value of 50 ppm nitrate. However, the many of the analyzed samples at least show decreasing concentrations, indicating that the amount of nitrate lost via leaching is becoming smaller.

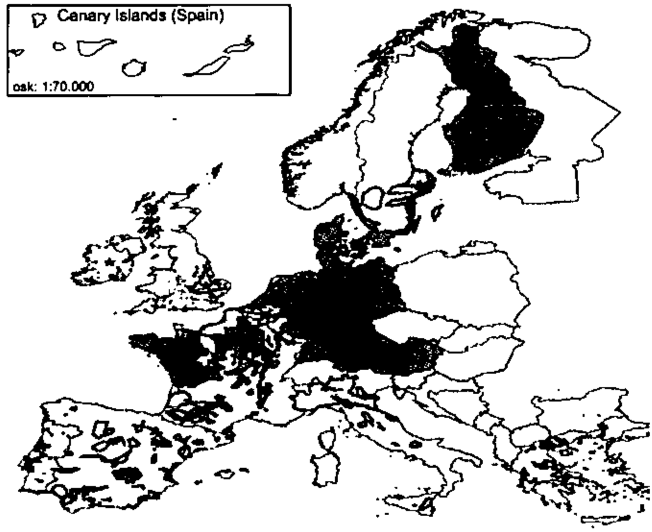

Fig 4. Nitrate vulnerable zones in Europe (Source: Leguen de Lacroix, 2003)

Specific Action Programs

Due to the fact that environmental conditions vary from region to region throughout Europe, member states were allowed to establish action programs considering climatic, soil as well as farming characteristics. Taking Denmark and the Netherlands as examples this can be illustrated.

During the early 1980s concerns in Denmark on the environmental impact of agricultural activities were growing due to frequent incidents of oxygen depletion in lakes, rivers and coastal waters. Although a correlation between N leaching from agricultural land and deoxygenation has not directly been proven, there is a general agreement that the frequency of these incidents has increased with an increased leaching of nitrogen. Implementing the EU "Nitrates Directive" into national legislation the whole country was designated as nitrate vulnerable zone. Besides regulations describing good agricultural practice (see below) a so-called "N quota system" was installed in 1998. On an annual basis each farmer has to calculate a farm quota representing the amount of N that is allowed to be used on the farm. These calculations are based on results from regional field trials where N uptake values of all relevant crops have been determined. Crop specific "N uptake norms" (although they are differentiated according to yield potential, soil types, pre-crop and some other parameters) are fixed 10% below optimum. In the next step of the calculation the amount of N in manure has to be subtracted and finally the recommendation for the farmer is adjusted according to meteorological data. Violations of these rules are prosecuted if the excessive use of nitrogen is above 10 kg ha^{-1}. According to Ambus *et al.* (2001) about 270 farmers (i.e. ca. 0.5 %) have been identified and put to court (Table 1). Fines are progressive and there have been some "show cases" where the farmers had to pay extremely high fines. Overall the use of mineral nitrogen in Denmark has decreased by 47% between 1989-91 and 2001 (Knudsen, 2003).

Table 1. Limits for excessive use of N on a farm basis, associated fines for violation of the rules and number of fines imposed in Denmark

Surplus per farm (kg)	Fine (€)	Number of incidences
< 500	400 - 670	86
500 - 1999	1040	134
2000 - 5000	1880	45
> 5000	individual	5

Source: Ambus *et al.* (2001)

In the Netherlands a mineral accounting system ("MINAS") was introduced in 1987 (Neeteson *et al.*, 2001). This legislation was based on the calculation of input/output nutrient balances and an allowable surplus at farm level for all Dutch farms with more than 2.5 livestock units. However, MINAS has to be seen as an approximation since for reasons of convenience and simplicity terms for atmospheric deposition, biological N fixation, denitrification, and internal stock changes (including soil pool changes) were not accounted for (Neeteson *et al.*, 2001). The major shortcoming of the MINAS approach was that quite high surpluses were allowed and that the fines for the farmers were quite low (e.g. 2.5 € per kg N surplus). However, this surplus oriented approach had to be modified based on the guidelines given in the "Nitrate Directive" and since 2006 Dutch farmers have to follow an input-oriented system. Maximum application rates per ha per year are prescribed taking into account different farm types and application rules for N concerning soil types and crop species have been specified. According to Schröder *et al.* (2005) one of the most important regulations for Dutch farmers is the limitation for N applied via manure (maximum 170 kg N ha^{-1} according to the Nitrate Directive).

To avoid undue hardship and to allow farmers to become accustomed with the new regulations at least for dairy farms with more than 70 % grassland it is accepted to apply up to 250 kg manure-N during a transitional period (2006-2009). A decline concerning the N surplus has been reported for Dutch farms and according to Fraters *et al.* (2004) water quality (with respect to nitrate concentration as well as eutrophication) improved due to measures taken since 1987.

Codes of Good Agricultural Practices

The extent of nutrient losses from agriculture into neighboring ecosystems is directly related to on-farm/on-field activities. One important target of then Nitrate Directive was therefore to force EU member states to establish guidelines for farmers describing so-called "codes of good agricultural practice". In Germany a so-called "Fertilizing decree" had been introduced in 1996 and just recently been amended in 2006 (Anonymous, 2006). In this decree very detailed instructions on all aspects of fertilization management are given, e.g. timing and rates for nutrient application, technical standards for spreader equipment as well as very detailed regulations on the use of organic fertilizers. Furthermore an input-output balance at field level has to be conducted and data recording and archiving is compulsory. Although fines are implemented, for farmers it is much more important to ensure that they act in accordance with the "EU Cross Compliance" regulations, because otherwise EU funds will be reduced.

Conclusions

Alarming indications on decreasing water quality in the early seventies have led to the establishment of an extensive European set of regulations aiming on the conservation of ground and surface waters. Reduction of nutrient inputs from agriculture was one of the focus areas of the EU legislation during the last three decades. With the implementation of the Nitrate Directive in 1991 certain measures at national level had been initiated in all EU member states. Although EU countries selected different options to convert EU law into national regulations (e.g. designation of nitrate vulnerable zones; implementation of GAP codes) reduction in nutrient use (especially nitrogen) can be observed all over Europe. The restriction of application rates for nutrients like P (e.g. based on nutrient export via the harvest) can be regarded as an adequate measure leading to reduced losses to the environment while ensuring economical farming. However, N application rates have to be adapted on a seasonal basis to the specific field depending on crop rotation, soil and climatic conditions (Olfs *et al.*, 2005) otherwise neither the ecological impact might not be realizable nor farm income is sustainable in the long run.

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Balanced Fertilization for High Yield and Quality of Cotton

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Abstract

Soil infertility is now recognized as a major abiotic factor limiting crop production. Nutrient management will be a key factor in order to bring about improvements in soil fertility and sustained crop production. Nutrient demand by 2020 would be >500 kg N-P-K ha^{-1}, in order to meet the production target of 35 million bales lint. In research station experiments, a negative nutrient balance was observed, especially for K, both in the irrigated as well as the rainfed cotton-based cropping systems. In the real world situations, farmers' fields, the situation could be still worse since farmers apply fertilizers at rates that are less than recommended. Results emanating from field experiments across locations, in general, indicate a positive response to application of potassium. At many locations in India there is also a need to include micronutrients as a part of the nutrient recommendation. A combination of organics and mineral fertilizers is by far the best management option that is currently available. Based on data emanating from field experiments conducted across India, we are convinced that adopting a balanced fertilizer schedule that includes organic manure can narrow the yield gap. However, ways and means are needed for efficient recycling of available organic materials so that INM becomes acceptable and easy to adopt.

Keywords: *Gossypium* sp., fibre quality, nitrogen, nutrient balance, phosphorus, potassium, zinc

Cotton (*Gossypium* sp.) is a major commercial crop in India. The genus Gossypium comprises 39 species of which four are cultivated. Based on the chromosome number, the species are classified as diploids (n=13) or tetraploids (n=26). The diploid species are also called as the Old World or Asiatic cottons and comprise the species *G. arboreum* and *G. herbceum*, popularly referred to as 'desi cotton' in India. *Gossypium hirsutum* and *G. barbadense* comprise the New World cottons and are also known as American or Upland cotton. India is the only country in the world where all the four cultivated species and their hybrid combinations and Bt transgenic hybrids are grown.

India occupies first position with regard to acreage (8.77 m ha) and ranks third in production (24.2 million bales) after China and USA. However, the productivity is among the lowest in the world. The present productivity is 466 kg lint ha^{-1}, which is 40% less than the world average of 720 kg lint ha^{-1}. One of the major causes is that 70% of the acreage is rainfed. Soil infertility is another major abiotic factor limiting crop production both in irrigated as well as rainfed ecosystems. Most of the cotton growing regions experience nutrient stress of one or more nutrients.

Cotton Growing Areas and Soil Type

Cotton in India is cultivated in three distinct agro-ecological regions of the country and on wide ranging soil types (Table 1). The north zone comprises Punjab, Haryana and Rajasthan and the entire area is irrigated. The major soil orders are Entisols, Inceptisols and Aridisols on which cotton is grown (Brar, 2001). The central zone comprises of Gujarat, Madhya Pradesh and Maharashtra that is predominantly rainfed and has nearly 60% of the cotton area. Maharashtra occupies nearly one-third of the area in the country but has less than 5% of the area under irrigation. Vertisols and associated soils are the major soil types in the region. In the south zone, cotton is grown in Karnataka, Andhra Pradesh and Tamil Nadu with about 60% of the area rain-dependent. Vertisols, Alfisols and Entisols are the major soil orders in this region.

Table 1. Cotton area and productivity of the major cotton growing areas in India (2005-06)

Zone	States	Major soil type	Acreage (million hectare)	Productivity (kg lint ha^{-1})
North	Punjab, Haryana, Rajasthan	Inceptisols, Entisols, Aridisols	1.62	489
Central	Gujarat, Maharashtra, Madhya Pradesh	Vertisols	5.59	456
South	Tamil Nadu, Andhra Pradesh, Karnataka	Vertisols and mixed red and black soils	1.56	479

Nutrient Demand and Requirement

Cotton being a long-duration crop removes large quantities of nutrients from the soil. In the rainfed regions, nutrient removal ranges about 6-7 kg N, 2-2.5 kg P, 7-8 kg K and 1.2-2 kg S per 100 kg of seed cotton produced. The nutrient removal is greater under irrigated conditions; 9-10 kg N, 3-4 kg P, 10-12 kg K and 2.5-3 kg S per 100 kg seed cotton produced (Palaniappan and Annadurai, 1995).

Cotton is characterized by five growth stages, namely, emergence, square formation, flowering, boll formation, boll maturity and opening. Although the present day cultivars are more determinate in nature, the vegetative and reproductive growth goes on simultaneously. In the early stages, nutrients get accumulated in the leaves (pre-bloom). Once boll set begins, nutrients are translocated from the leaf to the bolls. At harvest the nutrients allocated in the different plant parts is presented in Fig 1. Seed accounts for approximately 60% of the N and P uptake (Fig 1). The bur (carpel wall) has highest concentration of K. Therefore, K accumulation in bur alone accounts for 35% of the total K uptake, leaves and stem account for 45% and the rest in seed cotton.

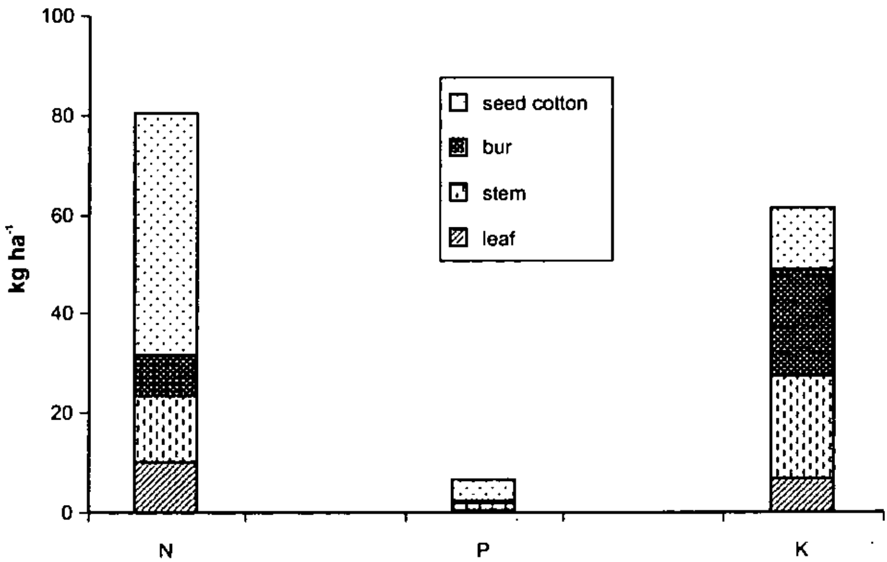

Fig 1. Partitioning of nutrients in the different plant parts at harvest of rainfed cotton (averaged over locations)

Cotton acreage has remained fairly constant over the years (8.5-9.0 million hectares). The projected nutrient requirement for cotton is given in Table 2. On an average, 203 kg N, 81 kg P (188 kg P_2O_5) and 240 kg K (300 kg K_2O) will be needed ha^{-1} to achieve the targeted production of 35 million bales of lint by 2020. The amount of nutrients needed is much greater than the current application rate. It amounts to 524 kg N-P-K ha^{-1}. That means fertilizer use should increase by nearly five-fold. It is not possible to meet such large amounts of nutrient demands through fertilizers alone. Part of the nutrient demand should be supplemented through organic sources and therefore, an integrated approach is essential.

Table 2. Nutrient removal and demand (million tones) for an anticipated production of 35 million bales of lint by 2020

Nutrient	Removal*	Requirement
Nitrogen (N)	0.80	1.83
Phosphorus (P)	0.22	0.73
Potassium (K)	1.08	2.16

*Based on assumptions of Tandon (1992)

Nutrient balance

With the application of recommended amounts of fertilizers, a negative nutrient balance was observed, especially for K (Table 3). The magnitude of negativity was greater in the irrigated cotton-wheat cropping systems. In the real world situations, farmers' fields, the situation could be still worse since farmers seldom apply fertilizers in recommended amounts (Blaise *et al.*, 2005; Blaise and Prasad, 2005). However, exceptions are Andhra Pradesh (Haffis *et al.*, 1997) and Gujarat (Blaise, 2005) where farmers apply more than the recommended amounts of N and P.

Table 3. Nutrient balance (kg $ha^{-1}yr^{-1}$) of major cotton-based cropping systems in India

Cropping system	Location	Soil type	Balance		
			N	P	K
Cotton-wheat	Sriganganagar	Typic Torripsamment	7.9	0.5	-193.1
Cotton-wheat	Hisar	Typic Ustochrept	-36.0	-12.3	-226.3
Cotton (irrigated)	Coimbatore	Udic Haplustalf	30.4	5.4	-19.2
Cotton (rainfed)	Nagpur	Typic Haplustert	15.4	13.2	-16.8
Cotton (rainfed)	Bhopal	Typic Haplustert	-0.2	10.9	-51.5
Cotton (rainfed)	Surat	Typic Chromustert	154.2	-10.4	-80.7
Cotton + mung	Surat	Typic Chromustert	81.9	-25.1	-127.8

Source: Blaise (2005)

At the national level, the estimated nutrient removal at current level of food grain production is around 25-27 mt. Thus a gap of 8-10 mt exists (Tiwari, 2002), which is approximately equivalent to a deficit of 55 kg NPK ha^{-1}. Nutrient balance (amount applied-crop removal) for the three primary nutrients was calculated for the major cotton-based systems. Data presented in Table 3 indicates a negative balance for K at all locations. This was mainly because K applied is lesser than what the crop removes. This is an alarming situation. While a negative nutrient balance exists for K, the balance is by and large positive for N. At Surat, Gujarat, N application rates were very high and the balance was highly positive (Table 3). Farmers in this region apply an excess of fertilizer-N. Thus substantial amounts of N would remain in the soil and is susceptible to loss. In general, fertilizer consumption is far below actual nutrient removal and export from farmers' fields (Blaise *et al.*, 2005). In the rainfed cotton-based cropping systems, Rego *et al.* (2003) reported a positive N and P balance on farmers fields. On the other hand, in the irrigated cotton based cropping systems (cotton-sorghum-finger millet, cotton-maize-finger millet) in south India, Palaniappan and Annadurai (1995) reported a negative nutrient balance for N, P and K. A negative nutrient balance suggests that mining of the soil is continuously taking place and deficiency of nutrients would be the end result. Consequently, response to applied nutrients will decline.

Declining factor productivity?

In the past, emphasis was on the application of N since responses to its application were striking. Continuous cropping with application of N alone resulted in nutrient deficiencies of major as well as emergence of secondary (S) and micronutrient (Zn) deficiencies (Swarup and Wanjari, 2001). The responses to application of N are either low or declining (NAAS, 2006). Transgenic cottons were introduced in the 2002. Despite high seed cost, Bt cotton was grown on nearly 1.3 million hectares area. Impressive yield gains were mainly due to an effective control of the bollworms. As a result the productivity and production of cotton increased contributing to a positive productivity trends (Fig 2). With a further decline in seed costs, large-scale adoption is foreseen with increasing yield trends in the near future. A positive yield trend indicates that there is no decline in factor productivity. In the past, cotton production operated at relatively low (<350 kg lint ha^{-1}) yield levels. Therefore, a dramatic decline in factor productivity as witnessed in the rice-wheat system (Yadav, 1995) was not noticed in the cotton-based cropping systems. Furthermore, cotton has a capacity to adjust morphogenesis and fruit set to establish a balance between the demand and the availability of nutrients. Growing transgenic cotton having high yield potential (>600 kg lint ha^{-1}) would put more stress on the soil nutrient reserves. It is thus expected that sooner or later yield levels may plateau.

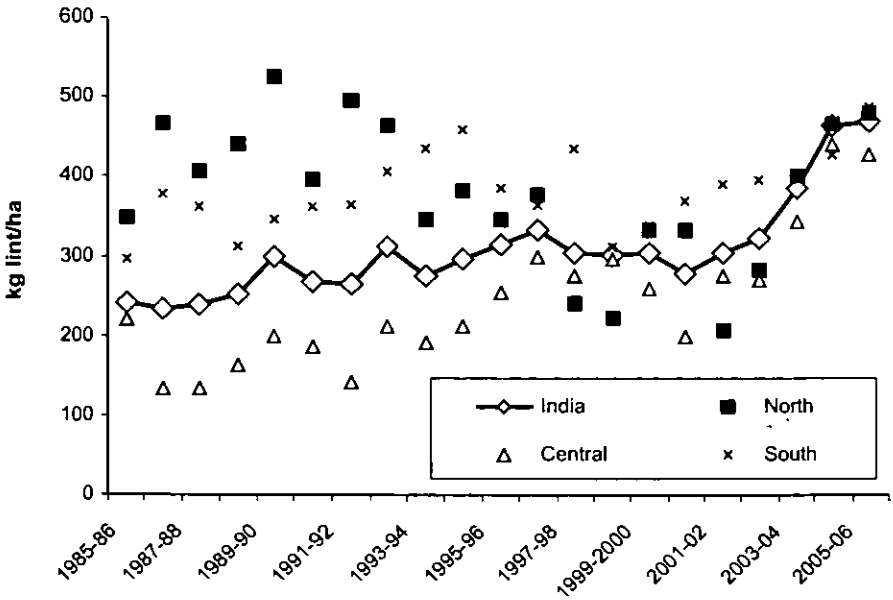

Fig 2. Productivity over time for different cotton growing zones

Response to N, P and K

Nitrogen

Soils in India, in general, are deficient in N and adequate amounts of N are supplied mainly through fertilizers such as urea, diammonium phosphate and to a limited extent through complex fertilizers (Prasad, 1998). Nitrogen requirement of cotton is more complex than any other field crop because of its perennial growth habit and indeterminate nature (Gerik *et al.*, 1998). A deficiency of N would reduce the squaring and flowering period (Radin and Mauney, 1986), induce premature senescence and potentially reduce yields (McConnell *et al.*, 1993). On the other hand, an excess of N prolongs vegetative growth because C is partitioned away from bolls (Gerik *et al.*, 1994) and delays harvest. Apart from this, cotton management costs may increase due to increased susceptibility to pests (Cisneros and Godfrey, 2001). Thus N supply should be in a balance to maximize yields. An adequacy of N can be determined based on tissue tests such as the petiole nitrate widely used in the US (Bassett and MacKenzie, 1983). Simpler tests that can be readily adopted by the farmers are needed such as the leaf colour charts that have been standardized for rice and wheat (Bijay-Singh *et al.*, 2002).

Response to N among the primary nutrients (N, P and K) is the greatest because soils are low in N. It is a reason why this fertilizer element is applied in large quantities as compared to phosphorus and potassium. The response varies with species, varieties, soils and agro-climatic regions (Kairon and Venugopalan, 1999). In general, Upland cottons (*G. hirsutum*) respond better to higher doses as compared to the Asiatic cotton cultivars. Irrigated cotton responds up to 100-150 kg N ha^{-1}, while in the rainfed areas with assured rainfall, 60-100 kg was the optimum N dose. Response beyond 40-60 kg N ha^{-1} is rare when cotton is grown on marginal lands under rainfed conditions. Hybrid cottons have been found to respond up to 320 kg N ha^{-1} under irrigated conditions.

Nitrogen is a fertilizer nutrient that is most susceptible to loss mechanisms. Most of the fertilizer-N is either broadcast applied or placed in pockets. In general, nitrogen use efficiency is low (30-40%). To improve N recovery and N utilization efficiency; nitrification inhibitors, coated urea products such as neem cake coated urea, and split application are recommended (Kairon *et al.*, 2002; Srinivasan, 2003).

Phosphorus

In general, cotton-growing soils are low to medium in 0.5 M $NaHCO_3$ extractable P (Kairon and Venugopalan, 1999) and adequate amounts of P must be supplied. However, in earlier studies response to P fertilizer application was not consistent (Mannikar, 1993). Low/poor response observed in earlier studies was attributed to the low P requirement of cotton (Mannikar, 1993), high P fixation (Pundarikakshudu, 1989) and/or ability to scavenge P from the deeper soil layers (Kapoor and Sekhon, 1985) Even the present day high yielding cultivars have a low P requirement (Fig 1) but a positive response is being noticed to applied P at many locations (Kairon and Venugopalan, 1999). However, variability in response still exists in cotton grown on Vertisols. Response was observed at some locations but not at other locations. Response to P application was found to vary with the soil type, P fixation and soil moisture. Among the Vertisols of four locations (Dharwad, Parbhani, Nandyal and Nagpur) studied, soils of Dharwad and Parbhani had a low sorption and therefore P requirement was low compared to those for Nagpur and Nandyal. P availability is also influenced by soil moisture regime, especially under rainfed conditions. An integrated use of fertilizer-P with manure was found to improve availability at low soil moisture conditions. Several on-farm trials revealed that soil water conserving practices (mulching, ridges and furrows) in combination with application of fertilizers improved seed cotton yield as well as nutrient utilization. Thus for rainfed cotton, it is necessary to apply mineral fertilizers in combination with organic manure and adopt soil moisture conservation practices.

Potassium

Brar (2001) reviewed the response of cotton to applied K for the three-decade period of 1963 to 1993. In general, cotton grown in the zone on alluvial, sandy loam soils was more responsive as compared to the other two zones. Dhanwinder-Singh *et al.* (1990) reported significant increase in yield with K application on soils testing less than 50 mg K kg^{-1} and less than 2% saturation. Our studies indicated a similar trend. Yield increases of 236 to 244 kg ha^{-1} were observed on the sandy loams of Ludhiana and Sri Ganganagar (Table 4). However, at Hisar, Haryana, on a similar type of soils, no response was observed. Vertisols had higher exchangeable-K content and therefore, yield increases observed with soil application were of a smaller magnitude in central and southern regions.

Table 4. Seed cotton yield (kg ha^{-1}) as influenced by soil and foliar application of K at various locations (mean of three years)

Location	Exchangeable-K (mg kg^{-1})	NP	NPK	NPK+ foliar K
Irrigated cotton-wheat				
Sri Ganganagar, Rajsthan	164	1438	1782	1958
Ludhiana, Punjab	169	2014	2250	2110
Hisar, Haryana	219	2759	2732	2732
Rainfed cotton-based system				
Banswara, Rajasthan	170	1327	1374	1438
Surat, Gujarat	330	1054	1146	1023
Parbhani, Maharashtra	154	935	1082	1229
Nagpur, Maharashtra	369	806	974	1059
Dharwad, Karnataka	265	993	1155	1197
Kovilpatti, Tamil Nadu	274	278	302	343

Source: Blaise (2006a)

A long-term study (1985-86 to 2002-03) conducted on the rainfed Vertisols at Nagpur, have indicated that yield stability is higher when all the primary nutrients are applied as compared to application of single nutrients (Table 5). All these data strengthen the viewpoint that a balanced fertilizer approach of NPK is needed. These results also strengthen the findings of earlier researchers (Randhawa and Tandon, 1982; Patel *et al.*, 1996). Randhawa and Tandon (1982) reported 44, 91 and 112% yield increase with N, NP and NPK, respectively, over unfertilized control under irrigated conditions. In a scenario with increasing area under transgenic cotton, balanced fertilization will assume greater importance. Multi-location trials are needed to estimate the nutrient demands of Bt cotton and whether they differ from the conventional, popular cultivars.

Table 5. Mean response and yield stability of balanced fertilizer application as compared to single nutrient application

Nutrient management practice	Mean yield response (kg ha^{-1})	Slope	R^2
N	634.7	0.63*	0.67
NP	920.5	0.92	0.83
NPK	950.2	1.09	0.94
NPK + FYM	1100.8	1.47*	0.88

Source: Blaise *et al.* (2006)

Apart from the primary nutrients N, P and K, secondary nutrients such as sulphur (S) are limiting in the intensive cropping zones. Deficiency symptoms, unlike N, appear on younger leaves. Response to use of S was evident in a few trials conducted in the irrigated north zone (Table 6). Calcium (Ca) and magnesium (Mg) are other two secondary nutrients. Cotton is grown on soils with pH 6.5-8.5 and availability of Ca and Mg is not much of a constraint. However, an excess of exchangeable Ca may cause Mg deficiency. Purple green leaves with defined green veins are the striking deficiency symptoms of Mg. The deficiency can be corrected by resorting to $MgSO_4$ application. To control reddening 1% $MgSO_4$ spray is recommended in Karnataka.

Table 6. Response to application of Sulphur

Location	NPK	NPK + S	Reference
Sirsa, Haryana	1272	1542	Singh and Kairon (2001)
Hisar, Haryana	2533	2895	TMC (2006)
Sri Ganganagar, Rajasthan	1193	1409	AICCIP (2004)
Kanpur, Uttar Pradesh	940	1091	AICCIP (2004)

Foliar application

Pre-plant and side dress methods of fertilizer applications have been recommended so far because it is convenient. Nutrient demand during the vegetative stage of the cop growth is met. However, nutrient demand, especially of N and K, is the greatest when the crop is in the fruit formation stage. Root activity declines after boll formation begins and concomitantly the nutrient uptake (McMichael, 1990). The situation is worse under rainfed conditions, where the crop also experiences moisture stress coinciding with the fruit formation stage. Furthermore, K is relatively immobile in the soil and moves slowly. Rate of plant uptake depends on root length and total root surface area. Cotton is characterized by low root density (Gerik *et al.*, 1987). In such situations, nutrient demand can be met through foliar feeding. Venugopalan *et al.* (1995) reported yield increases with foliar application of N and P fertilizers to Upland cotton grown on rainfed Vertisols. The earliest report of foliar N spray was of Mathur *et al.* (1968). Yield increases were observed with foliar spray of 1% KNO_3 and is now a recommended practice in Punjab. Oosterhuis and Bondada (2001) reported similar trends from late season foliar N fertilization in the US. Foliar application of K was found to increase yields in the rainfed growing areas (Table 4).

Response to Micronutrients

Before the introduction of Bt transgenic cotton the yield levels were almost stagnated, especially in the intensive irrigated areas of north India (Fig 2). Development of resistance to insecticides led to poor insect pest control (Kranthi *et al.*, 2002). Apart from poor pest control, nutrient exhaustion without sufficient replenishment and low usage of organic manure may have contributed to a decline in productivity. The quantity of micronutrients removed by cotton is presented in Table 7.

Table 7. Removal of micronutrients (g ha^{-1}) in selected cropping systems in Gujarat

Cropping system	Zn	Cu	Fe	Mn	B	Mo
Cotton + cowpea	230	75	1740	327	237	11.1
Cotton + cowpea-mung	203	122	1717	381	295	10.9
Cotton + sorghum	581	206	4973	459	439	18.0

Source: Dangarwala *et al.* (1983)

With continued reliance on mineral fertilizers, Rattan *et al.* (1997) reported an increase in deficiency of micronutrients across the country in various field crops. However, because of the fewer number of field experiments conducted on cotton, limited information was available. To understand the aspects of crop response and effects on fibre quality, Technology Mission on Cotton funded a multi-disciplinary, multi-location project on integrated nutrient management for high quality fibre and yield. A positive response to application of Zn was observed, with yield increase ranging from 0 to 200 kg seed cotton ha^{-1} (Table 8). However, at some locations (Nagpur and Dharwad), no/low response was observed in spite of the low Zn content (<0.6 ppm). This does not mean that Zn is not required at these locations. It is possible that the available Zn was efficiently utilized by the cultivars (NHH-44 at Nagpur and DHH-11 at Dharwad) grown at these locations. The aspects of nutrient x genotype interaction need to be studied elaborately. There is also an immediate need to map the deficient areas at the micro level (village or tehsil) and nutrient application should be included as part of the strategy.

Table 8. Response (seed cotton yield kg ha^{-1}) to application of Zn and B at various locations (mean of three years 2003-04 to 2005-06)

Location	Extractable Zn ($mg\ kg^{-1}$)	NPK	NPK +Zn	NPK + B
Sri Ganganagar, Rajasthan	0.57	1573	1895	1627
Ludhiana, Punjab	0.54	1976	2133	1973
Bhopal, Madhya Pradesh	0.40	1989	2268	2199
Parbhani, Maharashtra	0.41	1016	1236	1120
Nagpur, Maharashtra	0.60	1219	1292	1288
Dharwad, Karnataka	0.50	1626	1554	1558
Coimbatore, Tamil Nadu	-	1875	2101	1996

Source: Blaise (2006a)

Iron (Fe), manganese (Mn), boron (B), molybdenum (Mo) and chlorine (Cl) are other essential micronutrients. Iron and Mn are present in abundant amounts and cotton is basically tolerant to low levels of these micronutrients. Among the micronutrients, B plays a direct role in fertilization, flowering and fibre development. It is necessary for fibre elongation and prevention of callusing of epidermal cells (Birnbaum *et al.*, 1974). Without sufficient B, pollen tube growth down to the style is affected resulting in partial or complete failure of fertilization. This leads to characteristic boll drop and deformed fruits. About 33% of the samples analyzed across 20 states in India were observed to be deficient in B (Shrotriya and Philips, 2002). At present, B application as foliar spray (0.1-0.15%) is included as a fertilizer recommendation only in Andhra Pradesh (Shrotriya and Phillips, 2002). Significant yield increase due to B application was observed at just three of the 11 locations. At present, B may not be a factor limiting cotton yield in the irrigated north zone because of substantial amount of B supplied through irrigation water. On the Vertisols, response was observed at some and not at other locations. Reasons need to be elucidated. Application of Zn may be recommended along with the major nutrients NPK, more as a prophylactic measure.

Site-Specific Nutrient Management

Current recommendations are based on the nutrient response and a blanket recommendation is made. This does not take into account the potential contribution from soil and plant nutrient acquisition and demand. A better understanding of residual nutrient status and indigenous supply would benefit fertilizer management and improve fertilizer efficiency. Information available from a few experiments conducted across four locations, indicate site-specific nutrient management (SSNM) treatment was either equal to or better than the existing recommended practice (Table 9). In the SSNM, the nutrients were adjusted according to the targeted yield, plant uptake and soil nutrient status. However, the main difficulty is its adoption because of the wide variability in the soils, climate, and the large number of cultivars that are grown on individual farms.

Table 9. Seed cotton yield (kg ha^{-1}) in the site-specific nutrient management (SSNM) and recommended fertilizer practice (RDF) (mean of three years)

Location	Soil type	RDF	SSNM
Nagpur[1]	Typic Haplustert	1220	1526
Dharwad[2]	Typic Pellustert	2212	2552
Coimbatore[1]	Udic Haplustalf	1875	2088
Bhopal[1]	Typic Haplustert	1989	1975

Source: [1]TMC (2005); [2]Aladakatti *et al.* (2005)

Organic Manure as an Integral Part of Nutrient Management

More and more nutrient deficiencies are beginning to occur because of limited use of organic manure and reliance on high analysis fertilizers. An integration of organic and inorganic sources of nutrients is the right approach to offset the negative aspects of relying on mineral fertilizers alone (emerging nutrient deficiencies, negative nutrient balance, declining organic C, poor soil structure). Long-term studies conducted have indicated that productivity is greater in the integrated approach of nutrient management (Blaise *et al.*, 2006; Venugopalan and Pundarikakshudu, 1999). The INM plots receiving nutrients through organic manure and mineral fertilizers had registered a 0.24% $year^{-1}$ yield increase compared to a 0.3% yield decline $year^{-1}$ in the mineral fertilizer alone plots (Blaise *et al.*, 2006). A yield decline suggests that nutrients other than N, P and K are probably becoming yield-limiting factors. This problem is circumvented through the application of FYM which not only supplies primary nutrients but also is a storehouse of secondary- and micronutrients, improves soil organic matter and consequently physical properties (Mathur, 1997). Furthermore, application of organic manure imparted yield stability (Table 5, Fig 3). However, low availability of good quality organics, such as farmyard manure is a major constraint in the adoption of the integrated nutrient management (INM) technology. Integration of other available resources namely green manure, crop residues, foliar sprays of nutrients and bio-inoculants have indicated significant yield increases (Table 10).

Table 10. Effect of integrated nutrient management (INM) practices on seed cotton yield (% yield increase over recommended dose of fertilizers)

Location	Soil type	INM components	% increase
Delhi[1]	Typic Ustochrept	FYM, Azotobacter, 50% fertilizer-N	10.0
Akola[2]	Aridic Haplustert	Municipal solid waste, Neem seed cake, 50% fertilizer	8.3
Siruguppa[3]	Typic Chromustert	FYM, Crop residues	16.2
Nagpur[4]	Typic Haplustert	FYM, green manure, PSB, 2% DAP, 50% fertilizer-N	17.9
Dharwad[4]	Typic Pellustert	FYM, green manure, PSB, 2% DAP, 50% fertilizer-N	23.6

Source: [1]Das *et al.* (2004); [2]Padole *et al.* (1998); [3]Basavaneppa and Biradar (2002); [4]Singh (2003)

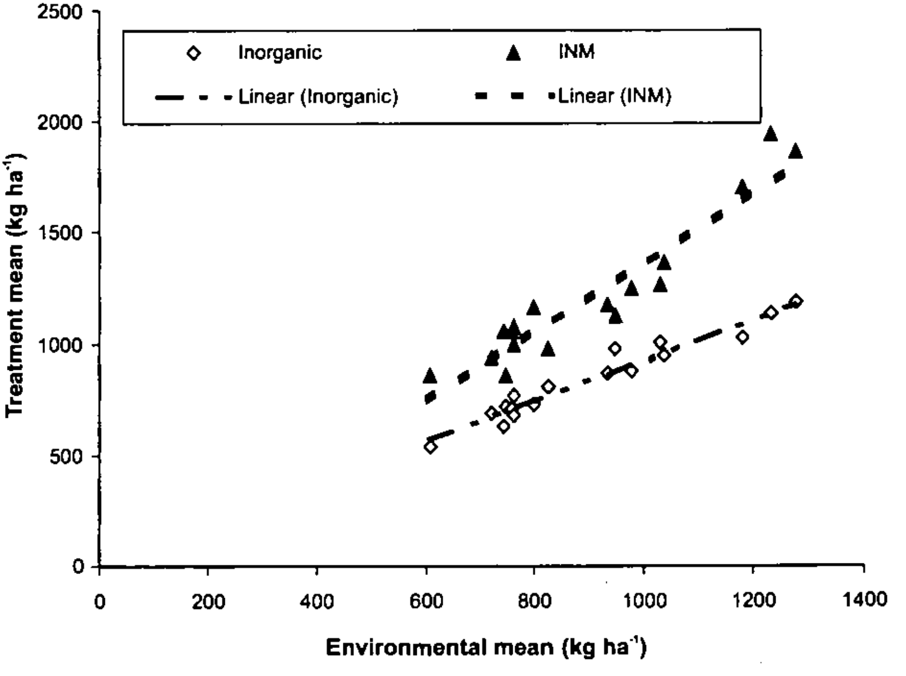

Fig 3. Yield trends for mineral fertilizers alone and fertilizers applied in combination with organic manure

Impact of Nutrients on Fibre Quality

Improvements in textile processing have led to emphasis on improved cotton fibre properties. Quality of lint produced is thus a major issue in the textile industry. Fibre development is basically under genetic control but influenced by environmental conditions. Johnston *et al.* (2002) observed that fibre quality parameters were strongly correlated with soil properties (moisture, organic matter, cation exchange capacity). In studies conducted in Australia, Constable and Hearn (1981) reported that N increased fibre length and strength but decreased micronaire. Whereas, Pettigrew *et al.* (1996), in studies conducted in the US, reported that N application had no effect on fibre length and uniformity. However, in a recent study Read *et al.* (2006) reported inferior quality cotton is produced when crops experience N deficiency. On the other hand, Chand *et al.* (1997) did not observe any effect of N and P application on sandy loams of Lakhaoti, Uttar Pradesh.

Potassium application increased fibre length and micronaire (Cassman *et al.*, 1990). A severe deficiency in cotton may decrease microanire when leaf K levels fall below 10 g kg^{-1} for an extended period (Read *et al.*, 2006). Pettigrew (1999) observed that severe K deficiency compromised the quality of fibre produced. Contrary to these reports, Matocha *et al.* (1994) did not notice any improvements in fibre properties. In studies conducted across 12 locations in India, in general, fertilizer application did not significantly influence fibre properties (TMC, 2005). Application of manure on a continuous basis can lead to fibre quality improvements because of improved soil physical properties and water holding capacity (Blaise, 2006b). Contradictory reports are due to the interactive effects of genotype, weather and soil (Minton and Ebelhar, 1991; Read *et al.*, 2006).

Conclusions

Based on the data emerging from field experiments conducted across the country, a balanced fertilizer approach integrating organic manure was found to be the best option available for high yields. However, making this technology acceptable and readily adoptable by farmers is the challenge. Some of the future research strategies are suggested below:

- Identification of genotypes that can grow well on soils with low/poor nutrient status is needed. Breeding programmes with an emphasis on nutrient use efficiency.
- Interactions between nutrient and other inputs (genotypes, water, tillage).
- Long-term studies to monitor the effects of nutrient management in different agro-eco regions and major cotton-based cropping systems.
- Ways and means to offset nutrient depletion: because application of nutrients at current recommendations seems to be insufficient.

- Information on nutrient uptake and residue recycling (litter fall).
- Accurate nutrient balance sheets to be worked out for the various agro-eco regions.
- Development of farmer-friendly plant diagnostic technique that aids a rapid correction of limiting nutrient.

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Potassium Nutrition of Sugarcane

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Abstract

A healthy sugarcane crop yielding 100-250 t ha^{-1}cane may recover 150 to 720 kg K_2O ha^{-1} from soils. The critical value of K content is 0.9 per cent in second leaf blade from top and 1.4 per cent in its leaf sheath at 90 days of plant growth, while it is 0.60 per cent in second leaf blade from top and 0.7 per cent in its leaf sheath at 150 days of growth. Potassium helps in increasing the number and height of millable canes to increase the cane yield. The responses of sugarcane to K fertilization largely depend upon the degree of K availability from the soil source. Sugarcane is able to utilize K from its K reserves in the soil, so the response to K fertilizers are not frequently observed in sugarcane. The balance application of NPK increases the cane yield considerably. Application of K increases juice extraction and induces drought tolerance in sugarcane. The net return (benefit : cost ratio) varied from Rs.5.61 to Rs.31.58 per rupee invested on potassium in sugarcane in India.

Keywords: Potassium, sugarcane, balanced fertilization

Sugarcane is one of the most important crops in the tropics. It covers a total acreage of 20.1 million hectares for a world production of 1317.9 million metric tonnes of cane having an average cane productivity of 65.6 t ha^{-1} (Table 1). India ranks second in the world both in cane production and in cane area, with cane productivity at 59.7 t ha^{-1}, which is less than the average cane productivity (65.6 t ha^{-1}) of the world and just half to that of Egypt (121.0 t ha^{-1}). The major reason of low cane productivity in India is that about 67.8 per cent of the total cane area is covered in sub-tropical region (Table 2), having cane productivity of 46.49 t ha^{-1}. This region contributes about 62 per cent of the total cane production. The remaining 31.6 per cent of the total cane area lies in the tropical region having 64.8 t ha^{-1} cane productivity comparable to that of average cane productivity of the world. The tropical region contributes about 38 per cent of the total cane production. However, the cane productivity of some of the Indian states in tropical region like Tamil Nadu, Kerala, Karnataka, Andhra Pradesh and Gujarat is comparable to that of Guatemala, Australia, Colombia and Brazil. Further more, a progressive farmer from Maharashtra in tropical region obtained the record yield of 464.03 t ha^{-1}cane and 51.02 t ha^{-1} sucrose, and a cane grower from Uttar Pradesh in sub-tropical region obtained 335.42 t ha^{-1} cane and 33.54 t ha^{-1} sucrose. The Agriculture Department, Trinidad, Indonesia recorded 360 t ha^{-1} cane and 32.4 t ha^{-1} sucrose during 1987-88. The highest harvestable sugarcane yield is close to 58 per cent of the theoretical yield potential. Sugarcane has theoretical potential for dry matter production 470 t ha^{-1}, wet cane yield 805.8 t ha^{-1}, sucrose yield 50-78 t ha^{-1} and total solar energy harvesting efficiency 8.5 per cent.

Table 1. Area, production and productivity of sugarcane in India in comparison to some other countries of the world during 2004

Country	Area (m ha)	Production (mt)	Productivity (t ha^{-1})
Egypt	0.135	16.3	121.0
Guatemala	0.186	18.0	96.4
Australia	0.415	36.9	88.9
Colombia	0.440	37.1	84.3
Brazil	5.455	411.0	75.3
Philippines	0.380	28.0	73.7
Indonesia	0.340	24.6	72.4
China	1.316	93.2	70.8
USA	0.389	27.5	70.7
Mexico	0.639	45.1	70.6
Argentina	0.305	19.5	63.9
South Africa	0.305	19.3	63.3
Thailand	1.050	63.7	60.7
India	4.100	244.8	59.7
Vietnam	0.310	16.6	53.6
Pakistan	1.049	52.0	49.6
World's total	20.100	1317.9	65.6

Source: FAO (2004)

Sugarcane in Indian Economy

Sugarcane occupies a prime position in the agrarian economy in India. About 45 million sugarcane farmers, their dependents and a large number of agricultural labourers are involved in cane cultivation. Besides, about a half million skilled and semi-skilled workers mostly from rural area are engaged in the cane industry, the second largest agro-based industry in India. The area, production and productivity of sugarcane, sugar recovery and utilization of sugarcane for white sugar reached maximum to 4.50 million hectares (2002-03), 299.324 million tonnes (1999-2000), 71.3 t ha^{-1} (1994-95), 10.48 per cent (2000-01) and 60.7 per cent (2001-02) during 1950-51 to 2004-05 (Table 3). The cane productivity has continuously declined from 71.3 t ha^{-1} (1994-95) to 59.4 t ha^{-1} (2003-04) with a marginal increase to 64.8 t ha^{-1} (2004-05). The sugar recovery is also falling down from 10.48 per cent (2000-01) to 10.17 per cent (2004-05). It is good that about 60-61 per cent of sugarcane is utilized for white sugar (2001-02). The sugar production jumped from 5.147 million tonnes (1980-81) to 12.046 million tonnes (1990-91) that increased steadily to the maximum level of 20.147 million tonnes during 2002-03. Again, sugar production decreased drastically during 2003 to 2005 and during 2004-05 it reached to the level (12.691 million tonnes) almost equal to that of 1990-91.

Table 2. Area, production and productivity of sugarcane in sub-tropical and tropical regions of India during 2004

State	Area (m ha)	Production (mt)	Productivity (t ha^{-1})
A. Sub-tropical region			
West Bengal	0.016	103.3	66.2
Haryana	0.130	806.0	62.0
Uttar Pradesh	1.955	11871.5	60.7
Uttranchal	0.107	644.1	60.2
Punjab	0.086	517.0	60.1
Rajasthan	0.006	27.7	48.5
Madhya Pradesh	0.052	214.8	40.9
Bihar	0.104	411.2	39.5
Assam	0.024	103.3	37.0
Jharkhand	0.004	14.2	36.3
Sub Total A	2.484	14713.1	46.49
B. Tropical region			
Tamil Nadu	0.232	2339.6	100.9
Kerala	0.003	28.3	94.3
Karnataka	0.178	1427.6	80.2
Andhra Pradesh	0.210	1573.9	74.9
Gujarat	0.197	1457.0	74.1
Maharashtra	0.324	2047.5	63.2
Orissa	0.015	86.0	55.8
Sub Total B	1.159	8959.9	67.93
India's Total	3.662	23708.8	64.8

Source: Anon. (2006)

Potassium Removal

Sugarcane is capable of rapidly depleting soil of nutrients, particularly potassium. Under Indian conditions, for instance, the aerial parts of sugarcane to yield 100-250 t ha^{-1} cane has been reported to contain 150-720 kg K_2O. Further, under conditions of Maharashtra, Tamil Nadu and Uttar Pradesh, each tonne of above ground portion of sugarcane removes 3.5 kg, 2.84 kg and 2.80 kg K_2O, respectively. Under South African conditions, the aerial parts of an adequately fertilized 12 month - old rainfed plant cane crop has been reported to contain 214 kg K ha^{-1} (Wood, 1990). Under irrigation, a cane crop of similar age and variety may remove as much as 790 kg K ha^{-1}. In the Histosols, an average of 343 kg K ha^{-1} was removed from the field at harvest of the sugarcane (Coale *et al.*, 1993). In Mauritius, more than 250 kg K ha^{-1} was recovered by sugarcane from soils high in available K even when no K was applied (Cavalot *et al.*, 1990). In Australia, the average kg K ha^{-1} in the above ground biomass of a crop of 84 tonnes cane ha^{-1} was 198 kg K ha^{-1} (Chapman, 1996). It is thus clear that for the long term and sustainable use of sugarcane lands, the removal of such large quantities of K needs to be balanced by adequate K inputs if a decline in soil fertility is to be avoided-hence the importance of K manuring in sugarcane cultivation.

Table 3. Area, production and productivity of sugarcane in India from 1950-51 to 2004-05

Year	Area (m ha)	Production (mt)	Productivity (t ha^{-1})	Sugar production (mt)	Sugar recovery of per cent sugarcane crushed	Utilization for per cent of production		
						White sugar	Seed and chewing	Jaggery and *khandsari*
1950-51	1.70	69.2	40.5	1.48	10.0	-	-	-
1960-61	2.45	110.5	45.0	3.02	9.7	-	-	-
1970-71	2.61	126.3	48.3	3.74	9.7	30.2	12.0	57.8
1980-81	2.66	154.2	57.8	5.14	9.9	33.4	11.8	54.8
1990-91	3.68	241.0	65.4	12.04	9.8	50.7	11.9	37.4
1994-95	3.86	275.5	71.3	14.64	9.9	53.6	11.9	34.5
1998-99	4.05	288.7	71.2	15.53	9.8	54.3	11.6	34.1
1999-00	4.22	299.3	70.9	18.20	10.2	59.6	11.5	28.9
2000-01	4.31	295.9	68.6	18.51	10.4	59.7	11.5	28.8
2001-02	4.41	297.2	67.4	18.52	10.2	60.7	11.7	27.6
2002-03	4.52	287.3	63.6	20.14	10.3	-	-	-
2003-04	3.93	233.8	59.4	13.54	10.2	-	-	-
2004-05	3.66	237.0	64.8	12.69	10.1	-	-	-

Source: Anon. (2006)

Role of K in Sugarcane

Potassium mainly acts as an enzyme activator in plant metabolisms such as in photosynthesis, protein synthesis, starch formation and translocation of proteins and sugars. K is fundamental to sugarcane for the synthesis and translocation of carbohydrates for the accumulation of sucrose. The hydrolytic activity of invertase may be intensified due to inadequate supply of K resulting in cane with high reducing sugars but low sucrose level. The increasing deficiency of K decreases the rate of photosynthesis. This results in retarded plant growth, shorter internodes and shorter stalks and smaller in diameter. Under water stress conditions, application of K decreases the transpiration rate and increases the leaf water potential, cane length, sucrose content in juice and cane yield. Thus, K induces tolerance to moisture stress and thereby impedes the decline in cane yield and quality of sugarcane.

Index of K Availability in Soils

Several extractants have been tested for extraction of available K in soils. However, the concentrated H_2SO_4 has been reported to be the best extractant for indexing K availability in soils. Based on this extraction, the soils having < 264 kg ha^{-1} K or < 120 ppm K, 265 to 440 kg ha^{-1} K or 120 to 200 ppm K and > 440 kg ha^{-1} K or > 200 ppm K have been rated low, medium and high in K availability, respectively (Hunsigi, 1977). These limits can safely be reduced nearly to half in calcareous soil. Nevertheless, the most commonly used extractant for available K indexing in soil testing is one normal ammonium acetate (pH 7.0). If the K extraction is <41.5, 42.3 to 82.9, 83.8 to 149.3, 150.2 to 207.4 and > 207.4 kg ha^{-1}, the soils are categorized as very low, low, medium, medium high and high in available K status, respectively, for recommending K fertilizers by Soil Testing Laboratories in Uttar Pradesh. Accordingly, Soil Testing Laboratories in the state recommend 37.3, 33.2, 24.9, 16.6 and 12.4 kg ha^{-1} K in these soils, respectively.

Critical Limits of K in Plant Tissue

K content in healthy sugarcane has been reported to range between 1.15 and 1.85 per cent in second leaf blade from top and 1.75 to 2.65 per cent in its sheath. The critical value of K content is 0.9 per cent in second leaf blade from top and 1.40 per cent in its leaf sheath at 90 days of plant growth (formative phase) while it is 0.6 per cent in second leaf blade from top and 0.7 per cent in its leaf sheath at 150 days of growth with (grand growth phase).

Response to K Application

The economical response of sugarcane to applied K depends upon the degree of K availability from the soil source. Higher the availability of K, lesser will be the response of added K and *vice-versa*. During 1979, it was reported that of 361 districts, soils of 47, 192 and 122 districts were low, medium and high in K fertility, respectively. Since then, K deficient areas have increased and sugarcane in many areas is responding to K where it was not responding some years ago.

Soils particularly of Indo-Gengetic Plains are mainly alluvial in nature and have dominance of illitic clays rich in K. As a result, these soils contained adequate levels of reserve as well as available K. The amount of K released from soils during crop season generally exceeded the requirements of sugarcane. Therefore, the responses of K application on the yield and juice quality were not observed. However, with intensive cropping, the need of K application is becoming necessary in alluvial soils of Indo-Gangetic Plains where the status of available K had been 300-600 kg ha^{-1} in the past.

According to FAO (2000), sugarcane was the most intensively fertilized in India during 1997-98 as 90 per cent of the cane was fertilized, having mean application rate of 97.1 kg N, 38.7 kg P_2O_5 and 25.2 kg K_2O ha^{-1}, totalling 161.0 kg ha^{-1} N+ P_2O_5+ K_2O, with 100 : 40 : 26 N P K ratio. However, 25 to 104 kg K ha^{-1} (Table 4) has been recommended in different states of India (TIFAC, 1991).

Table 4. Recommended rates of K application in India

K recommendation (kg ha^{-1})	State	K recommendation (kg ha^{-1})	State
25	Bihar, Rajasthan	91	Pondichery
37	Madhya Pradesh	91-141	Maharashtra
50	Assam, Nagaland	93	Tamil Nadu
	Orissa, West Bengal	104	Gujarat
62-66	Kerala	-	-
62-155	Karnataka	-	-

Source: TIFAC (1991)

Effects of K on cane yield

Sugarcane research conducted for 70 years from 1912 to 1981 at Shahjahanpur indicated that application of K directly to sugarcane did not increase the yield of sugarcane (UPCSR, 1983). Similarly, Lakholive *et al.* (1979) showed in a 3-year study under Vidrabha (India) conditions that there was no response to K applied at 50-100 kg ha^{-1}. Further, the effects of interactions between N x P, N x K and N x P x K were not found significant on the cane yield. Contrary to this, the responses of sugarcane to applied K in All India Coordinated Experiments on the cultivators' fields in different districts of Uttar Pradesh varied from 40 to 234 kg cane kg^{-1} applied K at 44.8 kg ha^{-1} of soil applied against 51 kg cane kg^{-1} applied K as the state average (Table 5). On an average, the marginal responses, for instance, 57, 52, 71, 76 and 101 kg millable cane per additional one kg of applied K were recorded in Punjab, Uttar Pradesh, Rajasthan, Delhi and Bihar, respectively (Bhendia *et al.,* 1964). Later while reviewing the K response on all India basis, in irrigated sugarcane under the K_2O experiments of AICRP on Sugarcane, Yadav (1993) observed that the yield of millable cane grown without K application ranged from 43.7 to 137.5 t ha^{-1} (Table 6). The yield responses to soil applied K_2O ranged from 0.10 to 3.52 q cane kg^{-1} K_2O. The large variations in the response of sugarcane to K application may be expected due to variations in soil types, climate, varieties, irrigation levels, K fertility levels and rates of K application. Further the results of Simple Fertilizer Experiments again conducted on cultivators' fields for 4 years from 1962-63 to 1966-67 revealed that response of sugarcane to applied K depended upon soil type (Table 7). Sugarcane responded maximum to K application in flat land followed by upland, recent alluvial and lowland in decreasing order. Also the application of K in soils having medium availability of K (232 kg ha^{-1}) did not affeet the yield of sugarcnae (Yadav, 1986). Prasad *et al.* (1996), on the other hand, found in a sandy loam calcareous soil of north Bihar that cane yield was increased from 50 t ha^{-1} without K fertilizer to 74.5 t ha^{-1} with only 60 kg K ha^{-1}. At IISR, Lucknow, sugarcane variety Co 1148 grown in soil having pH 8.0, available N 150 kg ha^{-1} and exchangeable K 182 kg ha^{-1}, yielded 117, 91 and 130 kg cane kg^{-1} of soil applied K at 62.24 kg ha^{-1} over control in planted cane, first and second ratoons, respectively (Table 8). Further, increase in K addition had no effect on cane yield. Application of K to sugarcane variety CoS 767 in soils having low availability of K (110 kg ha^{-1}) at Shahjahanpur during 1989-90 to 1991-92 increased cane yield by 207 kg cane kg^{-1} of soil applied K at 41.5 kg ha^{-1} (Table 9). Further increase in K application upto 166 kg ha^{-1} deereased the yield responses of K to 106 kg cane kg^{-1} of soil applied K. The results of 118 experiments conducted by CSAUAT, Kanpur and Potash and Phosphate Institute of Canada-India Programme, Gurgaon on cultivators' fields revealed that N, N+P and N+P+K increased the cane yield by 47, 63 and 70 per cent over 40.5 t ha^{-1} in control. This indicates that K application increased cane yield by 7 per cent.

Table 5. Response of sugarcane to soil applied K (@ 44.8 kg ha^{-1}) on cultivators in feeds in different districts of Uttar Pradesh

District	Yield in control (t ha^{-1})	Yield response (kg cane kg^{-1} added K)	District	Yield in control (t ha^{-1})	Yield response (kg cane kg^{-1} added K)
Pilibhit	44.8	63	Aligarh	40.7	111
Lakhimpur	44.3	59	Meerut	38.8	97
Varanasi	40.9	56	Moradabad	38.7	209
Saunpur	50.1	40	Rampur	34.0	234
Gorakhpur	50.9	96	Muzaffarnagar	42.1	83
Deoria	46.8	89	State Average	42.9	51

Source: Bhendia *et al.* (1964)

Table 6. Response of sugarcane (planted) to soil applied K under irrigated conditions at different locations in India

Location	State	Variety	Cane yield without K (t ha^{-1})	K_2O applied (kg ha^{-1})	Yield response (kg cane kg^{-1} K_2O)
Tropical region					
Kolhapur	Maharashtra	Co 7527	102.9	50	352
Padegaon	Maharashtra	Co 740	137.5	85	154
Anakapalle	Andhra Pradesh	Co 7706	108.9	50	269
Sub-tropical region					
Pusa	Bihar	BO 91	45.8	50	256
Shahjahanpur	Uttar Pradesh	CoS 767	63.8	50	100
Lucknow	Uttar Pradesh	Co 1148	43.7	75	10
Karnal	Haryana	Co 1148	71.8	50	20

Table 7. Response of sugarcane to soil applied K on cultivators's fields in different soil types

Soil type	Texture	No. of trials	Yield (t ha^{-1})		Yield response (kg cane kg^{-1} added K)
			$N_{210}P_{140}$	$N_{210}P_{140}K_{58}$	
Recent alluvial	Sand	81	53.45	55.86	40
Flat land	Loam	143	61.12	64.31	55
Upland	Sandy loam	303	66.98	69.54	44
Lowland	Clay loam	62	51.47	53.52	35

Source: Mehrotra *et al.* (1972)

Table 8. Effect of soil applied K on yield (t ha^{-1}) of sugarcane at Lucknow

Crop	Control	Soil applied K (kg ha^{-1})		C.D.
		62.2	124.5	(0.05)
Plant crop	35.7	43.0	42.6	1.2
First ratoon	35.4	41.1	43.5	NS
Second ratoon	28.1	36.2	38.5	5.4

Source: Jafri *et al.* (1988)

Table 9. Effect of soil applied K on the yield (t ha^{-1}) of sugarcane at Shahjahanpur

Year	K applied (kg ha^{-1})					C.D.
	0	41.5	83.0	124.5	166.0	(0.05)
1989-90	72.2	75.6	78.0	81.2	87.6	0.03
1990-91	74.3	77.7	79.5	80.4	82.4	N.S
1991-92	54.8	73.9	79.3	83.2	84.2	4.40
Mean	67.1	75.7	78.9	81.6	84.7	-
Response (kg cane kg^{-1} K)	-	207	142	116	106	-

Source: UPCSR (1989-90 to 1991-92)

Application of K with low level of N had no effect on the yield of seed cane at Pantnagar (Table 10). However, at higher level of N at 187.5 kg ha^{-1} being 125 per cent of the recommended N dose, the combined application of 33.2 kg ha^{-1} K significantly increased the yield of seed cane. Here each kg of soil applied K yielded 226 kg of seed cane. Evidently, K application is beneficial to match the higher N application for increasing the yield of quality seed in sugarcane.

Table 10. Effect of soil applied N and K on yield (t ha^{-1}) of seed cane at Pantnagar

K (kg ha^{-1})	N (kg ha^{-1})			Mean
	112.5	150.0	187.5	
0.0	69.2	73.4	77.7	73.4
33.2	69.6	76.7	85.2	77.2
Mean	69.4	75.0	81.4	-
C.D. (0.05)	-	-	-	5.1

Source: GBPUAT (1997-98)

The importance of a balanced nutrition particularly between N and K in getting the maximum yield and quality of sugarcane should also not be overlooked (Table 11).

Table 11. Effects of balanced application of NPK on cane yield (t ha^{-1}) and sugarcane quality at Ludhiana

Fertilizers (kg ha^{-1})			Plant crop	Ratoon crop	Plant crop	Ratoon crop
N	P	K			CCS (%)	
150	-	-	67.3	52.5	12.1	12.5
150	60	-	76.4	65.3	12.9	13.0
150	60	60	78.6	67.6	13.5	13.4
150	60	60+FYM	84.9	72.4	13.2	13.2
C.D. (0.05)			5.2	5.2	0.4	0.4

NB: In ratoon crop, 337 kg N ha^{-1} was applied
Source: Kapur and Bishnoi (1998)

Rabindra *et al.* (1993) demonstrated that sugarcane grown continuously from 1971 on a red sandy loam soil at Karnataka in India gave cane yield of 63 t ha^{-1} in 1971 with and without fertilizers, but in 1988 while the cane yield with N alone (250 kg N ha^{-1}) was 30-34 t ha^{-1}, application of NPK with K at 125 kg K ha^{-1} gave cane yield of 130-136 t ha^{-1}.

Effect of K on cane yield, sugar yield and cane quality under stress condition

The potassium fertilization either through soil or foliage, either K alone (Tables 12, 13) or with urea at very low concentration (Tables 14, 15) or with trash mulching (Table 15) helps to produce considerably higher yields of sugarcane and sugar and better juice quality under stress conditions.

Table 12. Effect of soil applied K on yield attributes of sugarcane

K_2O (kg ha^{-1})	Cane height (cm)	Millable cane (t ha^{-1})	Cane yield (t ha^{-1})
0	193.4	65.3	69.4
30	219.0	68.8	82.3
90	220.3	62.8	69.1
C.D. (0.05)	1.8	3.6	7.5

Source: Dwivedi and Srivastava (1996)

Table 13. Effect of soil applied potassium on juice quality of sugarcane at normal (0.03, - M Pa) and water deficit conditions (0.65, - M Pa)

K_2O	Cane juice extraction (%)		Pol (% juice)	
(kg ha^{-1})	Normal	Water deficit	Normal	Water deficit
0	59.6	58.0	17.6	17.8
30	62.2	62.7	18.1	19.3
90	62.5	62.3	18.6	20.2
C.D. (0.05)	1.2	1.2	0.8	0.9

Source: Dwivedi and Srivastava (1996)

Table 14. Effect of foliar spray of potassium during drought period on the yield of cane and sugar in different soil types

Treatment	Cane yield (t ha^{-1})		Sugar yield (t ha^{-1})	
	Sandy Loam	Loam	Sandy Loam	Loam
Drought crop (DC)	68.8	89.7	5.28	6.60
DC + 3 foliar spray of 2.5 % KCl	90.0	95.0	6.77	6.93

Source: Naidu *et al.* (1983)

Table 15. Effect of potassium on yield and juice quality in sugarcane under drought condition

Treatment	Cane yield ($t\ ha^{-1}$)	Sucrose (% juice)	Sucrose (% cane)
A. Foliar spray and mulching			
Control (drought)	66.1	13.69	9.02
Urea (2.5%) spray at 60, 90 and 120 days after planting (d.a.p.)	71.2	14.28	9.39
Urea + potassium (2.5% KCl) spray at 60, 90 and 120 d.a.p.	78.4	14.52	9.72
Mulching at 60 d.a.p.	72.0	14.85	10.02
C.D. (0.05)	5.7	NS	NS
B. Potassium (60 kg K_2O) and trash mulching for crop planted in June/July			
Control (drought)	99.9	15.00	11.05
K application in Feb. & March (2 irrigations before drought)	114.3	16.23	11.73
C.D. (0.05)	8.64	0.92	0.17

Source: Anonymous (1967)

Effect of K on cane juice extraction and quality

Potassium is known as 'quality element' and so is necessary for quality crop like sugarcane. Sucrose content in cane is affected primarily by variety and climatic conditions and only in a relatively minor extent by the fertilizers applied. Though reports exist to indicate that K is capable of raising sugar yields without a concomitant increase in the yield of cane.

Application of K either through foliar or partly through foliar and partly through soil at a later stage of crop growth increased juice extraction by 2 to 5 per cent. The effects of application of K alone or interactions between N x P, N x K and N x P x K were not found significant on the juice quality of sugarcane (UPCSR, 1983 ; Yadav, 1986; Jafri *et al.*, 1988). However, application of K after 180 days of crop growth helps to offset the reduction in sugar content in sugarcane due to delayed application of N till 180 days of crop growth. The content of reducing sugars significantly increased from 2.58 per cent in control to 2.69 per cent with application of K at 33.2 kg ha^{-1} in juice of seed cane at Lucknow. This indicates that seed cane fertilized with K had more reducing sugar which is beneficial for better germination.

Need for K Application in Soils

The external supply of K to sugarcane is governed by the economical response of sugarcane to added K which ultimately depends upon the degree of nutrient availability from the soil source. The response to K on cane yield were low in the past for the reasons mentioned above. However, the K responses on cane yield are on increase with time as indicated above due to emerging and increasing deficiency of available K in soils. Further, the NPK use ratio in Uttar Pradesh is very wide. It was as wide as 48.9 : 9.3 : 1 during 1993-94 against the desired ratio of 4 :2 :1 or 2:1:1. The removal of K from soil by sugarcane is also very high. Considering these facts, it is imperative to apply K in U.P. soils to restore soil K fertility at least to the extent or part of K removal by sugarcane vis-à-vis to satisfy K fixation in soils and for balanced application of NPK. A single application of K at planting in planted cane and at stubble shaving in ratoon is found as good as two or three split applications of K for getting higher cane yield. Split application either showed no promise or was uneconomic as the extra expenditure would not be offset by the increase in yield.

The available data in the literature shows that K, in spite of its important role in sugarcane plant, must be kept just adequate to produce optimum yields and to regulate maturity so that maximum sugar is recoverd from the millable stalks.

Economics of K Application

The economics of potassium use depends upon yield increase per unit input. The benefit : cost ratio in sugarcane with K application varied from 5.61 to 31.58 (Table 16). However, the reliance on benefit/cost ratio is not true, since even high ratio occurs with low yield and low rates of application of a nutrient and for this reason economic benefits per unit area also should be calculated.

Table 16. Economics of K application in sugarcane

State	Crop	Yield (t ha^{-1})		Application of K_2O (kg ha^{-1})	B : C ratio
		Without K	With K		
Uttar Pradesh	Plant	109.1	110.0	120	8.50
Haryana	Plant	49.0	53.6	50	8.59
	Plant	53.0	57.3	50	8.03
	Ratoon	52.9	57.4	75	5.61
Rajasthan	Plant	116.8	137.7	60	31.58
Maharashtra	Plant	125.0	149.0	120	9.91

Source: Tiwari (2005)

Future Research Needs

Based on the upto date available information on the subject, the gaps in the existing knowledge are identified and accordingly future needs are suggested as follows:

i. There is a need for delineation of K responsive soils and the supply of K fertilizers may be regulated to the need based locations.

ii. Interactions of K with other nutrients should be studied. Efficient method and appropriate timings of K application in different soil types under different sugarcane based cropping systems be worked out.

iii. Balance sheet of K be worked out for different bench-mark soils under different sugarcane based cropping systems.

iv. Soil test crop response correlation studies be carried out to recommend K fertilizers on soil test basis for getting better yield responses and higher profits.

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Balanced Nutrient Management for Improving Yield and Quality of Pearl millet, Clusterbean and Indian Mustard

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Abstract

Pearl millet, clusterbean and Indian mustard are important crops for sustainable production in arid and semi-arid regions of India. Introduction of high yielding, high fertilizer and irrigation responsive varieties; and improved management practices have resulted in increased productivity and production of these crops but the progress of productivity gains is now slowing down coupled with decline in soil health. Low and imbalanced use of nutrients is one of the major reason for low productivity and depletion in soil fertility. In this context, balanced nutrient management is very essential and is a prime necessity for maintaining soil health and sustaining agriculture. The results of studies conducted in India revealed that pearl millet responded favourably to application of 40 kg N, 20 kg P_2O_5, 20 kg K_2O and 20 kg $ZnSO_4$ ha^{-1} under rainfed conditions and to application of 90-120 kg N, 40-60 kg P_2O_5, 30 kg K_2O and 25 kg $ZnSO_4$ ha^{-1} under irrigated conditions. Balanced application of 15-20 kg N, 40-60 kg P_2O_5, 20 kg K_2O, 20-40 kg S and 25 kg $ZnSO_4$ ha^{-1} proved beneficial for clusterbean while application of 40-60 kg N, 20 kg P_2O_5 and 40 kg S ha^{-1} for rainfed mustard and 80-120 kg N, 30-40 kg P_2O_5, 40-60 kg K_2O, 40-60 kg S and 25 kg $ZnSO_4$ ha^{-1} for irrigated mustard is found to be optimum in terms of yield, quality and soil health. Integrated nutrient management further proved more effective.

Keywords: Pearl millet, clusterbean, mustard, nutrient management, yield, quality

In the modern era of intensive agriculture, increasing demand for food and high cost of living are forcing the country to produce more and more per unit area per unit time by increasing cropping intensity. On the other hand, higher yield associated with heavy fertilization through high analysis straight fertilizers and less use of organics result in imbalance in nutrient application and excessive mining of native fertility causing multi nutrient deficiencies. This emphasizes the need for sustaining the productivity and soil health. Sustainable agriculture is an important issue worldwide, which obviously requires enhanced flow of nutrients to crops. The soil is not an inexhaustible store of plant nutrients. Man has been exploiting the reserves of soil nutrients from time immemorial and during recent years, widespread deficiencies of secondary and micro-nutrients too have been surfacing.

The productivity and quality of crops and protection of environmental quality will not last long if we continue practices of using too much or too little nutrients with their concomitant inefficient utilization. In this context, balanced nutrition is necessary, which means application of all the deficient plant nutrients in sufficient amount, appropriate forms and ratios. It should not mean that every time a crop is grown, all the nutrients should be applied in particular proportion rather fertilizer application should be tailored to the crop needs keeping in view the capacity of the soil to fulfill these needs. To achieve this, it is necessary to keep an overall balance of nutrients in total cropping system. This may indicate the need for the application of different nutrients at specific times, in a particular order to drive the maximum benefit from the application of given quantity of nutrients.

Pearl millet, clusterbean and mustard are important crops for sustainable production in arid and semi-arid regions. The soils of these regions are not only light textured but are also low in organic matter and deficient in nutrients especially N, P, K, Zn and S. Introduction of high yielding, high fertilizer and irrigation responsive varieties; and improved management strategies has resulted in dramatic rise in productivity and production of these crops. But the process of productivity gain is now slowing down coupled with decline in soil fertility. Low and imbalanced use of fertilizers is one of the major reasons for low productivity and depletion in soil fertility. Therefore, there is an urgent need to promote the balanced use of fertilizer to not only increase the food production but also to enhance the nutritional quality of crops.

Balanced Nutrient Management in Pearl Millet

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] surpasses all domesticated cereals in drought tolerance and is largely grown as rainfed crop in arid and semi-arid tropics on sandy, alluvial, medium black soils and red earths in the areas receiving annual rainfall in the range of 150 to 1000 mm. It is used as a staple food for farming community as well as cattle fodder and poultry feed. It is grown in about 7.89 million hectares of land in India out of which about 90 per cent is rainfed. About 46 to 49 per cent area of pearl millet in the country is in the Rajasthan state. Maharastra, Gujarat, UP and Haryana are the other major pearl millet growing states of India. The average productivity of pearl millet is only 694 kg ha^{-1} which is very low (Annual Report, 2005-06).

The results of long term experiments conducted for seven years at Hisar (Haryana) showed that rainfed pearl millet responded to increasing dose of nitrogen upto 40 kg N ha^{-1} and phosphorus upto 20 kg P_2O_5 ha^{-1} in good and normal rainfall year but not in low rainfall years (Oswal, 1985). Sekhawat *et al.* (2005) also observed that under rainfed condition of hyper arid region of Rajasthan, application of 40 kg N with 20 kg P_2O_5 and 20 kg $ZnSO_4$ ha^{-1} gave significantly higher return over control, 40 kg N alone and 40 kg N with 20 kg P_2O_5 ha^{-1} by 88.3, 25.4 and 11.8 per cent, respectively (Table 1).

Table 1. Effect of fertilizer application on pearl millet yield and total returns

Treatments	Grain yield (q ha^{-1})	Total return (Rs.)
Control	4.45	2879
40 kg N ha^{-1}	6.84	4326
40 kg N + 20 kg P_2O_5 ha^{-1}	7.82	4851
40 kg N + 20 kg P_2O_5 + 20 kg $ZnSO_4$ ha^{-1}	8.73	5423
L.S.D. (0.05)	0.72	466

Source: Sekhawat *et al.* (2005)

The K nutrition in pearl millet has not been paid due attention in the past because of the general belief that Indian soils were well supplied with potassium. The results of experiment on effect of potassium in loamy sand soils of Jobner (Rajasthan) revealed that grain yield of pearl millet increased significantly with the increase in K level upto 20 kg K_2O ha^{-1} (Table 2). At 30 kg K_2O ha^{-1}, the grain yield was higher over 0, 10 and 20 kg K_2O ha^{-1} by 29.7, 26.5 and 14.5 percent, respectively (Yadav and Yadav, 2004). Whereas Patel *et al.* (1991) and Parsad *et al.* (1995) observed that under irrigated conditions application of 120 kg N and 40 kg P_2O_5 ha^{-1} was found to be more effective in increasing pearl millet grain yield and maintaining soil fertility.

Table 2. Effect of potassium levels on pearl millet yield

Treatments (kg ha^{-1})	Grain yield (q ha^{-1})
$N_{60}P_{30}K_0$	12.5
$N_{60}P_{30}K_{10}$	14.3
$N_{60}P_{30}K_{20}$	15.8
$N_{60}P_{30}K_{30}$	16.2
L.S.D. (0.05)	1.0

Source: Yadav and Yadav (2004)

Integrated nutrient management in pearl millet

Integrated nutrient management aims at exploiting all the available sources of plant nutrients such as organic manure, bio-fertilizer and inorganic fertilizers to improve soil health and crop productivity. In view of escalating prices of chemical fertilizers, energy crisis and nutrients mining by high yielding varieties, there is a strong need to adopt integrated nutrient supply system.

The results of experiment under rainfed condition (Table 3) at Jaipur (Rajasthan) revealed that application of 75 per cent of recommended fertilizer dose (RDF 40 kg N + 20 kg P_2O_5) alongwith 2.5 t ha^{-1} vermicompost and bio-fertilizer gave maximum grain (49.17 q ha^{-1}) and fodder (122.22 q ha^{-1}) yield and net returns of Rs. 13998 ha^{-1} (Annual Report, 2003-04). Similarly, the results of a field experiment under irrigated condition at Hisar (Haryana) indicated that application of 120 kg N and 60 kg P_2O_5 ha^{-1} alongwith 5 t ha^{-1} of vermicompost produced the highest grain yield of pearl millet as compared to application of 120 kg N ha^{-1} and 60 kg P_2O_5 ha^{-1} alone (Thakral *et al.*, 2001).

Table 3. Integrated nutrient management in pearl millet under rainfed condition

Treatments	Grain yield (q ha^{-1})	Fodder yield (q ha^{-1})	Net returns (Rs. ha^{-1})
100% RDF	44.5	107.4	13989
75% of RDF	38.4	101.8	12169
75% of RDF + Azotobacter + PSB	40.4	101.8	12752
75% of RDF + 2.5 t vermicompost ha^{-1}	47.9	120.4	13524
75% of RDF + 2.5 t vermicompost ha^{-1} + Azotobacter + PSB	49.2	122.2	13998
50% RDF	31.5	92.6	9848
50% of RDF + Azotobacter + PSB	33.7	96.3	10702
50% of RDF + vermicompost	44.4	103.7	11921
75% of RDF + Azotobacter + PSB	45.4	105.6	12341
L.S.D. (0.05)	6.2	12.8	2277

Source: Annual Report (2003-04)

Effect of nutrients on yield and quality of pearl millet

Balanced nutrition also plays an important role in improving the quality of produce. Rathore *et al.* (2004) observed that combined application of chemicals and bio-fertilizers significantly improved the nutrient uptake and protein yield of pearl millet (Table 4). Maximum increase in nutrient uptake and protein yield was recorded with application of 60 kg N + 40 kg P_2O_5 ha^{-1} closely followed by application of 30 kg N + 40 kg P_2O_5 ha^{-1} combined with inoculation of bio-fertilizers [Azosprillum + Phosphate Solublizing Bacteria (PSB)].

Table 4. Yield, nutrient uptake and protein yield of pearl millet as influenced by nutrient management under rainfed conditions

Treatments ($kg\ ha^{-1}$)	Yield ($q\ ha^{-1}$)	N uptake ($kg\ ha^{-1}$)	P uptake ($kg\ ha^{-1}$)	Protein yield ($kg\ ha^{-1}$)
Control	18.7	55.5	5.1	173.9
60 kg N + 40 kg P_2O_5	24.9	76.9	7.2	249.0
30 kg N + 40 kg P_2O_5	20.6	60.0	5.8	197.8
30 kg N + 40 kg P_2O_5 + Azospirillum	23.1	68.9	6.1	221.8
30 kg N + 40 kg P_2O_5 + PSB	22.5	68.0	6.4	216.6
30 kg N + 40 kg P_2O_5 + Azospirillum + PSB	24.6	73.9	7.3	243.5
L.S.D. (0.05)	1.3	9.6	0.7	21.9

Source: Rathore *et al.* (2004)

Studies conducted at Bawal (Haryana) on loamy sand soils indicated that pearl millet crop responded significantly upto 30 kg K_2O ha^{-1}. The mean increase in grain yield was 8.8 and 11.8 percent with 90 kg N ha^{-1} whereas this increase was 9.7 and 13.5 percent with 120 kg N ha^{-1} at 30 and 60 kg K_2O ha^{-1}, respectively, over control. Application of potassium significantly increased the K uptake by pearl millet. Protein content of pearl millet grain also increased with potassium application but this increase was significant only at 60 kg K_2O ha^{-1} (Table 5). Application of 60 kg K_2O ha^{-1} also maintained the available potassium status of soil after the harvest of pearl millet crop in pearl millet-wheat rotation (Annual Report, 2004-05).

Table 5. Effect of potassium on pearl millet yield, total K uptake and grain protein content (mean of two years)

Treatments ($kg\ ha^{-1}$)	Grain Yield ($q\ ha^{-1}$)	Total K uptake ($kg\ ha^{-1}$)	Grain protein content (%)
$N_{90}P_{60}K_0$	23.3	146.3	9.31
$N_{90}P_{60}K_{30}$	25.4	183.5	9.93
$N_{90}P_{60}K_{60}$	26.1	200.8	10.30
$N_{120}P_{60}K_0$	26.2	168.3	9.63
$N_{120}P_{60}K_{30}$	28.8	215.9	10.35
$N_{120}P_{60}K_{60}$	29.8	241.5	9.63
L.S.D. (0.05)	1.5	-	0.87

Source: Annual Report (2004-05)

Jat *et al.* (2002) also observed that application of 60 kg N ha^{-1} significantly increased protein content in grain and total sulphur uptake over control and 30 kg N ha^{-1}, whereas total N uptake increased markedly upto 90 kg N ha^{-1}. Fertilizing crop with 40 kg S ha^{-1} significantly enhanced total uptake of nitrogen and sulphur over control and 20 kg S ha^{-1}. Similarly, Sharma *et al.* (2004) observed that application of sulphur significantly increased the nitrogen, sulphur and protein content of pearl millet seed and the highest values were recorded under 60 kg S ha^{-1}. Whereas chlorophyll concentration increased significantly upto 20 kg S ha^{-1} (Table 6).

Table 6. Effect of levels of sulphur on N, S, protein and chlorophyll content of pearl millet

Treatments (kg ha^{-1})	N content (%)	S content (%)	Protein content (%)	Chlorophyll content (mg g^{-1} fresh weight)
$N_{20}P_{40}S_0$	1.67	0.14	10.4	2.72
$N_{20}P_{40}S_{20}$	1.90	0.16	11.9	2.90
$N_{20}P_{40}S_{40}$	2.06	0.18	12.9	2.82
$N_{20}P_{40}S_{60}$	2.17	0.20	13.6	2.83
L.S.D. (0.05)	0.16	0.02	0.9	0.08

Source: Sharma *et al.* (2004)

Nutrient Management in Clusterbean

Clusterbean [*Cyamopsis tetragonoloba* (L.) Taub], popularly known as guar, is a legume grown for seed, green fodder, vegetable, green manuring and guar gum. India is the largest clusterbean growing (2.33 million ha) and producing (1.02 million tonnes) country with average productivity of 428 kg ha^{-1}. Clusterbean has attained the status of a commercial crop as its seeds are the source of high quality galactomannan gum and protein rich (40-45%) guar meal as animal feed. India is the largest source of guar gum in the world and export it to 65 countries. India has earned Rs. 814.00 crores in 1999-2000 by exporting 1,10,000 tonnes of guar products (Kumar & Singh, 2002).

Effect of P, S and Zn on yield and quality of clusterbean

Being a legume, clusterbean does not require much nitrogen fertilizer except a starter dose of 15-20 kg N ha^{-1} is recommended for a good start.

The results of experiments conducted at Gwalior (M.P.) on response of P and S in Clusterbean revealed that application of 60 kg P_2O_5 and 40 kg S ha^{-1} significantly increased seed yield, P, S, protein and gum content (Table 7). The increase in yield was 10.3 and 28.3 per cent over 20 kg S ha^{-1} and control, respectively. The phosphorus content of seed was significant only at 40 kg S

ha^{-1} over control. The highest gum content was observed at 40 kg S ha^{-1} which was statistically at par with 20 kg S ha^{-1}. The highest yield of clusterbean was observed with a combination of 60 kg P_2O_5 and 40 kg S ha^{-1} (Bhadoria *et al.* 1997). Whereas, Kumar *et al.* (2003) at Bawal (Haryana) observed that under rainfed condition clusterbean yield increased significantly upto 20 kg P_2O_5 ha^{-1} and 20 kg S ha^{-1}.

Table 7. Effect of P and S levels on yield and quality of clusterbean

Treatments (kg ha^{-1})	Seed yield (q ha^{-1})	P content (%)	S content (%)	Protein content (%)	Gum content (%)
$N_{20}P_0K_{20}$	15.25	0.609	0.234	29.73	28.18
$N_{20}P_{20}K_{20}$	17.05	0.629	0.251	30.65	28.51
$N_{20}P_{40}K_{20}$	18.27	0.666	0.270	31.31	29.00
$N_{20}P_{60}K_{20}$	22.09	0.680	0.271	31.71	29.24
L.S.D. (0.05)	1.19	0.019	0.012	0.516	0.16
$N_{20}K_{20}S_0$	15.81	0.629	0.238	30.12	28.48
$N_{20}K_{20}S_{20}$	18.40	0.645	0.258	30.71	28.66
$N_{20}K_{20}S_{40}$	20.29	0.663	0.275	31.71	28.78
L.S.D. (0.05)	0.89	0.021	0.009	0.387	0.138

Source: Bhadoria *et al.* (1997)

Studies conducted at Bikaner (Rajasthan) revealed that application of 40 kg P_2O_5 ha^{-1} significantly increased dry matter accumulation per meter row length, N, P, protein and gum content over control and 20 kg P_2O_5 ha^{-1} (Table 8). Whereas 5 kg Zn ha^{-1} significantly increased dry matter accumulation, N, P and Zn content (Sunder *et al.* 2003).

Effect of potassium on yield and quality of clusterbean

Research conducted at Bawal (Haryana), indicated that application of potassium upto 20 kg K_2O ha^{-1} significantly increased the clusterbean yield (Table 9). The increase in mean seed yield was 12.4, 19.4 and 21.9 percent at 20, 40 and 60 kg K_2O ha^{-1}, respectively, over control. The seed K uptake also increased significantly with each level of potassium upto 40 kg K_2O ha^{-1}. The seed crude protein content also increased due to potassium application but its effect was significant only at 40 kg K_2O ha^{-1}. The mean increase in protein content was 4.6, 9.7 and 14.1 per cent at 20, 40 and 60 kg K_2O ha^{-1}, respectively, over control (Annual Report, 2003-04).

Table 8. Effect of P and Zn on dry matter accumulation, nutrient content and quality of clusterbean

Treatments ($kg\ ha^{-1}$)	Dry matter accumulation ($g\ m^{-1}$ row length)	Nutrient content in seed			Protein content (%)	Gum content (%)
		N (%)	P (%)	Zn ($mg\ kg^{-1}$)		
$N_{25}P_0$	98.5	3.79	0.31	29.9	23.7	27.3
$N_{25}P_{20}$	110.2	4.07	0.34	31.8	25.4	29.0
$N_{25}P_{40}$	118.8	4.25	0.35	31.9	26.6	30.3
$N_{25}P_{60}$	116.4	4.21	0.35	29.5	26.3	30.5
$N_{25}Zn_0$	99.5	3.87	0.35	27.9	24.2	27.7
$N_{25}Zn_{2.5}$	110.3	4.04	0.36	31.0	25.2	28.1
$N_{25}Zn_{5.0}$	118.2	4.24	0.34	33.0	26.6	30.3
$N_{25}Zn_{7.5}$	115.9	4.17	0.30	32.1	26.1	30.2
L.S.D. (0.05)	7.8	0.12	0.01	0.8	1.1	1.0

Source: Sunder *et al.* (2003)

Table 9. Effect of potassium on seed yield, K uptake and protein content of clusterbean

Treatments ($kg\ ha^{-1}$)	Seed Yield ($q\ ha^{-1}$)	Seed K uptake ($kg\ ha^{-1}$)	Seed Protein content (%)
$N_{20}P_{40}K_0$	8.39	9.31	27.95
$N_{20}P_{40}K_{20}$	9.43	11.97	29.20
$N_{20}P_{40}K_{40}$	10.02	13.59	30.40
$N_{20}P_{40}K_{60}$	10.23	14.23	31.80
L.S.D. (05)	1.02	0.95	2.41

Source: Annual Report (2003-04)

Integrated nutrient management in clusterbean

Meena *et al.* (2002) observed that application of 45 kg P_2O_5 ha^{-1} and seed inoculation with *Rhizobium* and Phosphate solublizing bacteria (PSB) significantly increased the seed yield, N and P content of clusterbean seed while gum content increased upto 30 kg P_2O_5 ha^{-1}. Studies conducted by Baboo and Rana (1995) at Lakhaoti (U.P.) showed that 60 kg P_2O_5 ha^{-1} helped in obtaining the highest seed yield of clusterbean, protein and gum content (Table 10). Further, it was observed that 20 kg N ha^{-1} with *Rhizobium* inoculation resulted in higher yield over their individual application and control. The highest values of yield, gum content and protein content were recorded with 60 kg P_2O_5 and 20 kg N ha^{-1} + *Rhizobium* inoculation.

Table 10. Effect of nitrogen, phosphorus and *Rhizobium* inoculation on yield and quality of clusterbean (Mean of two years)

Treatments	Seed yield ($q\ ha^{-1}$)	Gum content (%)	Crude protein (%)
P_2O_5 ($kg\ ha^{-1}$)			
0	15.8	22.6	23.6
30	18.2	26.4	25.3
60	17.5	34.4	26.7
L.S.D. (0.05)	0.6	0.9	1.1
N ($kg\ ha^{-1}$)			
0 (Control)	15.8	23.8	23.4
Inoculation alone	17.0	32.2	25.8
20 kg N alone	16.2	25.1	23.8
20 kg N + Inoculation	17.4	28.7	27.1
L.S.D. (0.05)	0.5	2.7	1.8

Source: Baboo and Rana (1995)

Balanced Nutrient Management in Indian Mustard

Indian mustard (*Brassica juncea* L.) is a major *Rabi* crop of dry land areas. The success of this crop largely depends upon availability of conserved moisture in soil profile at sowing time as the probability of winter rains are quite low. Mustard and rapeseed has an area of 5.38 million hectares with average productivity of 1151 kg ha^{-1} (Annual Report, 2005). About 34 per cent area is rainfed. The major rapeseed mustard growing states are Rajasthan, UP, MP and Haryana. Rajasthan alone contributes about 49 per cent in area and about 50 per cent in production of total rapeseed-mustard.

Effect of N, P, S and Zn on yield and quality of mustard

Under rainfed conditions of Hisar (Haryana) in light textured soils, Panwar *et al.* (2002) observed that mustard responded upto 40 kg N and 20 kg P_2O_5 ha^{-1} in good rainfall years (Table 11). Studies conducted in clayey soil at Parbhani (Maharashtra), Arthamwar *et al.* (1996) observed that there was linear increase in seed yield due to nitrogen application upto 100 kg N ha^{-1}. Nitrogen levels did not influence the oil content. Whereas every increase in the level of phosphorus upto 80 kg P_2O_5 ha^{-1} improved seed yield, oil content and oil yield of Indian mustard. Whereas Mangat *et al.* 2003 at Hisar (Haryana) on a sandy loam soil observed that seed yield of mustard significantly increased upto 75 kg N and 37.5 kg P_2O_5 ha^{-1} (Table 12). Increase in fertility level also significantly improved iodine value, protein content, allyl isothiocyanate and free fatty acid content.

Table 11. Effect of N and P levels on seed yield of mustard

Treatments	Seed yield (q ha^{-1})			
(kg ha^{-1})	1997-98	1998-99	2001-02	Mean
Control	8.4	8.7	20.9	12.6
$N_{20}+P_{10}$	10.5	10.8	25.0	15.7
$N_{40}+P_{20}$	11.6	11.9	28.6	17.4
$N_{60}+P_{30}$	11.0	11.3	27.1	16.5
L.S.D. (0.05)	1.2	1.2	2.9	-
Rainfall during *Kharif* (mm)	100	57	257	-

Source: Panwar *et al.* (2002)

Table 12. Seed yield, oil content, oil yield, protein content, protein yield and quality parameter of mustard as influenced by fertilizer levels (pooled data of two years)

Treatments (kg ha^{-1})	Seed yield (q ha^{-1})	Oil content (%)	Protein content (%)	Allyl isothio-cyanate content (%)	Free fatty acid content (%)	Iodine value (No.)
$N_{45}P_{22.5}$	12.4	41.3	13.2	0.41	0.55	99.6
$N_{60}P_{30}$	16.7	40.8	15.4	0.45	0.57	105.2
$N_{75}P_{37.5}$	18.5	40.1	16.0	0.49	0.62	107.2
$N_{90}P_{45}$	18.8	39.2	16.1	0.52	0.66	108.4
L.S.D. (05)	1.7	0.4	0.2	0.03	0.03	0.9

Source: Mangat *et al.* (2003)

Sulphur is often described as a quality element for mustard. Studies conducted under rainfed conditions at Hisar (Haryana) revealed (Table 13) that application of 60 kg N ha^{-1} and 40 kg S ha^{-1} significantly increased the seed yield and oil content of mustard (Singh and Kumar, 1996). Whereas under irrigated conditions, Kachroo and Kumar (1997) at Pant Nagar (U.P.) observed that Indian mustard responded significantly upto 120 kg N and 40 kg S ha^{-1}.

Table 13. Effect of N and S on yield and quality of Indian mustard

Treatments (kg ha^{-1})	Seed yield (q ha^{-1})	Oil content (%)
$N_0 P_{40} K_{20}$	8.3	39.8
$N_{30} P_{40} K_{20}$	10.1	41.5
$N_{60} P_{40} K_{20}$	12.7	42.5
$N_{90} P_{40} K_{20}$	13.8	42.4
L.S.D. (0.05)	0.8	0.8
$P_{40} K_{20} S_0$	9.4	40.5
$P_{40} K_{20} S_{20}$	11.2	41.5
$P_{40} K_{20} S_{40}$	12.5	42.5
L.S.D. (0.05)	0.9	0.7

Source: Singh and Kumar (1996)

In a field trial, Singh *et al.*, (1998) observed a significant increase in yield and quality of mustard upto 120 kg N with 60 Kg P_2O_5 and 10 kg Zn ha^{-1} (Table 14). Increase in S level upto 60 kg S ha^{-1} also increased seed yield however protein and oil content increased significantly upto 90 kg S ha^{-1}.

Table 14. Effect of N, P, Zn and S levels on yield and quality of Indian mustard

Treatments	Seed yield (q ha^{-1})	Protein (%)	Oil content (%)
N, P, Zn (kg ha^{-1})			
$N_{40} P_{20} Zn_0$	15.5	21.6	35.4
$N_{80} P_{40} Zn_5$	18.4	23.3	37.7
$N_{120} P_{60} Zn_{10}$	21.9	24.0	37.3
L.S.D. (0.05)	1.0	0.5	0.5
Sulphur (kg ha^{-1})			
0	17.3	21.8	35.3
30	18.1	22.5	36.3
60	19.0	23.3	37.3
90	20.0	24.3	38.3
L.S.D. (0.05)	1.1	0.6	0.6

Source: Singh *et al.* (1998)

Effect of K on yield and quality of mustard

The K nutrition in mustard has not been paid attention in the past in spite of its importance as a quality nutrient for crop production. The results of experiment (Table 15) indicated that there was improvement in yield attributes, yield and quality (oil content and oil yield) of mustard with increasing levels of K upto 60 kg K_2O ha^{-1} (Mondal *et al.*, 1997). Investigation carried out on a loamy sand soil revealed that residual effect of potassium on mustard yield, K uptake and seed protein in clusterbean-mustard crop rotation was found significant at 40 kg K_2O ha^{-1} (Annual Report, 2004-05). Whereas Mahadkar *et al.* (1996) at Dapoli (Maharastra) on clay loam soil observed that irrigated mustard responded significantly upto 90 kg K_2O ha^{-1} with 120 kg N ha^{-1}. Mishra (2003) at Kanpur (UP) observed that mustard seed yield and uptake of N, K and S increased in the linear order upto 40 kg S and 60 kg K_2O ha^{-1}. Oil, protein and total S-amino acid content increased significantly with application of potassium (Table 16). Potassium also influenced fatty acid composition, oleic and linoleic acid content whereas the erucic acid content decreased showing the improved quality of mustard oil. Chauhan and Tikkoo (2002) at Gurgaon (Haryana) also observed that mustard seed yield and oil content increased significantly upto 75 kg K_2O and 60 kg S ha^{-1}.

Table 15. Effect of potassium on yield and oil content of mustard

Treatments (kg ha^{-1})	Seed yield (q ha^{-1})	Oil content (%)	Oil yield (q ha^{-1})
$N_{60}P_{50}K_0$	9.0	35.5	3.2
$N_{60}P_{50}K_{20}$	11.3	36.8	4.1
$N_{60}P_{50}K_{40}$	13.4	38.0	5.1
$N_{60}P_{50}K_{60}$	14.7	41.9	6.2
$N_{60}P_{50}K_{90}$	14.0	40.6	5.7
L.S.D. (0.05)	1.2	1.8	-

Source: Mondal *et al.* (1997)

Table 16. Effect of K fertilization on yield and quality characteristics of mustard (Mean of two years)

Treatments (kg ha^{-1})	Seed yield (q ha^{-1})	Oil content (%)	Linoleic acid (%)	Erueic acid (%)	Protein (%)	S-amino acid (mg g^{-1} N)
$N_{120}P_{60}K_0$	13.5	37.6	12.7	49.4	34.7	66.5
$N_{120}P_{60}K_{30}$	15.9	38.4	13.3	49.1	35.7	68.1
$N_{120}P_{60}K_{60}$	17.3	39.4	13.6	48.9	37.3	69.9
$N_{120}P_{60}K_{90}$	17.2	39.6	13.8	48.7	37.6	70.7
L.S.D. (0.05)	0.9	0.2	0.5	0.3	0.4	0.7

Source: Mishra (2003)

Integrated nutrient management in mustard

Integrated nutrient management holds good promise in meeting the growing nutrient demand of intensive agriculture and maintaining the crop productivity at a high level. A study on organic manuring revealed that organic manuring with FYM @ 4 t ha^{-1}, vermicompost @ 4 t ha^{-1} and *dhaincha* green manuring increased the seed yield of rainfed mustard significantly over control while green manuring with cowpea could not have significant effect. Bio-fertilizers combination of Azotobacter + Phosphobacterium increased the yield of mustard significantly over control and was also at par with recommended dose of fertilizer (40 kg N + 20 kg P_2O_5 ha^{-1}) indicating thereby that organic farming can be successfully adopted without any adverse effect on mustard yield under rainfed conditions (Panwar *et al.* 2002). Whereas Singh *et al.* (2001) at Bawal (Haryana) observed that under rainfed conditions, integrated use of 40 kg N + 20 kg P_2O_5 + 10 t FYM + 40 kg S + 25 kg $ZnSO_4$ ha^{-1} was significantly better in term of seed yield, oil content and oil yield over all other possible treatments combinations of FYM, S and $ZnSO_4$ with recommended fertilizer dose (40 kg N + 20 kg P_2O_5 ha^{-1}). Whereas under irrigated conditions application of recommended dose of fertilizer (80 kg N + 30 kg P_2O_5 ha^{-1}) with 2 t FYM, 40 kg S, 25 kg $ZnSO_4$, 1.0 kg boron ha^{-1} and *Azotobacter* seed treatment gave maximum mustard seed and oil yield (Table 17). The lowest yield was recorded when crop received only 75 per cent of recommended dose of fertilizer (Annual Report, 2005).

Table 17. Effect of integrated nutrient management on seed yield (q ha^{-1}) and oil content (%) of Indian mustard

Treatments	Seed Yield	Oil content
T_1=RDF	16.83	40.9
T_2=T_1 + 2t FYM ha^{-1}	17.85	40.5
T_3=T_2 + 40 kg S ha^{-1}	19.67	40.8
T_4=T_3+25 kg $ZnSO_4$ ha^{-1}	20.79	40.3
T_5=T_4+1 kg boron ha^{-1}	21.26	41.5
T_6=T_5+Azotobacter	21.83	41.4
T_7=75% RDF	14.87	40.1
T_8=T_7+2 t FYM ha^{-1}	16.11	41.5
T_9=T_8+40 kg S ha^{-1}	17.75	43.3
T_{10}=T_9+25 kg $ZnSO_4$ ha^{-1}	18.93	43.1
T_{11}=T_{10}+1 kg boron ha^{-1}	19.33	41.5
T_{12}=T_{11}+Azotobacter	20.03	42.3
L.S.D. (0.05)	1.56	-

Source: Annual Report (2005)

Conclusion

Results of several experiments have shown that rainfed pearl millet responds favourably to application of 40 kg N, 20 kg P_2O_5 and 20 kg K_2O ha^{-1}. In zinc deficient soils, application of 20 kg $ZnSO_4$ ha^{-1} also found to be beneficial. Whereas under irrigated conditions, pearl millet responds to 90-120 kg N, 40-60 kg P_2O_5, 30 kg K_2O and 25 kg $ZnSO_4$ ha^{-1}. Application of 20 kg S ha^{-1} in sulphur deficient soil also found to be beneficial.

Clusterbean being a legume, does not require much nitrogenous fertilizer except a starter dose of 15-20 kg N ha^{-1} and responds favourably to application of 40-60 kg P_2O_5, 20 kg K_2O, 20-40 kg S and 25 kg $ZnSO_4$ ha^{-1} in soils deficient in these nutrients.

Application of 40 to 60 kg N, 20 kg P_2O_5 and 40 kg S ha^{-1} in rainfed mustard and application of 80-120 kg N, 30-45 kg P_2O_5, 40-60 kg K_2O, 40-60 kg S and 25 kg ZnSO ha^{-1} in irrigated mustard have been found optimum for obtaining good quality yield and maintaining soil health. Adaptation of integrated nutrient management practices further prove more effective in optimizing in crop production on sustainable basis and improving the quality of the produce.

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Balanced Nutrient Management of Groundnut, Castor and Sesamum in India

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Abstract

The quantity, quality and stability of oilseeds are essential for better processing, trade and business of these crops. Majority of the soils of oilseeds growing states in India are low to medium in available NP. Almost half of the oilseed farmers do not follow the fertilizer recommendations. The fertilizer applications to oilseeds are not in a balance proportion. Balance nutrition trials reviewed here exhibited higher and stable yields of groundnut, castor and sesamum. More sophistication in nutrient management is possible through STCR, target yield equations and DRIS norms as evident from the trials under State Agricultural Universities. Moreover, there are separate fertilizer recommendation for oilseed base cropping sequence. The recommendations for oilseed based mix and relay cropping are yet to be devised.

Keywords: Balanced nutrient management, groundnut, castor, sesamum, India

Balanced fertilization is the application of essential plant nutrients, particularly major nutrients - N, P and K, in right proportion and in optimum quantity, through correct method and time of application tailored for a specific soil-crop-climatic condition. Oilseeds are cash crops. With ever increasing population and industrial growth the demand of vegetable oil will remain at its highest peak. Oilseed production is effectively helping not only in mitigating the oil demand of large segment of world population but also creating millions of extra jobs by producing, processing, trading and marketing of the same thereby bringing the dynamic socio-economic development across the world.

With the appraisal of world oil seed scenario; it has been evident that almost one-third of the total quantity of oil is under international trade. In the world output of 17 oilseeds, the major players are USA (22.0%), China (16.1%), Brazil (15.5%), Argentina (11.6%) and India (8.0%) contributing 73 per cent in aggregate (Table 1). The oilseeds of our concern are groundnut, castor and sesamum. The total world production of groundnut from an acreage of 25 m ha was 35.8 mt in the year 2004-05 with an average yield of 1.43 t ha^{-1}. India contributes about one forth of the world groundnut productions (Table 2). World production of castor seed was 1.4 mt from 1.4 m ha with an average production of 1 t ha^{-1}. India is the largest producer of castor seed. Almost half of the world production of castor comes from India. Similarly, world production of sesamum was around 3.3 m t from an area of 7.5 m ha with an average productivity of 0.44 t ha^{-1}. India is the largest producer of sesamum contributing around 26 per cent of the world production. Though production is about 24 m t of oilseeds annually, the productivity is strikingly low in India.

Table 1. World output of oilseeds during 2003-04

Country	Production (mt)	Percent
India	26.23	7.57
China	55.73	16.10
Brazil	53.50	15.45
Argentina	38.99	11.26
USA	76.03	21.96
Canada	9.84	2.84
USSR ASIA	3.32	0.96
East Europe	6.06	1.75
EU-15	13.92	4.02
Total - World	346.22	81.91

Source: FAO (2006)

Table 2. Area, production and productivity of major oil seeds in world and India (2004-05)

Crop	World/ India	Area (m ha)	Production (mt)	Productivity (kg ha^{-1})
Groundnut	World	25.2	35.8	1421
	India	6.6	5.9	894
Castor	World	1.4	1.4	1000
	India	0.8	0.9	1087
Sesamum	World	7.5	3.3	440
	India	1.8	0.7	378

The oil extraction and post harvest processing attracts large section of producers, processors and traders all over the world. However, it requires quantity, quality and stability in the oilseeds produced. It is now realized that large improvements in the productivity may only be obtained by balanced nutrition along with crop protection measures, agronomic packages and with growing the improved varieties. Possibly the most striking interaction between oilseed production functions is between HYVs and balanced nutrition package (Arnon, 1979). Importance of this interaction has also been realized for groundnut (Patil *et al.*, 2000), Castor (Anon., 2005) and sesamum (Jaishankar and Whab, 2005).

Present paper is an attempt to ventilate different facets of balanced nutrition management of the oilseeds especially groundnut, castor and sesamum in India.

Nutrient Status

The status of major nutrients in the major states growing groundnut, castor and sesamum is our concern. More than half of the soils are rated low for nitrogen in the groundnut growing states viz., Gujarat, Orissa, Tamil Nadu and Rajasthan (Singh *et al.*, 2004). In all the groundnut growing states the half of the soils are rated low in phosphorus. One fourth of the soils under these crops in India are rated low in potassium (Tandon, 1990).

Nutrient Uptake

The nitrogen uptake by groundnut is 5 to 6 times more than phosphorus and; potassium uptake is about 65 per cent of that of nitrogen (Table 3). Whereas, potassium uptake by castor is almost double than that of nitrogen and phosphorus uptake is one-third of the nitrogen. The uptake of nitrogen and potassium goes parallel in sesamum. The P uptake is again one-third of that of the nitrogen. Thus while planning the balance nutrition package for these oilseeds the nutrient uptake pattern by these crops should be considered. The castor is a voracious feeder of potassium hence the subsequent crop always give poor harvest if not fertilized in a balanced proportion (Dudhatra, *et al.*, 2000).

Table 3. Uptake of major nutrients by groundnut, castor and sesame

Crop (yield)	N	P	K	S	Reference
	kg ha^{-1}				
Groundnut (1700 kg ha^{-1})	170	30	110	15	Pasricha and Tandon (1990)
Castor (2570 kg ha^{-1})	155	57	391	6	Pasricha and Tandon (1990)
Sesamum (1200 kg ha^{-1})	62	24	64	14	Pasricha and Tandon (1990)

Critical Limits

The critical limit of NPK in groundnut is 3.5 to 4.5, 0.2 to 3.5 and 1.7-3.0 per cent, respectively (Table 4). The critical limit of NPK in soil for the same crop is 125, 20-40 and 145 kg ha^{-1} in that order (Golakiya, 1999). The potassium requirement of groundnut is 3.8 kg q^{-1} (Subba Rao and Srivastava, 2001). The critical limit of NPK for castor is 3.0 to 3.5, 0.3 to 0.4 and 1.0 to 2.0 per cent. The potassium requirement of castor is 3.69 kg q^{-1}. The critical limit of NPK in sesame is 2.0 to 2.5, 0.2 and 0.88 per cent. The K requirement of the same is 4.35 kg q^{-1} (Golakiya and Patel, 2001).

Table 4. Critical limits of nutrients in plant for groundnut, castor and sesamum

Crops	N	P	K	S	Fe	Zn
	%				mg kg^{-1}	
Groundnut	3.5-4.5	0.20-0.35	1.7-3.0	0.2-0.3	100-200	20-50
Castor	3.0-3.5	0.30-0.40	1.0-2.0	0.3-0.4	150-200	30-50
Sesamum	2.0-2.5	0.20	0.9	NA	NA	NA

Source: Rathore (2001)

Fertilizer Recommendations

The fertilizer recommendations for groundnut castor and sesamum in the major states are given in Table 5. In case of groundnut, there is no recommendation of potassium in Gujarat, Maharashtra and Rajasthan. These are the major states producing groundnut since last more than five decades. Thus balanced nutrition package is not followed in the major groundnut growing regions of India. Similar is the case for castor and sesamum. The reason being put forth is that the soils of these regions are well supplied with potassium. But the sporadic experiments conducted in groundnut (Kunjadia, 2006), castor (Anon., 2002) and sesamum (Mondal *et al.*, 1993) indicated response to balanced nutrition. Moreover the depletion of soil potassium during last two decades in these region is alarming (Rao and Bansal, 2000). This is a critical issue demanding a comprehensive debate among the concerned.

Adoption of fertilizer package

Apathy of farmers towards the adoption of fertilizer recommendations has remained a pivotal problem of transfer of technology (Table 6). About 60 per cent of the farmers adopted fertilizer reeommendations for oilseed crops (Kiresar *et al.* 1995). Maximum adoption was reported in sesamum (73.5) followed by castor (Golakiya and Patel, 2001). Contrarily just about 24 per cent of the fertilizers recommendations are adopted in groundnut- the main oilseed crop.

Table 5. Fertilizer recommendations for groundnut, castor and sesamum in India (major states)

Crop	Major State	Fertilizer recommendation (N:P:K kg ha^{-1})
Groundnut	Gujarat	12 : 25 : 00
	Andhra Pradesh	20 : 40 : 20
	Haryana	15 : 50 : 25
	Himachal Pradesh	16 : 40 : 25
	Karnataka	25 : 75 : 25
	Maharashtra	12 : 25 : 00
	Punjab	15 : 20 : 25
	Rajasthan	15 : 60 : 00
	Tamil Nadu	10 : 10 : 45
Castor	Gujarat	40 : 40 : 00 (75 : 50 : 00 Irrigated).
	Andhra Pradesh	40 : 20 : 20 to 40
	Haryana	37 : 00 : 00
	Himachal Pradesh	-
	Karnataka	37 : 37 : 25
	Maharashtra	60 : 40 : 00
	Punjab	-
	Rajasthan	40 : 00 : 00
	Tamil Nadu	30 : 15 : 15
Sesamum	Gujarat	25 : 25 : 00
	Andhra Pradesh	50 : 50 : 25
	Haryana	37 : 00 : 00
	Himachal Pradesh	60 : 40 : 20
	Karnataka	37 : 25 : 25
	Maharashtra	25 : 12 : 00
	Punjab	35 : 00 : 00
	Rajasthan	20 : 25 : 00
	Tamil Nadu	23 : 13 : 13 (35 : 23 : 23 Irrigated)

Sources: Tandon (1990)

Table 6. Per cent adoption of balanced fertilizer components in major oilseeds

Adoption level	Groundnut	Castor	Sesamum
Complete	24.3	42.6	73.5
Partial	71.4	56.2	25.5
Non-adoption	4.3	2.2	1.0

Source: Kiresur *et al.* (1995)

The average actual consumption ratio of NPK in groundnut, castor and sesamum is 5:2:1, 13:3:1 and 7:1.4:1, respectively (Table 7). It means that in the actual field conditions these crops are being fertilized in highly imbalanced proportion. Therefore, the balance nutrient management in these crops assumes special importance (Golakiya and Patel, 2001).

Table 7. Actual nutrient application (average) in groundnut, castor and sesamum in India

Crops	N	P	K	N : P : K
	kg ha^{-1}			
Groundnut	49	18	10	5.0 : 2.0 : 1.0
Castor	51	11	4	13.0 : 3.0 : 1.0
Sesamum	35	7	5	7.0 : 1.4 : 1.0

Sources: Golakiya and Patel (2001)

Balance Nutrient Studies

About 17 major oilseeds are grown all over the world in varied soil and agro-climate conditions. Balanced nutrition management in them varied with nutrient status of soils, crops, varieties, soil types, season etc. To rectify the effect of these factors on crop response to balance nutrition, an example of groundnut crop with data base of over 100 field trial is reviewed here.

The productivity of groundnut ranges from 1000 to 6000 kg ha^{-1} in the soils of Western India. Almost a dozen soils with low productivity (<1000 kg ha^{-1}) registered yield increment upto 24 per cent under balanced nutrition package (12.5 N, 25 P_2O_5, 80 kg K_2O per hectare over NP only). The yield increment under medium (1000 to 2000 kg ha^{-1}) and high (>2000 kg ha^{-1}) productive soil was 12 and 22 per cent, respectively, under same nutritional package (Viradia *et al.*, 2004). Thus, low and highly productive soils need more care about the balanced nutrition management for the better harvest of groundnut.

Groundnut is grown during monsoon and summer. Season also play a pivotal role in managing balanced nutrition of crops. Summer groundnut responded to balanced nutrition ($N_{25}P_{50}K_{120}$) by 25 per cent (mean 33 trials) while the monsoon crop responded just up to 12 per cent ($N_{12.5}P_{50}K_{80}$). This is because the groundnut yields under summer are stable and above 1000 kg ha^{-1} due to better management and assured irrigation (Golakiya and Patel, 2001).

Oil seed farmers are vary adaptive towards new varieties. Varied genotypes of castor, groundnut and sesamum are grown in the same season.

Table 8. Balance nutrition studies in groundnut, castor and sesamum

Variety	Control yield (kg ha^{-1})	Best treatment yield (kg ha^{-1})	% Increase	Location	Reference
Groundnut					
JL-24	1757	2751	56.3	Sangali (Maharastra)	Kathmale *et al.* (2000)
VRI-2	1890	2460	30.2	Vridhachalam (T.N.)	Balasubra-maniam (1997)
GG-20	1968	2792	41.6	Junagadh (Gujarat)	Kunjadia (2006)
GG-20	1674	2472	47.7	Junagadh (Gujarat)	Kachot *et al.* (2000)
Castor					
GCH-5	1787	2469	38.2	Mandor (Rajasthan)	Annonymous (2002)
GCH-5	501	1214	142.3	Yathapur (T.N.)	Annonymous (2002)
GCH-6	1481	3352	126.3	Junagadh (Gujarat)	Annonymous (2005)
GCH-6	1101	1857	68.7	S.K. Nagar (Gujarat)	Annonymous (2005)
Sesamum					
B-67	900	1350	50.0	Mohanpur (West Bengal)	Mondal et al. (1993)
TMV-3	540	749	38.7	Annamalai-nagar (T.N.)	Singarvel *et al.* (2002)
VRI-1	710	1008	44.0	-	Jaishankar and Whab (2005)

The varietal response of groundnut, castor and sesamum under balanced nutrition studies have been reported by many workers (Kathamale *et al.*, 2000, Balasubramanian, 1997; Anonymous, 2002; 2005; Mondal *et al.*, 1993; Singarvel *et al.*, 2002). Groundnut varieties respond to balanced nutrition in the range of 30 to 57 per cent (Table 8). So also the castor varieties by 38 to 142 per cent. Similarly, the yield of sesamum varieties ranged between 38 to 50 per cent under best treatment over control.

It was found in over 11,000 experiments on farmers fields that the addition of 60 kg K_2O ha^{-1} along with recommended NP responded in HYV's producing 1.1 to 1.3 more units of seeds/kernels per unit of applied K over that locally improved tall varieties (Tandon and Kanwar, 1984). In many case the root characteristics of genotypes also play a major role in the yield response to the nutritional package (Zizala *et al.*, 2000, Subba Rao and Srivastava, 2001) also observed wide variation in the yield response of groundnut and mustard to balanced nutrition.

Majority of soils of groundnut, castor sesamum growing states in India are low to medium in NP and high in K. The crop under medium NP and high K fertility soils also responds well to balance nutrition package (Golakiya and Patel, 1988). The groundnut crop under high available K soils respond by 18 per cent to $N_{12.5}$, P_{25} K_{80} fertilizer package over NP. The reason is high calcium activity of soil (Bunsa and Golakiya, 2000), mid season short supply of bio-available K in the soil (Chhodvadia *et al.*, 2000) and hence the hidden hunger of K in the crop.

While practicing the balanced nutrient management in oilseeds one of our aims is to derive benefit from the synergistic nutrient interactions. In practice, positive interactions are a real bonus and farmers should be guided to exploit it. Through balanced nutrition it is possible to realize most from the positive interactions in term of yield, nutrient use efficiency and net return while avoiding negative interactions. Many times negative interactions occur due to lack of appreciation for balanced nutrient application which is in its broad sense means taking care of all the nutrient deficiencies. Potassium plays an important role in ensuing efficient utilization of nitrogen, zinc, calcium and boron in groundnut, sesamum and castor (Table 9). The pod and haulm yield of groundnut increased by 17 and 21 per cent, respectively, under synergistic N x K interaction. So also the shelling and oil content by 2 and 0.5 per cent, respectively (Golakiya 1999, Gundalia *et al.*, 2000). With the same interaction in sesamum, the seed yield increased by 19 per cent (Singh *et al.* (1991). The yield of castor increased by 38 per cent due to K x S synergism.

Soil test crop response (STCR), diagnosis and recommendation integrated system (DRIS) and yield targeting

The STCR studies have been conducted in groundnut since long (Raizudin *et* *al.*, 2001; Rao *et al.*, 1998). About 20 to 25 q ha^{-1} pod yields have been harvested on the basis of STCR fertilizer package (Lognathan *et al.*, 1995). In case of castor about 400 kg ha^{-1} of additional yield have been realized through STCR based fertilizer management. Off late the DRIS norms have been fixed for groundnut and castor (Dadhania *et al.*, 2000). Moreover the yield target equations based fertilizer management in castor and groundnut also offered best alternative of cost effective balanced fertilizer management in groundnut and castor (Anonymous, 2004).

Groundnut $FN = 5.29\,T - 0.22\,SN$

$FP_2O_5 = 8.74T - 2.44\,SP$

$FK_2O = 18.19 \times T - 0.755\,K$

Castor $FN = 6.13 \times T - 0.22\,SN$

$FP_2O_5 = 3.35 \times T - 0.77SP$

$FK_2O = 3.38 \times T - 0.11SK$

Where T is yield target; SN, SP and SK represents soil test values for N, P and K (kg ha^{-1}), respectively.

Table 9. Interaction effects in balance nutrition of major oilseeds

Crop	Interaction (level kg ha^{-1})	Plant part	S/NS	% yield increase	Reference
Groundnut	$K_{20} \times N_{25}$	Pod	S	16	Golakiya (1999a)
		Haulm	S	21	Golakiya (1999)
	$K_{60} \times N_{50}$	Pod	S	17	Gundalia *et. al.* (2000)
		Shelling	S	2	Gundalia *et. al.* (2000)
		Oil	S	0.5	Gundalia *et. al.* (2000)
	$K_{60} \times Zn_{50}$	Pod	S	27	Polara *et. al.* (2000)
	$K_{100} \times Ca_{100}$	Pod	S	32	Singh (2000)
	$K_{100} \times B_2$	Pod	S	25	Singh (2000)
Sesamum	$K_{60} \times N_{60}$	Grain	S	19	Singh *et. al.* (1991)
Castor	$K_{60} \times S_{35}$	Bean	S	38	-

Fertilizing Oilseed Based Cropping Sequences

Oilseeds are a core group crops in the popular cropping sequences all over the world. Fortunately, we have results of LTFE's with balanced nutrition in oilseed based cropping sequences (Table 10). Potassium has been an integral component of balance ratio in the fertilizer package for the cropping sequences. Of course, the yield increase is a time dependant variable in such trials. The groundnut yield increased by 20 to 80 per cent in NP vs NPK treatments. The yield of subsequent crops increased in the range of 20 to 37 per cent.

Table 10. Increase in yield (%) with K application in oilseed based cropping sequence

Cropping Sequence	% increase			Reference
	I	II	III	
Groundnut (I) - Wheat (II) (12 year pooled)	45.4	24.6	-	Golakiya *et al.* (2000)
Groundnut (I) - Pearl millet (II) (3 year pooled)	26.2	41.1	-	Golakiya *et al.* (2001)
Groundnut (I) - Wheat (II) - Sorghum (III) (20 year pooled)	79.8	42.6	39.1	Golakiya (1998)
Sunflower (I) - Soybean (II)	27.2	26.5	-	Kunaul *et al.* (1990)
Mustard (I) - Sorghum (II)	20.0	33.4	-	Prasad (1993a)
Groundnut (I) - Wheat (II) (12 year pooled)	20.0	26.7	-	Prasad (1993b)

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Nutrients Management in Vegetable Crops

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Abstract

Vegetables are the health capsules being the main source of vitamins and minerals besides providing other dietary elements. Vegetable production in India needs to be increased to meet the consumption of the minimum recommended quantity of about 250 g/person/day. Therefore, increasing the crop and cropping efficiency is the only way to increase vegetable production and consumption as no more area can be brought under vegetable cultivation at the risk of reducing the area under other essential food and commercial crops. Fertilizer needs of the crop vary with the crop, variety, duration, soil type, soil fertility, season, irrigation practice, type of cultivation and economics. Crop response to applied nutrients depends mainly on fertility status of the soil; therefore the recommendations need to be based on crop response to applied nutrients at different fertility levels. Applications of micronutrient like B and Zn, conjunctive use of organic and inorganic sources of nutrients, foliar application of major and micronutrients and starter solutions to quick start the crop, have increased the yield of vegetable crops. Form, quantity and number of split applieation of fertilizers have increased yields and improved nutritional and keeping quality in different vegetables. Postponing the basal application of N to 7 days after transplanting, 2-3-split application and deeper placement of P have been found beneficial for improving the use efficiency of applied fertilizers. Nutrient requirement of a cropping system is more specific compared to that of an individual crop. Integrated nutrient management (INM) involving the application of bio-fertilizer, vermicompost and foliar formulations of water soluble fertilizers have shown to improve erop productivity. Greenhouse vegetables, like tomato and capsicum, responded to continuous supply of nutrients throughout the crop growth through fertigation.

Keywords: Vegetables, nutrition, INM, nutrient requirement

Vegetables are considered to be the health capsules being the main source of vitamins and minerals besides providing other dietary elements like carbohydrates, proteins, fiber, fats and enzymes. India is endowed with favourable tropical, sub-tropical and temperate climates conducive for producing high quality vegetables round the year in one or the other part of the country. Vegetable production has gained momentum during and after third five-year plan, increasing from 23.45 million tonnes in 1961-65 to 84.82 million tonnes in 2002-03 and it is projected to be 92.42 million tonnes in 2006-07. With ever-increasing pressure on land it is difficult to increase the area under vegetables, therefore, quantum jump in vegetable production has to come from increase in productivity by intensive cultivation using hybrids, fertilizers, water and other inputs efficiently. The only way to increase vegetable production and consumption is to increase crop efficiency (vegetable yield per unit land area) and cropping efficiency (vegetable yield and returns per unit of time; Prabhakar and Srinivas, 1994). More than 40 kinds of vegetables are grown in India in tropical, subtropical and temperate regions, important of them being, tomato, onion, brinjal, cabbage, cauliflower, beans, peas and okra.

High yielding varieties and hybrids of vegetables have been developed in both public and private domain especially to respond to increased doses of fertilizers besides incorporating resistance/tolerance to many nagging pests and diseases. Intensive cultural practices like ridge and furrow cultivation, line sowing or transplanting with optimum spacing to enable potential production of biomass and higher vegetable yield, adequate supply of water, pest and disease management with target chemicals have facilitated increased use and utilization of fertilizer nutrients. Further, continuous cropping resulted in excess mining of native reserves of secondary and micronutrients requiring more of these to sustain the intrinsic potential of high yielding hybrids. Plant nutrients available in concentrated form are often lost due to leaching, erosion, and volatilization, as opportunity time for absorption is limited by the capacity of the plant at different growth stages to take up the nutrients and the capacity of the growing medium to retain and release the applied nutrients. Indiscriminate use of chemical fertilizers with least regard to balancing with organics has disturbed the physical, chemical and microbial properties of the soils rendering vegetable production uneconomical. Water-soluble sources of nutrients are in increasing demand now a day for fertigation. Beside major nutrients, application of secondary and micronutrient is also gaining importance in nutrient management. Deficiency symptoms of Fe, Zn, Mn, Mo and B have been reported in different crops. Management of micronutrients in light and porous soils with less organic matter is essential as they are easily lost. In such cases application of heavy doses of organic matter becomes essential to hold the metallic micronutrients such as Fe, Zn, Mn and Cu (Chadha and Shikhamany, 1990). Major, secondary and micronutrients need to be supplied in sufficient quantities through either organics exclusively, or through both organic and inorganic sources. Application of organic manures exclusively to meet the demand of the entire nutrient requirement of the crop (organic crop culture) or judicious and conjunctive use of both the sources (organic and inorganic) is the option available to supply nutrients to vegetable crops (Chadha and Prabhakar, 1997).

Nutrient Requirement of Vegetable Crops

Crop response to applied nutrients depends mainly on fertility status of the soil; therefore, the recommendations are based on crop response to applied nutrients at different fertility levels (Velayutham *et al.*, 1985). However, the quantity required depends on factors like crop, variety and crop sequence, sole or inter crop, soil type, fertility, soil reaction, irrigation, season, crop duration, type of cultivation (rainfed, irrigated, protected) and economics. A warm weather crop requires more N than a cold season crop. Similarly a long season variety/hybrid requires more N than a determinate variety. FAI (1999) summarized the removal of plant nutrients from soil by some vegetables (Table 1). Fertilizer recommendations for some vegetables based on multi location testing have been reported in Table 2. The average quantities of fertilizers recommended are 111 kg N, 60 kg P_2O_5 and 59 kg K_2O $ha^{-1} crop^{-1}$. Tandon (1991) summarized fertilizer recommendations for tomato from different states of India as 107 kg N, 71 kg P_2O_5 and 67 kg K_2O ha^{-1} $crop^{-1}$, which compares well with the above general recommendation for a vegetable. The response studies indicated that the recommended doses are 71%, 111% and 30% of the crop removal of N, P_2O_5 and K_2O, respectively. The difference of 29% of N could be from other organic sources, the excess of P (21%) is due to fixation in the soil and the large difference in K (70%) indicates luxury consumption by the crops from native reserves. Therefore, 100-120 kg N, 60 kg P_2O_5 and 60 kg K_2O ha^{-1} $crop^{-1}$ can be a general recommendation for a vegetable crop. However, the fertilizer needs vary with the crop, variety, soil and environment.

Table 1. Nutrient removal by some vegetable crops

Crop	Yield ($t\ ha^{-1}$)	Nutrients removed ($kg\ ha^{-1}$)		
		N	P_2O_5	K_2O
Cabbage	70	370	85	480
Carrot	30	125	55	200
Cauliflower	50	250	100	350
Cucumber	40	70	50	120
Egg Plant	60	175	40	300
Okra	20	60	25	90
Onion & Garlic	35	120	50	160
Spinach	25	120	45	200
Tomato	50	140	65	190

Source: FAI (1999)

Table 2. All India vegetable improvement project recommendations made on nutrient requirement of Vegetables

Crop	Nutrients (kg ha^{-1})			Center
	N	P_2O_5	K_2O	
Tomato	150	60	60	Sabour
	150	60	60	Kanpur
	150	60	60	Bhubaneswar
Brinjal	150	60	-	Bangalore
	100	60	-	Hissar
Chilli	120	60	-	Kalyanpur
	120	60	40	Jabalpur
Cauliflower	120	60	60	Kalyanpur
	120	60	60	Jaipur
	100	60	60	Faizabad
Cabbage	150	80	75	Bhubaneswar
	180	50	50	Jabalpur
Onion	150	60	60	Jabalpur
Garlic	100	80	50	Hissar
	100	80	60	Kalyanpur
Okra	150	150	150	Jabalpur
Bitter gourd	90	60	60	Faizabad
Muskmelon	100	60	60	Durgapura
	100	60	60	Faizabad
Watermelon	100	60	60	Faizabad

A crop producing 38 t ha^{-1} of tomato removes 104 kg N, 22 kg P_2O_5 and 14 kg K_2O. Tomato hybrid responded to N application up to 200 kg ha^{-1} (Prabhakar, 1993). Paulraj *et al.* (1982) reported better response of tomato to ammonium sulphate in Madurai district of Tamil Nadu, whereas Kooner and Randhava (1983) observed calcium ammonium nitrate to be more efficient in meeting N needs of tomato in Punjab. A brinjal crop yielding 60 t ha^{-1} removes 190 kg N, 25 kg P_2O_5 and 159 kg K_2O (Gnanakumari and Sathyanarayana, 1971). Conjunctive use of organic N and urea (50% N each) provided the highest yield of brinjal. Foliar application of N along with soil application is reported to be beneficial in increasing brinjal yield. Increases in yield were also observed with the application of B and Zn in intensively cultivated crop (Jose *et al.*, 1988). Srinivas and Prabhakar (1982) reported response of capsicum to 150 kg N ha^{-1} applied in three splits. Manchanda and Singh (1987) recorded the best yield with 160 kg N ha^{-1} in Palampur. Application of urea, single super phosphate (SSP) and muriate of potash (MOP) in 2:1:1 ratio as the starter solution (300 ml $hill^{-1}$) gave the highest yield in chilli (Pawar *et al.*, 1985). Prabahakar *et al.* (1985) reported response of muskmelon up to 100 kg N ha^{-1}. However, Ramachander *et al.* (1988) observed that the response varied with the growing conditions. In high yielding environment the crop responded to 75 kg N ha^{-1} while in low yielding environment the response was noticed up to only 50 kg N ha^{-1}. Muskmelon responded to 50 to 125 kg N ha^{-1}, 25 to 75 kg P_2O_5 and 30 to 60 kg K_2O ha^{-1} in different locations (Tandon, 1987). Watermelon responded up to 120-140 kg N ha^{-1}. Foliar spray of B, Zn and Mo (3 g L^{-1}) at 2 to 3 leaf stage increased the fruit yield (Choudhury, 1982). Cucumber responded to 25-100 kg N ha^{-1}, 24-75 kg P_2O_5 and 0-50 kg K_2O ha^{-1} (Tandon, 1987). Umamaheswarappa *et al.* (2005) found 120 kg N and 50 kg P ha^{-1} to be optimum for cucumber (Poinsette) in southern dry region of Karnataka. Bitter gourd removed 56 kg N, 28 kg P_2O_5 and 28 kg K_2O ha^{-1} (Das, 1987). Application of sunhemp @ 20 t ha^{-1} resulted in higher NPK uptake by garlic (103, 23 and 74 kg ha^{-1}) during *Kharif* and (108, 25, 76 kg ha^{-1}) during *Rabi*. The bulb yield did not differ among the treatments of 20t ha^{-1} of sunhemp (73 q ha^{-1}), 2.5 t ha^{-1} poultry manure (68 q ha^{-1}) and 5 t ha^{-1} vermicompost (70 q ha^{-1}) application (Shashidhar *et al.*, 2005). Prabhakar *et al.* (1987) observed linear yield response in chilli up to 90 kg N and 30 kg P_2O_5 ha^{-1} and opined that higher doses could be remunerative. Application of 150 kg N ha^{-1} in 3 equal splits (basal, 30 and 60 days after planting) resulted in higher yield of capsicum (124 q ha^{-1}; Srinivas and Prabhakar, 1982). Bell pepper responded linearly up to 180 kg N ha^{-1} with the nutrient use efficiency of 19.38 kg capsicum kg^{-1} N with BCR of 1:8.75 (Vishnu Shukla *et al.*, 1987). Analysis of nutrient and monetary efficiency in cabbage indicated that N fertilization was efficient even at 150 kg N ha^{-1} which recorded 97 kg cabbage heads kg^{-1} N and Rs. 13.18/Re. invested on N fertilizer. In case of P the yield with 40 and 80 kg P_2O_5 ha^{-1} were at par but BCR of 1:1.92 indicating the nutrient use efficiency up to 80 kg ha^{-1} (Prabhakar and Srinivas, 1990; Table 3). Fruit yield of long melon increased with higher dose of fertilizer (180 kg N + 100 kg P_2O_5 + 100 kg K_2O ha^{-1}) and spacing of 200 cm x 45 cm recording 128 q ha^{-1} (Vishnu Shukla and Prabhakar, 1988). Yield of bottle gourd with 180 kg N + 100 kg P_2O_5 + 100 kg K_2O ha^{-1} with the spacing of 300 cm x 45 cm was 38 t ha^{-1} (Vishnu Shukla and Prabhakar, 1987). Di calcium phosphate was equally effective compared to single super phosphate in soils having initially high build up of P while water soluble form (SSP) proved superior in soil with low P status (Prabhakar *et al.*, 1986). French bean yield increased with P application up to 75 kg P_2O_5 ha^{-1} (Prabhakar *et al.*, 1984). Application of sulphate of potash was preferred over muriate of potash for *Kharif* onion due to seedling mortality caused by chloride (Singh and Singh, 1984). Number and weight of root nodules in French bean increased with the treatment of seeds with Rhizobium culture but it was not translated into higher pod yield. In the same experiment, application of 80 kg N and 150 kg P_2O_5 ha^{-1} resulted in higher yield and BCR (20 and 37 t ha^{-1} and BCR 1:16.85 and 1:8.89 respectively; Srinivas and Prabhakar, 1985). Among the tomato lines screened, IIHR 707 and Arka Vikas recorded higher fruit yield of 522 and 556 q ha^{-1}, respectively with lower level of 60 kg N ha^{-1} (Tikoo *et al.*, 1989).

Table 3. Nutrient and economic efficiency of N and P fertilization in Cabbage

Nutrient level (kg ha^{-1})	Yield (t ha^{-1})	Additional yield over control (t ha^{-1})	Nutrient efficiency (kg yield kg^{-1} nutrient)	Marginal returns (Rs ha^{-1})	Marginal cost (Rs ha^{-1})	Benefit: cost ratio
Nitrogen						
0	2.34	-	-	-	-	-
75	10.39	8.05	107.0	4830	332.2	14.54
150	17.69	7.90	97.0	4380	332.2	13.18
Phosphorus						
0	5.63	-	-	-	-	-
40	12.07	6.44	161.0	3964	206.0	18.76
80	12.73	0.66	16.5	396	206.0	1.92

Source: Prabhakar and Srinivas (1990)

Prabhakar *et al.* (1992) developed a general model to estimate the optimum level of N (133 kg N ha^{-1}) for tomato across varieties and environments. Similar functions can be developed for other nutrient elements and crops since a large amount of data is available on nutrient responses of different vegetable crops at different locations over years. Subramanyam *et al.* (1990) developed dummy variable approach to screen tomato lines for response to low level of N that could be used to study different genotypes across different levels of the nutrient. In muskmelon, decision theory and marginal analysis were tried to find out optimum fertilizer recommendation. Though both the approaches were close in estimation of physical level of fertilizer, there was considerable difference of Rs.170 to 1430 ha^{-1} in the estimation of expected returns based on different criterion. Therefore, though marginal analysis could be used for deciding fertilizer recommendations in annual crops caution is necessary in projecting the estimated returns (Subramanyam, 1987). Ramachander *et al.* (1989) suggested stability analysis as an alternative to pooled analysis to recommend fertilizer dose based on repeated fertilizer trials at number of locations over years for annual crops like muskmelon. Based on the stability analysis it was recommended that application of 100 kg N, 26 kg P_2O_5 and 50 kg K_2O ha^{-1} was found suitable for favourable environment.

Fertilizers and Vegetable Quality

Fertilizer application leads to large differences in N and other minerals found in leafy vegetables (amaranth, spinach, cabbage), smaller differences in storage organs, bulbs, roots and tubers (onion, radish, carrot, potato) and negligible differences in fruit vegetables (tomato and melons). Under-fertilized lettuce grows slow, bitter in taste and throws seed stalks. Heavy fertilization increases sugar content and P application hastens maturity in muskmelon. Canning tomatoes are the least affected, however high N dressings lower total soluble solids and increase acidity in fruits. Low K reduces colour in carrots. High N lowers starch content in potato. Fertilizers influence the physiology of plant and thereby determine the composition of fruits and vegetables and resistance of these plants to environmental stress. Application of K, P and Ca under saline conditions improved fruit electrolytes and total soluble solids in tomato (Satti and Al Yahai, 1995). Use of potassium sulphate is recommended for good keeping quality of potato tubers (UAS, Bangalore, 1984). Choudhury (1982) recommended sulphate of potash for chilli and Kirthi Singh (1976) opined that the same might be recommended for other vegetables as well. Nurzynski (1976) recommended application of K in the form of muriate and sulphate of potash in equal proportion to spinach, carrot, cauliflower, tomato and lettuce cultivated on peat. At the end of vegetative period, chlorine content of 580 ppm in the peat and 2.78% Cl in leaf petioles had no adverse effect on yield and quality.

Improving Fertilizer Use Efficiency

Studies by Iyengar *et al.*, 1994 revealed that improving fertilizer use efficiency is important not only for reducing the cost of cultivation but also to prevent soil and environmental degradation. Nitrogen use efficiency generally ranged from 13.9% in chilli to 44.7% in brinjal. A large portion of unused N remained in the top 30 cm of the soil after the crop harvest (31.7% after onion and 90% after French bean) and loss of applied N ranged from nil after French bean to 50.7% after onion. Recovery of applied N after the first and second crops was from 0.9% to 5.1% in French bean and from 0.6 % to 6.1 % in onion. Postponing the basal application of N for 7 days after planting and application in 2 to 3 splits between 7 and 36 days after planting was found beneficial for tomato. Placement of fertilizer at 5 cm depth resulted in better absorption and utilization of applied P saving the cost on fertilizer by 20% in tomato and onion and 40% in brinjal. Okra responded to deeper (10-15 cm) placement of P. High yielding varieties of French bean (Arka Komal, Selection 909 and Contender) have shown higher uptake and utilization compared to low yielding genotypes.

The crop management that reduces pest and disease incidence and crop sequences that take best advantage of soil and climatic factors do better in utilizing the applied nutrients. Legumes with optimum nutrition fix higher amounts of atmospheric N than those that have constrained supply of other nutrients. French bean being a poor nodulator responds to applied N even up to 90 kg N ha^{-1}. Vegetables are sensitive to the deficiency of secondary and micronutrients like Mg, B and Zn. B deficiency is frequently observed and manifested in browning of curds and Mo deficiency results in whiptail of cauliflower, which is more pronounced in acid soils. B deficiency results in poor root growth and fruit cracking in tomato. Brinjal demands Zn and Mo for proper fruiting and quality.

Fertilizer Management in Vegetable Cropping Systems

Fertilizer application is more specific in cropping systems compared to that for individual crops. Radish yield increased with the level of NPK applied to the preceding crops okra and brinjal (Rao and Suryanaryana, 1977). Onion bulb yield increased with higher rates of N and K applied to the previous crop potato. The third crop of onion in tomato-French bean-onion sequence removed 26.44% from direct application and 14.13% from that applied to the first crop of tomato (Iyengar *et al.*, 1994). Intercropping systems okra + French bean and okra + radish responded better to the applied NPK than that by the individual companion crops (Prabhakar and Vishnu Shukla, 1990). Rao *et al.* (1977) reported the residual and cumulative application of P in Rice-cabbage-tomato system. Application of 2 levels of P to French bean-cabbage-tomato system, the residual and cumulative effects of fertilization depended on the position of crop in the sequence and the level P added to the preceding crop. Citrate soluble showed an advantage in building up P status in the soil. Application of 75 kg P ha^{-1} was found sufficient to support 3 crops in a sequence (Prabhakar *et al.*, 1986). Prabhakar *et al.* (1987) observed that the response to K varied with the crop and vegetable yield increased with residual and cumulative applications. The yield of brinjal, onion and carrot were unaffected by the residual K, while cabbage and French bean responded to residual and cumulative applications. Cabbage, radish, carrot and brinjal mobilized the native K in the soil while okra did not utilize the same.

Integrated Nutrient Management

Generally, 20 to 25 tonnes of FYM is recommended for vegetables. Therefore an integrated approach of supplying nutrients through organic and inorganic sources is followed for growing vegetables. In rainfed tomato variety (Arka Meghali) Azatobacter treated plots recorded 22 percent higher yield compared to control (Prabhakar and Hebbar, 2005). Soil application (75%) supplemented by foliar feeding (25%) of nitrogen was found beneficial for crops like tomato, brinjal, okra and onion (Prabhakar *et al.*, 2000; Table 4) and drumstick (Prabhakar *et al.*, 2003). Foliar spray of potassium nitrate (5 times @ 0.5 %) increased the yield of onion by 12 percent. Application of Vermicompost and foliar application of water-soluble fertilizers improved the yield of rain fed tomato in the range of 12 to 26 % depending on the combinations. For rainfed tomato variety Arka Meghali, application of 25 t ha^{-1} FYM and 60:50:30 kg NPK ha^{-1} was found superior (16.87 t ha^{-1}) compared to the application of 25 t ha^{-1} FYM alone (14.08 t ha^{-1}). In rainfed chilli (Arka Lohit), 5 t ha^{-1} FYM +Vermicompost 2.5 t ha^{-1} + recommended NPK (100:50:50 kg N, P_2O_5 and K_2O ha^{-1}) recorded significantly higher dry fruit yield (29.7 q ha^{-1}) as compared to

FYM (10 t ha^{-1}) + vermicompost (2.5 t ha^{-1}). In rainfed onion variety, Arka Kalyan, application of 20 t ha^{-1} FYM + 100 percent of recommended NPK (125:50:125 kg ha^{-1}) recorded significantly higher yield of 27.19 t ha^{-1} compared to no FYM treatment (23.94 t ha^{-1}). In vegetable pigeon pea (Hyd-3C), 10t FYM + 1.25 t vermicompost + half the recommended dose of NPK + bio-fertilizer + foliar spray was found to be superior with respect to growth characters and vegetable pod yield (73.33 q ha^{-1}) compared to recommended practice. In cauliflower, bio-fertilizers like Azospirillum, Azatobacter, PSB and VAM along with recommended chemical fertilizers increased the yield from 10 to 25 percent. Supplementing inorganic fertilizers with bio-fertilizers along with mulching increased the fruit yield of drumstick (Damodaran *et al.*, 1999).

Table 4. Effect of FYM, NPK and irrigation on growth and yield of onion

Treatment	Plant Height (cm)	No. of leaves $plant^{-1}$	Stem diameter (cm)	Bulb diameter (cm)	Bulb yield (t ha^{-1})
FYM (1/2) + NPK (F) *	48.1	9.9	1.4	30.9	5.2
FYM (1/2) **	45.2	9.7	1.3	27.9	4.2
FYM (1/2) + KNO_3 (F)	47.3	11.3	1.3	30.4	5.6
FYM (1) + NPK (F)	49.3	10.1	1.4	31.8	4.5
FYM (1) ***	45.5	9.7	1.4	28.3	4.9
FYM (1) + KNO_3 (F)	47.7	11.3	1.5	32.0	5.8
FYM (1) + Supplementary Irrigation	53.3	11.6	1.5	42.6	5.6
C.D. (0.05)	6.1	2.47	NS	5.5	0.8

* F: Foliar Spray, ** ½: 50% and *** 1: 100% of recommended dose

Source: Prabhakar *et al.* (2000)

Nutrient Management in Greenhouse Grown Vegetables

Greenhouse provides congenial microclimate for increased crop productivity. Reduced light levels in tropics and increased humidity facilitates a huge biomass production. Therefore, training and pruning are the two important and essential operations carried out in greenhouse vegetable production. Regulating the crop growth helps to convert vegetative into reproductive growth that enables to produce high quantities of vegetable yield. Capsicum yields about 40 tonnes per hectare in open field in a favourable cool season. The same crop yields 100 to 120 t ha^{-1} in a greenhouse. The plant grows up to 6 to 7 feet tall and produces a large quantity of biomass to support high yield. Therefore, nutrient removal is 200 kg each of NPK per hectare (Prabhakar, 2004). Hybrids of vegetables with indeterminate growth habit are selected for greenhouse cultivation. Continuous growth needs continuous supply of nutrients that are supplied mainly through fertigation.

Greenhouse production is done on raised beds or containers (plastic pots or bags). The growing medium or the root bed is modified to promote continuous and healthy growth of the plants. Vegetables like capsicum respond to better aeration in the rhizosphere that facilitates favourable water and nutrient dynamics. Carbon rich substrates like coir dust, saw dust and paddy husk make a suitable medium after decomposition for at least three months before planting crop. The medium serves the purpose of providing anchorage and physical medium for movement of air, water and nutrients. Uninterrupted root proliferation helps movement of water and nutrients into the plant system.

In a greenhouse, most of the nutrients are supplied through fertigation throughout the crop growth in dilute concentrations at frequent intervals. Minimum quantity of nutrients (2 to 2.5 g L^{-1}) in each fertigation ensures maximum uptake by the plants leaving behind negligible amount in the root bed. Nutrient use efficiency is high since the root proliferation is also confined to the surface and the movement of moisture and nutrients are also regulated. Basal application is given in the form of solid fertilizers to the extent of 50 kg NPK ha^{-1}. Vegetables like tomato and capsicum respond to Ca application and its deficiency leads to the serious malady of blossom end rot reducing the productivity and quality of the vegetable. Therefore, Ca application through calcium ammonium nitrate as a source of N and fertigation with calcium nitrate ensures adequate supply of the nutrient. Soil application of Ca has been found to be more efficient than foliar feeding. Water-soluble formulations containing N, P and K, are used in commercial greenhouses. Traditional fertilizers like urea and muriate of potash can also be used efficiently for fertigation. Phosphoric acid/urea phosphate is generally used to supply P, because single super phosphate may clog the emitters interrupting water and nutrient flow through the drip system. Secondary and micronutrients are given through foliar spray 2 to 3 times during crop growth up to four months after planting. Other systems of greenhouse cultivation of vegetables are hydroponics or exclusive organic culture. Nutrient management changes accordingly to supply need based nutrients throughout the crop to ensure higher yields.

Vegetable production in India will continue to be dependent on both organic and inorganic sources of nutrients, nevertheless economics of both has to be worked out for a given production system. Safe production of vegetables is the need of the day that ensures quality of vegetables, sustainable production and safety of environment.

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Nutrition and Nutrient Management of the Mango (*Mangifera Indica* L.) - New Thrust for the Future Perspective

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Abstract

Fruit crops being perennial in nature are quite different from seasonal crops in their nutritional requirement due to their plant size, density, growth rate, rooting pattern and phenomenon of bud differentiation and its relationship with the yield during the following season yr^{-1}. Crops, which shed leaves, return a part of the absorbed nutrient through leaf fall. Mango removes about 6.7 kg N, 1.7 kg P_2O_5 and 6.7 kg K $tonne^{-1}$ of produce. In mango, the critical values for N and K were found generally higher than those for seedlings indicating that younger plants are more sensitive than older ones. Mango crop some time exhibit multi nutrient deficiency particularly that of N, P, K, S and Zn in India. It is largely because of increased crop removal due to increased crop productivity and sub optimal and unbalanced use of fertilizers. Besides, the nutrient use efficiency is very low. In calcareous soils mango trees show severe chlorosis and stunted leaf growth called 'little leaf' and 'rosetting' combined with malformation of leaves, which are typical for Zn deficiency. These symptoms were cured by different Fe treatments. It was assumed that Fe deficiency might inhibit in some way acquisition and/or utilization of Zn in young growing leaves and cause subsequently Zn deficiency. Hence there is an urgent need for balanced fertilization.

Keywords: Mango (*Mangifera indica* L.), nutrition

Mango (*Mangifera indica* L.) is the most important fruit of India. It is grown over an area of 1.23 million hectares (m ha) in the country producing 10.99 million tones (mt). It accounts for 22.1 per cent of total area (5.57 m ha) and 22.9 per cent of total production of fruits (47.94 mt) in the country. The mango will grow well in a wider range of soils. The loamy alluvial soils of the Indo-Gangetic plain are ideal (Gangolly *et al.*, 1957). Extremely sandy soils, shallow rocky soils, water logged soils and alkaline or calcareous soils are not suitable for mango cultivation. Mango does well over a pH range from 5.5 to 7.5, but it is not tolerant to salinity. The ideal climatic conditions for combined growth and fruiting appear to be a cool winter and a hot summer with relatively small changes of temperature during both seasons, an annual rainfall of 30 to 40 inches, provided that from the start of blossoming until the fruit starts sizing. Inspite of growing large area, its present level of production is not sufficient enough. However, the fruit yield can be increased 2-4 times over the national average by planting the best available material, improved management practices including balanced fertilizers.

To ensure high economic productivity and to sustain the available soil nutrient status at a desirable level, correct dose of manures, bio and chemical fertilizers must be applied, based on use of reliable diagnostic tool. Considering energy, economy and environment, it is imperative that manures, bio-fertilizers and chemical fertilizers should be used efficiently. The best diagnostic tool is one that recommends nutrient application only in a direct economic response of the fruit crop. Diagnostic tools are designed to avoid nutrient shortage or excess and if used properly, no decrease in fruit production or quality should occur. Leaf analysis seems to be the best method for identifying the need for application of nutrients. Determination of the nutritional needs of fruit trees must be made prior to the renewed growth or determination of potential yield.

Nutrient Status in Mango Orchards

The mango is able to obtain adequate mineral nutrients from most soils on which it is grown. It appears from the literature that the study of the problem of mango manuring is still in its infancy, and thorough research from several angles is necessary before any definite conclusion can be drawn. In India some work has been done, mostly in sand culture, to develop deficiency symptoms but levels of the various nutrients as related to fruit production have not been developed.

Surveys of commercial orchards have been conducted at some places of mango orchards to determine their leaf nutrient status in respect of macro and microelements (Ahlawat *et al.*, 1985; Chauhan and Cahoon, 1987) but the data in most cases were not correlated with growth and yield to draw meaningful conclusions (Table 1).

A survey was also made to investigate the micronutrient status of 30 mango orchards in Lucknow region. It was found that most of the orchards were deficient in Zn contents. Cu, Mn and Fe contents of mango leaves were in optimum range and they were significantly higher in the leaves sampled during 'off' year as compared to 'on' year (Thakur *et al.*, 1981). Yield was found to differ significantly in 'on' and 'off' year obviously due to alternate bearing.

Table 1. Micronutrient status and yield of 30 mango orchards

Nutrient and yield	'On' Year		'Off' Year		CD for orchard
	Range	Mean	Range	Mean	
Zn (mg kg^{-1})	10.3 - 23.3	16.7	10.6 - 24.6	17.2	6.1
Cu (mg kg^{-1})	5.0 - 20.0	11.6	7.5 - 21.3	15.1	NS
Mn (mg kg^{-1})	30.0 - 110.0	64.0	36.0 -164.0	82.0	40.1
Fe (mg kg^{-1})	67.0 - 339.0	171.0	130.0 -385.0	250.0	NS
Fruit number per tree	145 - 733	438.0	1 - 133	93.0	NS

Recently, a survey was made in 20 orchards of mango situated in different regions of Uttar Pradesh. A large variation in nutritional levels of their soil and plant were observed. The orchards of Langra situated at Varanasi were found deficient in phosphorus content whereas other orchards situated at Saharanpur, Meerut regions were deficient in most of the micronutrient content (Table 2).

Table 2. Nutrient status in Uttar Pradesh mango orchard soils

Orchards	OC (%)	Available P (mg kg^{-1})	Available K (mg kg^{-1})	Available Ca (mg kg^{-1})	B (mg kg^{-1})	EC (dS m^{-1})
Lucknow	0.3-0.6	4.5-12.5	57-116	268-373	0.9-1.0	0.02
Varanasi	0.2-0.8	2.0-24.0	89-350	270-408	1.0-1.5	0.04
Saharanpur	0.2-0.6	6.8-12.0	46-100	400-410	4.1-5.0	0.05
Meerut	0.4-0.7	9.1-11.5	55-105	280-389	3.8-4.7	0.04
Bulandshahar	0.5-0.8	10.0-13.5	65-115	180-250	2.1-3.5	0.04
Bijnaur	0.4-0.6	9.0-13.0	75-110	190-280	2.9-3.5	0.44

Biswas *et al.* (1987) observed significant correlation between leaf N and organic carbon of surface soil whereas leaf P and K were significantly correlated with P and K content of surface and sub-surface soil. However, a positive correlation was observed between leaf P and available P in the deeper soil layer. The variation in the production efficiency of orchards is attributed to variation in soil and leaf nutrients. High yielding orchards have higher leaf N, P and K content. Fruit yield has significant correlation with leaf K before flowering and soil K during flowering and at peak stage of fruits. It was suggested that leaf nutrient status explains the yield variation better than soil nutrient content (Table 3).

Table 3. K status of high and low yielding trees from different orchards

Status	Average fruit yield (kg plant^{-1})	Leaf K (%)				Soil K (kg ha^{-1})			
		AH	BF	F	P	AH	BF	F	P
High	193.4	0.90	0.81	0.67	0.72	285	293	289	340
Low	101.2	0.85	0.78	0.68	0.67	344	302	319	325
Mean	147.3	0.87	0.79	0.67	0.69	314	293	304	332

AH: After harvesting, BF: Before flowering, F: Flowering, P: Pea stage

Balanced use of plant nutrients is of great relevance for the sustainability of mango crop. Most of the orchardist apply only N, P and K. Application of NPK fertilizers alone has failed to give the expected return as they were given earlier, mainly because secondary and micronutrients are being depleted and not being replenished along with NPK. As replenishment of micronutrients is generally ignored, such a situation is causing tremendous nutrient imbalances and serious problems of micronutrients deficiencies in soils and plants as reported from different Indian states (Table 4).

Table 4. Extent of micronutrients deficiency in soils of India

State	Percent soil samples deficient					
	Zn	Cu	Fe	Mn	B	Mo
Andhra Pradesh	49	<1	3	1	-	-
Assam	34	<1	2	20	-	-
Bihar	54	3	6	2	39	-
Delhi	20	-	-	-	-	-
Gujarat	24	40	8	4	2	10
Haryana	60	2	20	3	-	28
Jammu & Kashmir	12	-	-	-	-	-
Karnataka	73	5	35	17	32	-
Kerala	34	31	<1	0	-	-
Madhya Pradesh	43	<1	7	1	22	18
Meghalaya	57	2	0	23	-	-
Orissa	54	-	0	0	-	-
Pondichery	8	40	2	3	-	-
Punjab	48	<1	14	2	-	-
Rajasthan	21	-	-	-	-	-
Tamil Nadu	59	6	17	6	18	-
Uttar Pradesh	46	<1	6	3	24	-
West Bengal	36	0	0	3	68	-
Whole of India	48	2	12	5	33	13

Modern orcharding leads to heavy withdrawal of nutrients from soils and its success depends largely upon the external application of nutrients commensurating with the nutrient uptake. If the application of nutrients is repeatedly unbalanced and does not correspond to the need of the soil and the crop grown on it, crop response to fertilizers is bound to decline. A crop's overall demand and the amount removed from the soil must be replaced, if soil fertility levels are to be maintained. Nutrient removal by the fruit crops depends on the plant parts, which are harvested, their composition and their share in total dry matter production. Crops, which shed leaves, return a part of the absorbed nutrient through leaf fall. In mango, N (6.7 kg $tonne^{-1}$) and K (6.7 kg $tonne^{-1}$) were removed in a similar amount after harvesting the produce, whereas P in terms of P_2O_5 was removed @ 1.7 kg $tonne^{-1}$ of produce (Table 5).

Table 5. Nutrient removal by mango crop

Nutrient removal in kg $tonne^{-1}$ of produce			Ratio of K_2O and P_2O_5 removal relative to N		
N	P_2O_5	K_2O	N	P_2O_5	K_2O
6.7	1.7	6.7	100	25	100

Assessment of nutrient needs and their critical limit

The nutrient status of plants can be assessed on the basis of critical limits of nutrients in plant and soil. Various types of disorders associated with deficiencies or toxicities in mango can be adjudged with their nutritional level. Critical level of nutrients for mango is depicted in Table 6.

Table 6. Suggested critical level of nutrients in mango

Nutrient	Samra *et al.* (1978)	Bhargava and Chadha (1988)	Biswas *et al.* (1987)	Chatterjee and Dubey (2002)
Nitrogen (%)	1.23	1.23	1.18	1.18
Phosphorus (%)	0.06	0.06	0.08	0.08
Potassium (%)	0.54	0.54	0.52	0.52
Calcium (%)	1.71	1.71	0.89	<0.25
Magnesium (%)	0.91	0.91	0.90	$<4\%$ CEC
Sulphur (%)	0.12	0.12	0.92	8-30 mg kg^{-1}
Iron (mg kg^{-1})	171	171	45	4.5
Manganese (mg kg^{-1})	66	66	21	2.0
Zinc (mg kg^{-1})	25	25	18	0.6
Copper (mg kg^{-1})	12	12	7	0.2

In mango, the critical values for N and K were found generally higher (Biswas *et al.*, 1987) than those for seedlings indicating that younger plants are more sensitive than older ones. In this approach, deficiency of a particular nutrient was created in the artificial media and deficiency symptoms were described through leaf analysis at various stages of growth. However, after surveying the leaf nutrient status of various bearing mango orchards, it was proved that analysis at juvenile stage has some limitation due to its restricted root system and media culture does not represent the root-soil interface in the field conditions.

Plant nutrient status evaluation

Leaf analysis has been used in mango as a diagnostic tool to indicate the plant nutrient status in relation to critical value (Bhargava and Chadha, 1988). Recently mature leaf on vegetative shoot, 5 month old, middle leaf in the shoot and sample size 30 was standardized as a nutritional index for mango (*Mangifera indica* L.). A direct correlation between leaf nutrient content and yield was found (Rao and Mukherjee, 1987).

The optimum level of leaf N is in the range of 1.40 to 1.50 per cent for maximum production of mango. However, mineral composition of mango leaves is affected by factors such as age, placement on the shoot, time of emergence, season, sampling height, sampling direction, rootstock, reproductive stage of the shoot and type of soil and fertilizer management. The increase in leaf N and carbohydrate by the application of calcium nitrate have been worked out. Interaction between source and level of nutrients showed a significant difference with only Ca and K, however the leaf age is a vital factor responsible for variation in the mineral composition of mango leaves.

The stability period of nutrients in the leaves varied from 4-12 months, however, Pathak and Pandey (1976) advocated that the stability period of individual element varied with the age of leaves. There are also conflicting reports regarding N, P, K, Ca and Mg levels in leaves from basal to terminal position on the shoot. However, in general, an increase in Ca and Mg and decrease in K and Mn from basal to terminal position on the shoots have been reported. It appears that higher amounts of nutrients are present either in basal or in terminal leaves. Therefore, leaves borne on the middle part of the shoot should be sampled for nutrients analysis. Leaf nutrient content also varies from flush to flush beside age (Devrani and Ram, 1980). Therefore, the leaves of a particular age and flush should be sampled. The elevation of the leaves on the crown may also cause variation in the nutrient levels and thus the lower, middle and upper part of the crown should be considered for leaf sampling (Chadha *et al.*, 1980). The levels of Mg, S, Mn and Fe in the leaves of Chausa cultivar were observed to be 4.35, 7.14, 9.42 and 7.71 per cent, respectively. The partial regression co-efficient was found to be significant for K, Ca, Mg, S, Cu and Mn (Rao *et al.*, 1980).

In leaves of mango the N and P level were explained by a quadratic fit up to an extent of 75.36 and 95.65%, respectively (Fig 1). K content decreased and Ca content increased linearly with leaf age having 75.52 and 89.00% as r^2 values, respectively (Fig 2). Mg, S and Mn had Cobb-Douglas relation with leaf age where age contributed 65.67, 74.86 and 68.04 per cent, respectively (Fig 3 and 4). Zn content was found to be not affected by any of the factors studied.

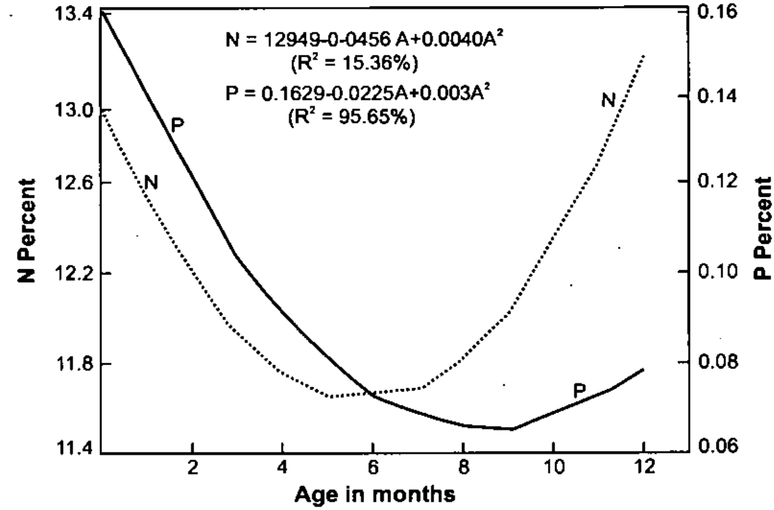


Fig 1. Regression of N and P on leaf age

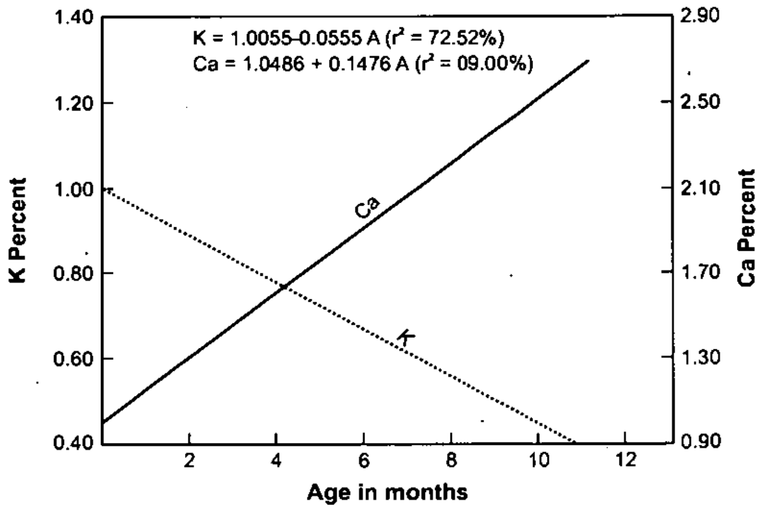


Fig 2. Regression of K and Ca on leaf age

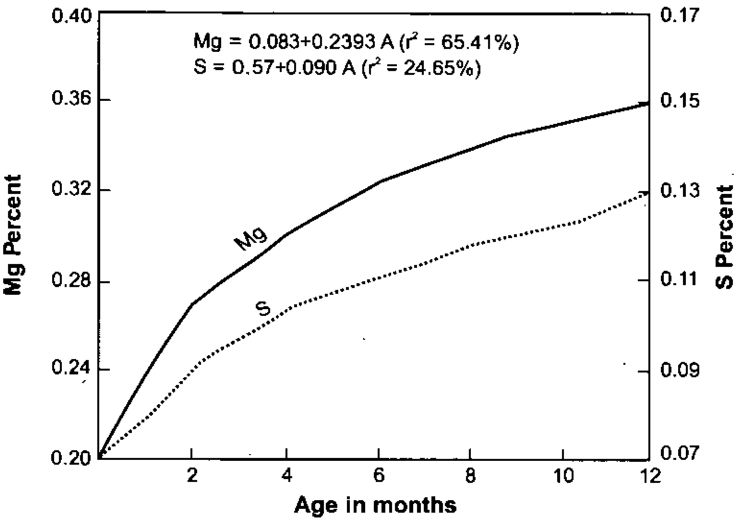


Fig 3. Regression of Mg and S on leaf age

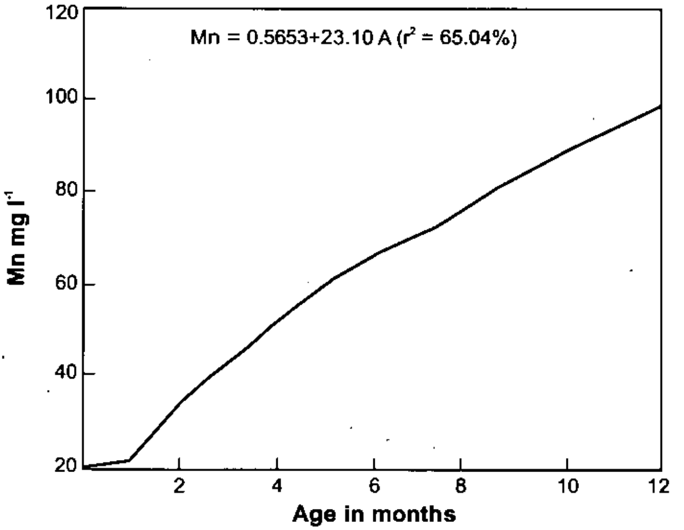


Fig 4. Regression of Mn on leaf age (Source: Rao *et al.*, 1980)

In one study it was indicated that the presence or absence of flowers or fruits on the shoot at the time of sampling may affect nutrient status and sufficient levels of nutrients should be built through fertilization application at proper time before flowering for their utilization during fruit development (Rajput *et al.*, 1987).

Nutrient Deficiencies and Appearance of Symptoms

Most of the experiments for producing the deficiency symptoms were made in sand culture. Several deficiency symptoms of the elements were noticed when N, P, K, Ca, Mg and S in seedling leaves reached the levels of 0.63, 0.03, 0.24, 0.81, 0.10 and 0.32 per cent, respectively. The level of zinc 27.5 mg kg^{-1} was found in deficient leaves whereas healthy leaves contained 35.2 mg kg^{-1} and 0.2 per cent zinc sulphate was suggested to correct the deficiency. Depending on the inability of nutrients in plants, the deficiency symptoms appear either on the lower or upper parts of plants. On the basis of their mobility the plant nutrients are classified in two types. First deficiency symptom of those nutrients which are highly mobile such as N, P, K, Mg and Zn, appear on older or lower leaves. Secondly deficiency symptoms of those nutrients which are less mobile such as Ca, B, Cu, Mn, S and Fe, occur on younger leaves or bud leaves.

Several kinds of disorder associated with deficiencies or toxicities of micronutrients have been reported in fruit crops. The limits of nutrient for normal mango are presented in Table 7. In mango fruit drop, internal necrosis of fruits (Fig 5), curling in leaf (Fig 6), little leaf (Fig 7), die back (Fig 8) and gummosis (Fig 9) in shoots of mango have been found to be related with the deficiencies of B, Zn and Cu, respectively. On the other hand, excess uptake of chloride and manganese has been reported to cause scorching (Fig 10) and death of trees, respectively. Deficiency of magnesium was found to cause fading between the veins of leaves (Fig 11). Deficiency, sufficiency and toxic limit of macro- and micro nutrient for mango are as follow:

Table 7. Deficiency, sufficiency and toxic limit of macro- and micro nutrient for mango

Nutrient		Deficient	Sufficient	Excess
Macronutrient (%)	N	0.70 - 0.99	1.00 - 1.50	>1.50
	P	0.05 - 0.07	0.08 - 0.25	>0.25
	K	0.25 - 0.39	0.40 - 0.90	>0.90
	Ca	1.00 - 1.99	2.00 - 5.00	>5.00
	Mg	0.15 - 0.19	0.20 - 0.50	>0.50
	S	0.05 - 0.19	0.20 - 0.60	>0.60
Micronutrient (mg kg^{-1})	Fe	25 - 49	50 - 250	>250
	Mn	25 - 49	50 - 250	>250
	Zn	15 - 19	20 - 200	>200
	Cu	5 - 6	7 - 15	>50
	B	20 - 49	50 - 100	>100
	Mo	0.01 - 0.04	0.05 - 1.0	>1

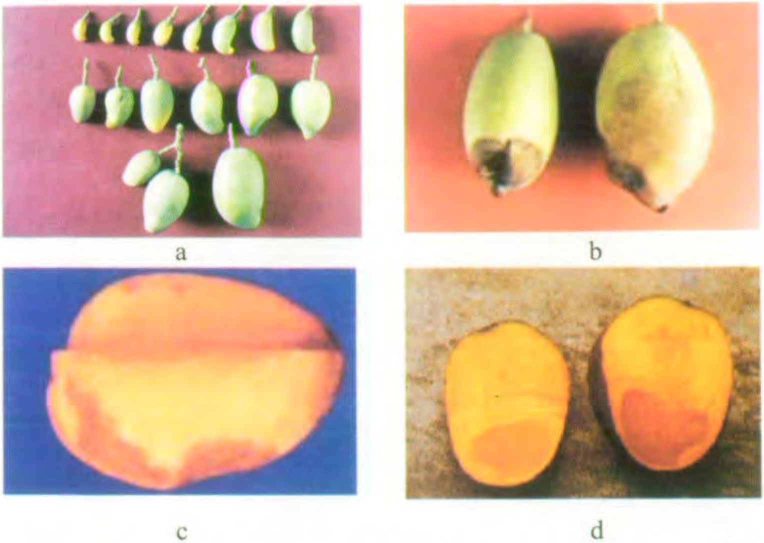


Fig 5. Disorder and symptoms appear due to boron deficiency in mango, fruit drop (a), internal necrosis (b), pulp affected (c), affected lower part of pulp (d)

Fig 6. Curling in leaves due to boron deficiency in mango

Fig 7. Zn deficiency and reduction in leaf size in mango

Fig 8. Die back in mango tree

Fig 9. Cu deficiency with gummosis in mango shoot

Fig 10. Chloride toxicity

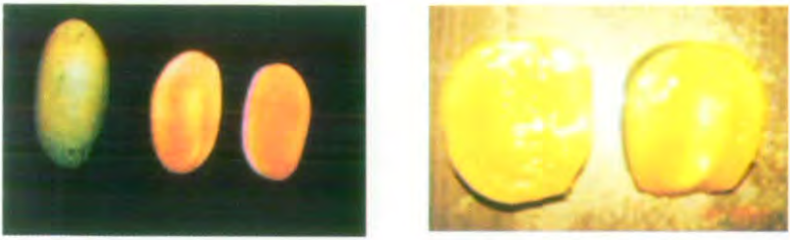
Fig 11. Manganese deficiency with fading between veins of mango leaves

Deficiency of K and regular use of Muriate of Potash (MOP) was also found to cause the discolouration of fruit besides scorching of the leaf margin (Fig 12). Potassium deficient trees often produce small fruits with poor colour (Fig 13). Under sever deficiencies, fruit drop could also occur.

Fig 12. Deficiency of K showing scorching in leaves of Langra mango

Fig 13. K deficiency in fruit showing poor colour in fruit

Fruits with jelly seed in Dashehari (Fig 14a) and Langra (Fig 14b) mango and spongy tissue in Alphonso (Fig 15a) and Mallika (Fig 15b) cultivars were found to be deficient in Ca and K and excess in N in affected part. On the other hand no significant differences were found in micronutrient level in the affected tissue of Dashehari mango when compared with normal ones. It was interesting to note that the element Ni was recorded less (0.71 ppm) in affected tissue as compared to normal (1.82 ppm). The Cd and Cr levels were also analysed and they were found below detective level in normal as well as in affected tissue of mango fruit.



a b

Fig 14. Jeely seed in mango Dashehari (a), Langra (b)

a b

Fig 15. Spongy tissue Alphonso (a), Mallika (b)

In calcareous soils mango trees show severe chlorosis and stunted leaf growth called 'little leaf' and 'rosetting' combined with malformation of leaves, which are typical for Zn deficiency. These symptoms was cured by different Fe treatments. It was assumed that Fe deficiency might inhibit in some way acquisition and/or utilization of Zn in young growing leaves and cause subsequently Zn deficiency. Sometimes severe Fe deficiency results in inhibition of protein synthesis and growth depression with expression of the atypical symptoms (little leaf) as known for Zn deficiency. The micro nutrient level differs in cultivars, fruiting and non-fruiting terminals and age of foliage and direction etc. This is probably one of the reasons that critical limits of Zn reported by different authors are at variance.

Injurious effects of micro nutrient excess like Mn toxicity have been noted in India. Its injurious effects (Mn) could be counteracted by the addition of iron at levels, which could raise the Fe: Mn ratio of the nutrient medium to 1.5. It was further reported that foliar iron content of 600-700 mg kg^{-1} and Mn content of 350-730 mg kg^{-1} would ensure normal plant growth. Excess of chlorides have been found to cause leaf scorching in mango. It first starts from tip of a leaf, then extend to the lower parts and ultimately leaf appears brick red.

On the whole, now a days deficiency of micronutrients in soil is increasing and several suitable test for diagnosis and assessment of such deficiencies can be employed for delineation of soil fertility, for making practical recommendations and for monitoring the soil nutritional status. However, there are several factors influencing the availability of the micronutrients, which are listed below (Table 8).

Table 8. Factors affecting the availability of micronutrient in plants

Factors	Impact
Soil	Minerals, total content, soil reaction (pH), redox, cation exchange capacity, organic matter, nutrient balance, moisture, aeration, soil microorganism
Plant	Nutrient uptake efficiency, root shoot transport, nutrient accumulation, compartmentalization, nutrient utilization, transformation in to biogenic molecules, metabolic activity, rate and stage of growth
Environmental	Light intensity, temperature, drought, flooding, hypoxia
Cultural practices	Cultivation practices, fertilizer use

Micronutrient recommendations for mango crops include both applications to the soil as well as leaves (foliar sprays), however foliar spray is commonly recommended in mango. The dose of micronutrient for overcoming the micronutrient deficiencies in mango is depicted in Table 9.

Table 9. Corrective measures for micronutrient deficiencies

Element	Source	Spray (%)	Soil application (kg ha^{-1})
Zn	Zinc sulphate	0.5	25
Mn	Manganese sulphate	0.5-2.0	20
Cu	Copper sulphate	0.1	10
Fe	Ferrous sulphate	1.0-3.0	20
B	Borax	0.2-0.5	10
Mo	Sodium molybdate	0.1-0.3	10

Response to Applied Nutrients

Rajput and Tiwari (1975) studied the effect of four concentrations of urea (0-6%) spray for two years in August and December on 8 and 10 month old shoots of three mango cultivars. Samra *et al.* (1977) conducted an experiment on the foliar application of 4% @ 8 liters (5 kg ha^{-1}) per fully grown tree at full bloom stage and during fruit development. Four per cent urea spray gave the highest average number of fruits and fruit weight but delayed fruit maturity and increased N concentration of leaves significantly. Nijjar *et al.* (1976) recommended 27.5 mg kg^{-1} Zn in deficient leaves whereas healthy leaves contained 35.2 mg kg^{-1} and suggested 0.2% spray of $ZnSO_4$ to correct the deficiency. In field conditions, appearance of deficiency symptoms is a complex phenomenon that changes with age, time of emergence, season, sampling height, sampling direction, root stock, reproductive stage of the shoot and type of soil and fertilizer management.

In Totapuri cultivar nutrient concentration of mango leaf as affected by application of varying levels of nitrogen, phosphorus and potassium was monitored for a period of nine years (Raghupathi *et al.*, 2004). Relationship between nutrient concentration vs. fruit yield was established based on the mean nutrient concentration determined for different treatments. The data was sub-divided into low and high yielding population based on yield performance. The Diagnosis and Recommendation Integrated System (DRIS) ratio norms were developed from high yielding population, while diagnosis of nutrient imbalance was made in low yielding plants. Total imbalance of nutrients in plants was reflected through sum of DRIS indices irrespective of sign. Result clearly revealed with this model that the greater imbalance of nutrient resulted in lower fruit yield.

Near-ripe 'Kensington Pride' mango (*Mangifera indica* L.) fruit in with green skin colour generally return lower wholesale and retail prices. Pre-harvest management, especially nitrogen nutrition, appears to be a major causal factor. Therefore, the effect of N application on skin colour was investigated on three orchards, one with a high green (HG) skin problem and two with a low green (LG) skin problem. N was applied at pre-flowering and at panicle emergence at the rate of 75, 150, 300 g $tree^{-1}$ (soil) or 50 g $tree^{-1}$ (foliar) for the LG orchards. In all orchards the proportion of green colour on the ripe fruit was significantly ($p<0.05$) higher with soil applications of 150 g N or more $tree^{-1}$. Foliar sprays resulted in a higher proportion of green colour than the highest soil treatment in the HG orchard, but not in the LG orchards (Nguyen *et al.*, 2004).

Influence of potassium on flowering and yield

Research carried out in some tropical and subtropical regions showed that the use of potassium nitrate (KNO_3) containing 13 per cent nitrogen in the form of nitrate and 46 per cent K_2O can stimulate profuse flowering even in the 'off' year of mango and help to increase the number of panicle per tree and thereby increase the production of mango. However, some of the experiments conducted at Central

Institute for Subtropical Horticulture, Lucknow did not show consistent results.

In another experiment at Central Institute for Subtropical Horticulture, Lucknow in mango cultivar Langra (25 year age) indicated the importance of potassium nutrition in enhancing its productivity. Available K in soil was also increased by the application of potash particularly sulphate of potash (Table 10). Similar type of experiment was also done on Alphonso mango at Konkan Krishi Vidyapeeth, Dapoli, and fruit yield was significantly improved by the basal application of K through SOP + foliar spray of potassium nitrate (Fig 16).

Table 10.Effect of potassium on yield and other physical attributes of mango cv. Langra

Treatment	Yield (kg tree^{-1})	pH	Organic carbon (%)	Available K (mg kg^{-1} soil)
Control	203	6.9	0.31	117
0.48 kg K_2O (SOP) Basal + 2 spray of 2% SOP	240	7.0	0.44	345
0.96 kg K_2O (SOP) Basal + 2 spray of 2% SOP	296	6.6	0.55	432
0.60 kg K_2O (SOP) Basal + 2 spray of 2% SOP	265	6.9	0.44	357
0.48 kg K_2O (SOP) Basal + 3 spray of 2% SOP + N (2%)	270	7.0	0.42	340
1.05 kg K_2O (MOP) Basal	239	7.0	0.33	267
0.96 kg K_2O (SOP) Basal	186	6.9	0.33	267

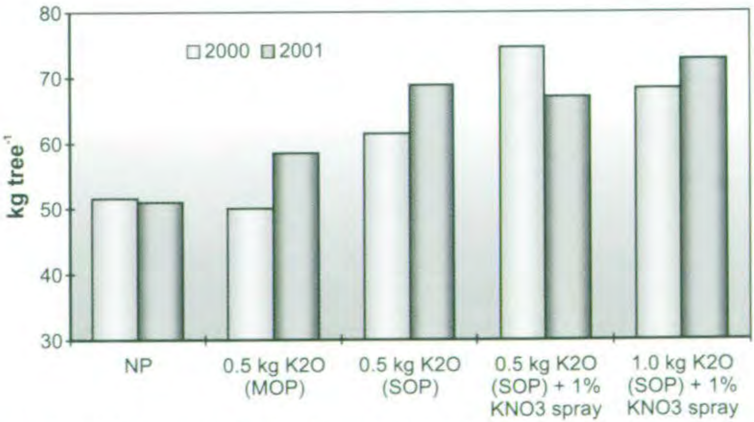


Fig 16. Effect of potassium on fruit yield of Alphonso mango

Response of different forms of potassium on fruit quality

The shelf life of fruit increases by the application of K as fruit tends to remain green for longer period on full maturity. In Dashehari mango, foliar spray of 1, 2 and 3 per cent each of N, P and K improved fruit size by 18 per cent and increased TSS from 16.5 to 17.9 per cent and sugars from 11.3 to 14.7 per cent with increase in carotenoid level from 4.01 mg $100g^{-1}$ to 5.85 mg $100g^{-1}$ of fruit pulp (Singh, 2003). Experiments conducted in Ratnagiri district of Maharashtra, where mango orchard soils are poor in K, clearly showed that to obtain quality fruits with attractive colour, potassium application is a must.

Nutrient interactions

Most of the orchardists apply only nitrogen and over application of nitrogen results in reduced uptake of P and K, which result into poor fruit quality. Similarly, low uptake of K reduces the fruit quality and storage life of the fruit. Therefore, application of nutrients in balance quantity is essential for proper nutrient interaction in the soil (Table 11). Potassium has been found to influence the use efficiency of other nutrients by the crops. Experiments conducted at several places throughout India have clearly indicated increased efficiency of N, P and Zn with K fertilization emphasizing once again that for maximizing fertilizer use efficiency, all nutrient deficiencies must be corrected.

Table 11. Nutrient interactions in soil

Nutrients excess	Causes deficiency
N	P, K, Mg, Zn, Cu, Fe, Mn
P	Ca, Mg
K	Zn
S	Ca
Ca	Fe, B, Mn
Mn	Fe
Na	K
Cl	Fe
Zn	N, Fe
Cu	Fe

Enhancing Nutrient Use Efficiency

Mineral nutrients are the major contributors in enhancing crop production which encompasses higher use of fertilizers. Enhanced use of fertilizers raises concerns due to adverse effects on the environment. Therefore, nutrient use efficiency (NUE) and improved soil management become important for quality production of fruit. Fruit crops generally require more of potash followed by nitrogen and phosphorus

(Kumar *et al.*, 2006). Mango crop some time exhibit multi nutrient deficiency particularly that of N, P, K, S and Zn in India. It is largely because of increased crop removal due to increased crop productivity and sub optimal and unbalanced use of fertilizers. Besides, the nutrient use efficiency is very low. Hence, there is an urgent need to improve the nutrient use efficiency in mango. The following approaches could be attempted to increase the nutrition uptake in mango plant.

Nutrient responsive genotype and balanced fertilization

In annual crops considerable progress have been made to develop nutrient efficient genotype, such type of work is at present needed in mango. However, there is a lot of variability between varieties for their response to nutrients application in fruit crops. The recommended balanced fertilizers may be emphasized to increase the nutrient use efficiency.

Efficacy of modified sources of fertilizers

Several slow release and modified urea fertilizer are being used to increase the efficiency of urea. Neem coated fertilizers get mineralized at a slower rate than just urea and also provide residual nitrogen for future growth and development. Experiment conducted with SOP and MOP as a source of potassium for mango at CISH, Lucknow (as cited earlier) revealed that application of SOP improved the potash use efficiency with quality production of fruits.

Integrated nutrient managemtment (INM)

Integrated use of organic and mineral fertilizers has been found to be more effective in maintaining higher productivity and enhancing fertilizer use efficiency. Experiment conducted in mango of full bearing tree showed that when recommended fertilizer dose is supplemented with FYM (40 kg tree^{-1}) and 250 g culture of Azospirillum, yield of fruits and quality get enhanced even under reduced NPK level. Azospirillum and phosphobacteria besides micorrhizal fungi has been shown to reduce the N and P fertilizer requirement without affecting the production, thus maintaining higher fertilizer use efficiency in fruits, however, such type of information is lacking in mango. Therefore, this type of work is needed in this crop for increasing nutrient use efficiency.

Rootstocks

Mango is propagated by vegetative method of propogation. Every rootstocks differs in its capacity to absorb nutrients and has significant effect on the level of nutrient of scion. Therefore, stionic effect is to keep in mind before nutrients application. They have reciprocal influence on nutrient uptake pattern and thereby on leaf nutrient status. Significant difference for N, P, K, Fe, Ca, Mn and Cu was found in Alphonso mango when grafted on different rootstock (Kurian *et al.*, 1996). It was also noted that vigorous rootstock led to higher leaf N content as compared to lowest values of N, K and Fe in least vigorous root stock (Table 12).

Table 12. Effect of rootstock on leaf nutrient status of Alphonso mango

Rootstock	N	P	K	Ca	Mg	Fe	Mn	Cu	Zn
	(%)					(mg kg^{-1})			
Alphonso	1.56	0.20	0.96	1.84	0.22	75	248	30	12
Vellaikolumban	1.40	0.15	0.78	1.98	0.28	56	238	12	11
Bappakai	1.61	0.21	0.94	1.59	0.16	81	139	12	11
Chandrakaran	1.47	0.17	0.88	2.39	0.28	85	169	15	15
Kurukkan	1.49	0.14	0.95	2.21	0.27	96	213	14	11
Muvandan	1.64	0.16	0.79	2.29	0.23	110	154	17	12
Mylepelian	1.49	0.18	0.81	1.70	0.20	92	199	11	12
Olour	1.59	0.21	0.98	2.05	0.14	96	243	12	9

Fruit yield per tree of Alphonso was found higher on the Olour, Muvandan and Bappakai rootstock (Kurian *et al.*, 1996) (Table 13).

Table 13. Effect of rootstock on yield of 13 year old 'Alphonso' mango trees

Rootstock	Fruit yield per tree		Cumulative fruit yield per tree for 13 yrs.	
	No.	Wt. (kg)	No.	Wt. (kg)
Alphonso	116	33.2	322	87.0
Vellaikolumban	83	27.1	231	63.0
Bappakai	228	64.5	536	137.9
Chandrakaran	146	43.3	310	84.3
Kurukkan	148	47.8	457	129.3
Muvandan	189	65.3	546	155.1
Mylepelian	98	29.9	366	101.7
Olour	231	77.7	617	170.4
C.V.%	34	40.4	-	-

Source: Kurian *et al.* (1996)

Rumani, Ambalvi and Dashehari rootstock had highest levels of N, Fe and Zn + Cu, respectively. On the otherhand ST-9 absorbed more P and K, Nakkare more Ca, Mg, Mn and Bappakai more S. In Israel under medium lime content, the trees of 'Maya' grafted on 13-1 rootstock showed excellent performance, while those grafted on Sabre rootstock showed severe symptoms of Fe deficiency and the trees on peach rootstock died (Gazit and Kadman, 1980). The rootstock '13-1' has relative high salt tolerance under field conditions (Table 14).

Table 14. Response on nutritional level in different cultivar scions

Rootstock	Scion	Influence on scion
Goa	Baneshan & Neelum	Significantly higher N
Pahutan		Lower N
Olour		
Rumani	Dashehari	More N
ST-9		More P & K
Nakkare		More Ca, Mg & Mn
Dashehari		More Zn & Cu
Bappakai		More S
Ambalvi		More Fe
13-1	Maya	Excellent performance
Peach		Severe Fe defeciency
Sabre		Degenerated & died

Mulching

Mulching is a technology of covering the soil around the tree canopy to prevent the loss of moisture by evaporation and prevent weed growth. Mulches such as artificial (plastic), organic (compost, straw, manure, leaf etc.) or living have been found to improve the flowering, fruit set and yield (Fig 17a, b) through increase in uptake of nutrient in various crops. However, in an experiment conducted at CISH, Lucknow in Chausa, Langra, Dashehari and Mallika mango with black plastic mulch showed the increase in levels of N, Ca, Zn, Cu, Mn and Fe in soil and P and K in plants. Significant enhancement in flowering and yield in term of fruit number and fruit weight were also obtained (Table 15) (Singh, 2006).

Table 15. Response of plastic mulch (black 100 μ thick) on nutritional level of soil and leaves in Chausa mango tree

Treatment	pH	OC (%)	N (%)	Zn (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	P (mg kg^{-1})	Ca (mg kg^{-1})	K (mg kg^{-1})
Soil										
Control	7.2	0.55	1.90	0.75	0.66	3.60	9.52	12.96	440.95	115.0
Plastic mulch	7.2	0.51	2.50	0.93	1.61	4.90	6.66	11.69	521.95	100.0
C.D. (0.05)	NS	NS	0.85	0.26	0.04	0.85	0.35	0.57	10.74	4.2
Leaves										
Control	-	-	1.65	25.0	10.0	95.0	96.0	0.15	100.0	56.0
Plastic mulch	-	-	1.68	28.0	12.0	98.0	105.0	0.21	158.0	80.0
C.D. (0.05)	-	-	NS	NS	0.05	0.03	2.50	0.05	10.48	0.03

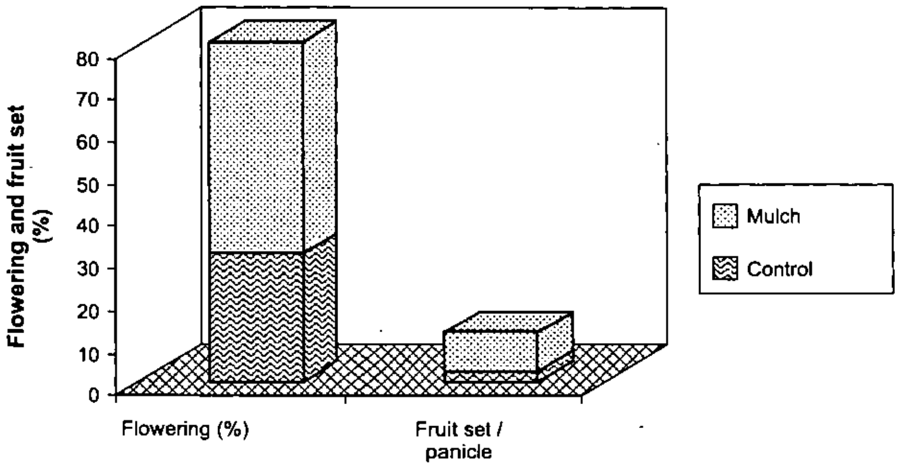


Fig 17a. Response of mulching on flowering and fruit set in mango cv. Chausa

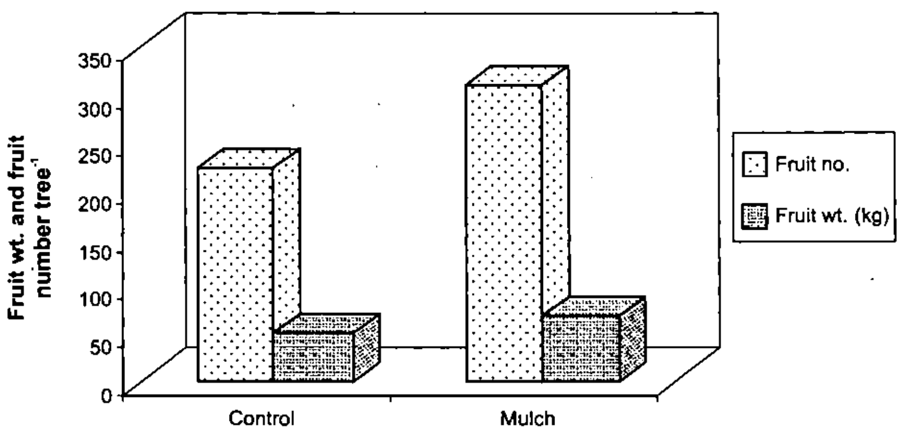


Fig 17b. Response of mulching on fruit number and fruit weight in mango cv. Chausa

Existing Nutrient Recommendations

Mango requires nutrients depending upon their age, 'off' and 'on' year, spread, pre-bearing and bearing stage. They may require two or more applications per year depending upon main seasons and irrigation schedule. Organics are also required for increasing bio-physical parameters of soil. Fertilizer recommendations are only guidelines and should be modified by growers according to local needs of their orchards. Placement of recommended dose of nutrient as given in Table 16 in 40 cm deep trench 2 meter away from the trunk in commercial cultivars of mango gives high yield under north Indian conditions.

Table 16. Existing nutrient recommendation for mango (Mangifera indica L.)

Age	FYM / compost	Nutrient dose tree^{-1}						Remarks
	(kg)	N (g)	P_2O_5	K_2O	$CuSO_4$	$ZnSO_4$	Borax	
1st year	10	100	50	100	25	25	-	Borax is applied from 5th year @125g tree^{-1} and increased by 25 g every year up to 10th year.
10th year and above	100	1000	500	1000	250	250	250	

Future Thrust

- Preparation and updating of thematic maps of macro and micronutrient deficiencies.
- To develop strategy for increasing nutrient uptake efficiency for improving quality production.
- The effect of rootstock in increasing nutrient use efficiencies needs thorough studies.
- Monitoring of micronutrient deficiency and to develop suitable models for forecasting emerging micronutrient availability and their transformation.
- The effect of rootstock in increasing nutrient use efficiency needs thorough studies.
- Strategy should be developed for integrated nutrient management for higher yield.

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Nutrient Management in Citrus Orchards of Himalayan Mid-hill Regions of India

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Abstract

Citrus belts along the northwest and northeast regions are the two premier citrus regions of India growing predominantly Kinnow mandarin and Khasi mandarin, respectively, with contrasting agropedological conditions and, therefore, warrant a different nutrient management strategy. In northwest citrus belts, large scale soil salinity/alkaline pH-induced multiple nutrient deficiencies are common in major soil orders viz., Entisols < Inceptisols < Aridisols. To combat these problems, micro-irrigation-based fertigation and site specific nutrient management with variable rate application, in addition to integrated nutrient management (involving organic manures, inorganic fertilizers and bioinoculants) backed up by combined use of growth regulators (2,4-D or GA_3) with micronutrient formulations as foliar fertilization are the plausible answers. On the contrary, the productivity of citrus orchards in northeast is limited by different magnitudes of sub-soil acidity-induced nutrient deficiencies on major soil orders viz., Alfisols < Ultisols < Inceptisols < Entisols. The problem is further intensified through cultivation on sloppy land, depleting soil fertility under the influence of high rainfall to varying proportions. Citrus orchards in this region need to be manured, pre-mixed with rock phosphate/basic slag on the pre-limed orchards to be established preferably on half moon terraces. Besides, all these changes, the major challenge lies in establishing the reasons for inconsistency in response to fertilization and modulating the quality production.

Keywords: Citrus, northwest, northeast, nutrient deficiency, nutrient management

Globally, citrus is the leading fruit crop, with a total production of 104.5 million tonnes (mt), with the maximum production of 32.6 mt in Asia followed by 25.8 mt in South America, 23.6 mt in North and Central America, 10.1 mt in Africa, 10.7 mt in Europe, and 0.61 mt in Oceania. Countrywise, Brazil tops the list with a production of 19.9 mt, followed by USA (14.1 mt), China (12.1 mt), Mexico (6.2 mt), Spain (5.9 mt), and India (5.7 mt) (FAO 2004). The commercial cultivation of citrus, is confined upto an altitude as high as 2400 m above mean sea level (MSL), but some of the ornamental species of citrus are grown upto 2800 m above MSL in the areas close to the equator. The highest quantum of production harvested globally comes from citrus growing in soils represented by the orders, Alfisol, Oxisol, Ultisol, Entisol, and Inceptisol with major 16 benchmark soil series of India (Table 1) represented by these soil orders only (Kohli and Srivastava, 1997; Srivastava and Kohli, 1999; Srivastava and Singh, 2002).

Table 1. Major benchmark soil series where citrus is grown in North-West and North-East India

Soil series	Citrus belt covered	Major soil great groups
Chinwali	Paui, Garwal, Almora, Pithoragarh, Dehradun	Ochrept, Orthent, Aquept, Fluvent, Aqualf, Udalf, Ustalf
Kalpa	Palampur, Kangra, Dhulakuan, Sirmour	Ustorthent, Udorthent,Udalf, Udult
Fatehpur	Ludhiana, Ferozpur, Hoshiarpur	Typic Ustipsamment, Aquept, Orthent, Ustochrept, Ustalf
Haldi	Nainital, Almora, Pithoragarh	Typic Hapludoll, Typic Eutrochrept/ Dystrochrept, Ustoll, Haplaquoll
Nabha	Patiala	Udic Ustochrept, Psamment,Orthent, Ochrept
Sadhugarh	Patiala	Vertic Ustochrept, Ustalf, Aquept, Ochrept, Psamment
Bijapur	Fatehpur	Udic Ustochrept, Orthent, Aqualf
Chomu	Jaipur, Sriganganagar	Typic Ustipsamment, Ustorthent, Ustochrept
Hanrgram	Pedong, Kurseong	Vertic Eutrochrept, Haplustalf, Ustochrept, Dystrochrept, Udalf, Udult
Lahangaon	Jorhat, Tinksukhia	Aquic Udifluvent,Udorthent, Udochrept, Aquevt, Ustalf, Paleudalf, Ochraqualf, Eutrochrept, Udipsamment, Fluvaquent, Udifluvent,
Gemotali	Siang (Arunachal Pradesh)	Typic Hapludalf, Hapluquent, Haplaquent, Haplustalf
Dialong	West district (Mainpur)	Ultic Hapludalf, Udic Hapludalf,Typic Paleudalf, Paleudult/Hapludult
Phullen	Mizoram	Lithic Udorthent, Typic Dystrochrept, Paleudult, Hapludult
Gemotali	Siang (Arunachal Pradesh)	Typic Paleudalf, Hapludalf, Rhodustalf, Hapludult, Haplaquoll
Jiraina	West district (Tripura)	Ultic Hapludalf, Udic Hapludalf, Typic Paleudalf, Typic Paleudult, Hapludult
Selsekgiri	East Khasi hills, Tura Garo hills (Meghalaya)	Umbric Dystrochrept, Hapludult, Paleudult, Dystrochrept, Palehumult, Lithic Udorthent, Haplaquoll, Typic Hapludalf, Udorthent, Palehumult

Source: Srivastava and Singh (2002)

Like any other fruit crop, the performance of citrus is constrained by variety of soil fertility and plant nutrition-based factors. Diagnosis of nutrient constraints and their efficient management are the two pillars of successful citrus nutrition program. The necessity of balanced nutrition has to be, hence, viewed from the angle of striking a balance of nutrient demand between above ground canopy and underground root volume. Since there is a large variation in cultivation practices between northwest and northeast citriculture, the former involves heavy expenditure on fertilizers using Kinnow mandarin as major commercial citrus cultivar, while latter largely practising Khasi mandarin of seedling origin, is claimed to be organic by default. Various issues pertaining to nutrient management are discussed with reference to two major citrus growing belts viz., northwest India and northeast India.

Occurrence of Nutrient Constraints

Reduced production in citrus orchards due to occurrence of different types of nutritional disorders is a common feature in northwest India due to colossal gap between the amount of nutrients added and that what removed annually by the crop (Dey and Singha, 1998; Srivastava and Singh, 2003b; 2004a). In sweet orange belts of Marathwada region of Maharashtra, disproportion in exchangeable cations was observed to be the major cause of citrus decline. The mean exchangeable-Ca^{2+} was observed to be higher (33.8 me 100 g^{-1}) under healthy trees compared to declining Nagpur mandarin trees (29.2 me 100 g^{-1}) established on Entisol, Inceptisol and Vertisol soil orders (Srivastava and Singh, 2004b).

Northwest citriculture

The major area and production in northwest India emerged from Punjab where citrus is grown under wide ranging climate and soils (Table 2). Soil factors such as high pH, presence of hard pan in subsoil, free lime, deteriorated soil structure (Kanwar and Randhawa, 1960; Kanwar and Dhingra, 1961; Shome and Singh, 1965; Chohan, 1966; Randhwa *et al.*, 1966; Dhingra *et al.*, 1966; Dutta and Bhambota, 1967; Munshi *et al.*, 1979; Yamadagni *et al.*, 1983) and their integrated effect leads to chlorosis induced (Dhingra *et al.*, 1965) decline in productivity. These features are very much evident from data presented in a representative soil profile (Table 3).

Table 2. Climate and soil characteristics of citrus belts of Punjab

Citrus regions	Climate features			Soil types
	Annual rainfall (mm)	MAST (°C)	LGP (days)	
Dry sub-humid/moist sub-humid covering Gurdaspur, Hoshiarpur and Ropar	900-1500	22	150-210	Typic Udorthents, Typic Udipsamments, Typic Eutrochrepts, Dystric Eutrochrepts, Fluventic Eutrochrepts
Dry sub-humid, northern plain with alluvium derived soils covering southern parts of Gurdaspur, Hoshiarpur, Jallandhar etc.	800-900	22	120-150	Typic Ustipsamments, Typic Ustifluvents, Typic Ustorthents, Typic Ustochrepts, Udic Ustochrepts, Fluventic Ustochrepts
Semi arid, northern plain alluvian derived soils covering northern parts of Firozepur, Faridkot, Bathinda and Sangrur	500-800	24	90-120	Udic/Fluventic Ustochrepts, Vertic Ustochrepts, Typic Haplustalfs, Typic Ustifluvents
Arid western plain with desert soil covering southern parts of Firozepur and Faridkot	400-500	25	60-90	Ustic Torripsamments, Ustochreptic Camborthids, Ustochreptic Calciorthids

MAST and LGP stand for mean annual soil temperature and length of growing period, respectively
Source: Sidhu *et al.* (1995)

Table 3. Typical soil profile representing soil series (Nihal Khera Series) and taxonomically classified as imperfectly drained Typic Calciorthid

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH	EC ($dS\ m^{-1}$)	O.C. (%)	$CaCO_3$(%)		Total bases ($me\ l^{-1}$)
							>2 mm	<2 mm	
0-10	65.1	30.0	15.3	8.1	0.18	0.43	0.0	4.1	6.91
10-33	60.5	33.0	27.3	8.2	0.10	0.38	0.0	5.0	7.71
33-56	65.6	35.8	18.0	8.1	0.22	0.31	0.0	8.0	7.62
56-76	62.4	34.8	14.4	8.3	0.15	0.35	5.0	9.0	7.42
76-147	58.4	40.6	13.3	8.3	0.10	0.36	26.0	13.5	6.90
147-186	82.8	12.5	6.0	8.5	0.10	0.15	-	4.3	5.20

Source: Sehgal *et al.* (1992)

Kanwar and Randhawa (1960) suggested that inadequate drainage is one of the important factors responsible for citrus decline in Punjab. Occurrence of lime concretion layer upto 75 cm of soil surface or within the feeding zone of plants also contributed significantly to the citrus decline due to restricted root development. Randhawa *et al.* (1961) observed reduced availability of Mn in soil with increase in $CaCO_3$ content. Kanwar *et al.* (1963) observed low calcium content in the leaves of declining/chlorotic citrus trees. A survey of citrus orchard soils of Sangrur district of Punjab showed poor growth of citrus in the soils having accumulation of clay and free lime at 30-150 cm. Such soils are friable when wet but extremely hard when dry. These structural changes are supposed to be the contributory factors for citrus decline (Chadha, 1966). Dhingra *et al.* (1965) observed that the soils of citrus orchards of Hissar, Ferozepur and Bathinda are light textured and low in N, Zn and Fe. They further observed that the soils of Nihal Khera series are more calcareous and are prone to deficiency of Fe and Zn, while those of Khepan series possess unfavourable salinity.

Studying the leaf nutrients status in healthy and declining sweet orange trees in Punjab, Mann *et al.* (1979) reported no significant difference between healthy and declining trees for P, Mg, Fe, Mn, and B. But the differences were significant for N, K, Cu, and Zn. The N and Zn were deficient to low in healthy as well as declined trees. The other nutrients viz., P, Ca, and Mg were low to optimum and K, B, Cu, Fe and Mn were optimum to high in most of the other orchards regardless of the tree conditions. Nutritional status of sweet orange orchards of Abohar and Bathinda of Punjab showed a large scale deficiencies of Zn, Cu, Mn and P in 97%, 44%, 18% and 22% orchards, respectively (Sekhon *et al.*, 1983).

Horizonwise analysis (Table 4) of soil profile of sweet orange orchard at Bathinda indicated that different horizons had deficient level of Cu, Zn and Fe and high level of K (Mann and Sidhu, 1983). Nutritional survey of mandarin orchards of Abohar (Punjab), Ganganagar (Rajasthan) and Delhi indicated optimum status of leaf Mn content (Nair *et al.*, 1968). The N content in leaves of healthy plants was markedly higher than those of chlorotic ones (Randhawa, *et al.,* 1967; Nijjar and Singh, 1971). Generally, chlorotic leaves were deficient in N. But the fact that some of the chlorotic plants also showed either optimum or high N level, dose not permit a generalization that low N supply was causing the malady. The average concentration of P in the mildly and severely chlorotic leaves was invariably high. The unfavourable influence of P and Zn availability is well known. There was no obvious relationship between K concentration versus chlorotic condition and chlorosis versus Mn and Cu in citrus leaves (Nair *et al.*, 1968). Singh and Sharma (1983) observed significant correlation of total S and sulphate S content with organic carbon content of soil in citrus orchards of Agra region of Uttar Pradesh. Another study from the same region involving analysis of leaf and soil samples collected from healthy and chlorotic orchards showed that chlorosis of sweet orange in Agra region of UP is mainly due to Zn deficiency caused by antagonistic effect of Fe on Zn availability (Singh and Tripathi, 1985).

Table 4. Physico-chemical properties of sweet orange orchard at Bathinda, Punjab

Depth (cm)	pH (1:2)	EC (dS m^{-1})	$CaCO_3$ (%)	Organic carbon (%)	Available		DTPA extractable micronutrients			
					P	K	Zn	Cu	Mn	Fe
					(mg kg^{-1})					
0-15	8.8	0.20	3.7	0.45	15	400	0.36	0.70	3.70	3.30
15-30	8.7	0.30	2.2	0.40	14	350	0.25	0.62	3.00	2.30
30-60	8.7	0.20	2.2	0.40	13	340	0.14	0.60	2.20	1.80
60-90	8.5	0.20	2.5	0.41	8	310	0.16	0.55	2.40	2.60
90-120	8.5	0.20	3.7	0.38	5	305	0.10	0.53	2.60	2.60
120-150	8.4	0.40	1.5	0.36	5	300	0.09	0.54	1.90	2.50
150-180	8.4	0.30	1.8	0.34	4	305	0.09	0.55	2.00	2.50

Source: Mann and Sidhu (1983)

Citrus growing soils of Hoshiarpur, parts of Jallandhar, Faridkot, Ferozepur and Bathinda are sandy to sandy loam in texture, low in N, P and Zn medium in K and alkaline pH (7.0-9.0) with $CaCO_3$ concentrated in sub-surface. Based on soil analysis, Dhatt (1989) observed medium level of available K in Kinnow mandarin growing soil of Hoshiarpur, parts of Jallandhar, Faridkot, Ferozepur and Bathinda. The survey of fertility status of citrus growing soils of Ferozepur district of Punjab revealed the minimum organic carbon (0.18%) and available P (5 mg kg^{-1}), whereas in Fazilka and Nihal Khera orchards, the available K ranged from 13.3 to 212.1, mg kg^{-1} (Dhillon and Dhatt, 1988).

Mineral nutrient status of citrus orchards of Nurpur area of Himachal Pradesh showed higher N in healthy (1.86%) than in declining (1.63%) orchards without any significant difference with regard to P concentration. The leaf K status on the other hand, was higher in declining (0.58%) than in healthy (0.50%) orchards. All the nutrients except Mn (28.2-33.0 mg kg^{-1}), P (0.14-0.15%), Ca (5.31-5.67%), Mg (0.43%), Fe (180-201 mg kg^{-1}) and Mn (28.2-33.0 mg kg^{-1}) irrespective of healthy or declining status, were observed to be deficient (N 1.63-1.86%, K 0.50-0.58%, Cu 4.0-4.7 mg kg^{-1}, and Zn 15.2-16.3 mg kg^{-1}). Survey of citrus orchards by Rana *et al.* (1984) showed the order of deficiency of different nutrients in form of: Zn>Ca>N>Mg>K. On an average, frequency distribution of different nutrient constraints were observed to be: optimum in Zn (75%), Ca (37%), Mg (28%), Mn (3 %) and K (1%). Whereas, 69% of orchards were high in K (mean 2.50%), 58% in P (mean 0.14%) and 65% in Fe (mean >120 mg kg^{-1}). Some orchards (33%) had excess Fe (> 200 mg kg^{1}).

In citrus orchards of Dhaulkuan in Sirmour district of Himachal Pradesh, Raina (1988) observed that soils were medium to high in available K and sufficient in Cu and Fe deficient in Mn and Zn. Later, Sharma and Mahajan (1990) observed optimum available N (75-180 mg kg^{-1}), low P (2-6 mg kg^{-1}), K (49-69 mg kg^{-1}) and Mn (1.1-2.1 mg kg^{-1}), optimum in Ca (532-964 mg kg^{-1}) and Mg (469-745 mg kg^{-1}), low to high in available Zn (0.9-1.5 mg kg^{-1}) and high in Cu (1.2-2.2 mg kg^{-1}) and Fe (4.8-10.2 mg kg^{-1}) in Kinnow mandarin orchards soils upto 90-120 cm in Nagpur-Indora area of Himachal Pradesh. Singh and Tripathi (1985) observed large scale Zn deficiency in sweet orange orchards of Agra region of Uttar Pradesh. In these orchards, available Fe, Mn, Zn and Cu were observed to vary from 1.68 to 25.2 mg kg^{-1},7.2 to 32.0 mg kg^{-1}, 0.84 to 5.84 mg kg^{-1} and from 0.5 to 2.4 mg kg^{-1}, respectively. All the micronutrients in soil properties correlated significantly with organic carbon content of soil.

Average concentration of most of the nutrients was low in leaves of declining Kinnow plants during May and September (Saini *et al.*, 1999). The average concentration of leaf N in healthy and declining plant was optimum at Abohar (2.41%), but deficient (2.26%) at Hoshiarpur during mid May due to low to deficient level of N in orchard soil. The leaf P level was optimum at both the locations (0.16% at Abohar and 0.12% at Hoshiarpur), considering healthy as well as declining types of plants. Likewise, mean leaf K was optimum (1.61%) at Abohar and deficient (0.97%) K at Hoshiarpur. Among the micronutrients, Zn (11.7-13.2 ppm), S (0.10-0.13%), and Ca (2.2-2.4% in leaf) were highly deficient with optimum Fe (72.2-80.2 mg kg^{-1}) and Mn (36.5-150.0 mg kg^{-1}).

Northeast citriculture

A vast majority of citrus orchards, especially the Khasi mandarin are seedling in origin. The region is characterised by steep to very steep slopes in Arunachal Pradesh, Sikkim, Nagaland, Manipur, Mizoram and Tripura and gentle slopes in Assam valley through which flow Brahmaputra and its tributaries. The region falls under high rainfall areas, with Cherapunjee plateau receiving over 400 cm during monsoon season. The temperature varies from 0°C in Himalayan range to 35°C in some parts of Tripura. In the past, several attempts have been made to establish the possible causes of citrus decline. Most of the problems of northeast citrus is low soil pH related (Sharma *et al.*, 2006). As high as 22.1% soils are strongly acidic (soil pH < 4.5), 40.3% soils moderately acidic (pH 4.5-5.5), 19.5% soils slightly acidic (pH 5.5-6.5) and other 13.0% soils are non-acidic (pH > 6.5).

During the first nutritional survey, Ramamurthy and Desai (1946) observed large scale Fe toxicity in the declining citrus orchards. Thereafter, the deficiency of Zn, B and Ca has been reported by many workers as one of the causes of citrus decline (Choudhary and Dutta, 1950; Choudhary, 1954; Dutta, 1959). Ghosh *et al.* (1982) after reviewing the citrus decline problems of north-east region suggested foliar application of Zn, Cu, Mn and B with soil application of dolomite once in two-three years. Prasad and Ghosh (1976) recorded the soil pH of citrus orchards to vary between 4.7 to 5.8. Under such soil pH values, application of dolomite is mandatory to maintain the favourable soil pH and physical condition of soil. The heavy loss of top fertile soil year after year from unterraced sloppy citrus orchards under the influence of high rainfall depleted the fertility and contributed significantly to the citrus decline (Ghosh, 1978). The characteristics features of a typical soil profile, Mwyanram series reveal some of the prominent soil features under which Khasi mandarin is grown (Table 5).

Table 5. The typical soil profile characteristics of a soil under Khasi mandarin (Mwyanram series) on well drained Typic Haplumbrept

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	O.C. (%)	pH	CEC (me 100 g^{-1})	Exch. base (me l^{-1})	Exch. Al. (me l^{-1})
0-25	19.5	40.0	40.0	3.41	5.1	28.0	21.0	7.0
25-65	20.0	20.0	60.0	1.20	4.4	15.0	12.3	2.3
65-125	24.9	18.6	57.5	1.37	4.0	15.4	9.6	3.7
125-200+	36.0	20.0	44.0	0.30	4.5	16.6	7.3	7.3

Soil suitability appraisal of citrus was carried out by Maji and Singh (2002) in Meghalaya state. A total 24 mapping units belonging to 4 orders, 14 grade groups and 25 sub groups most of the soil units like comprising Typic Kandiudults, Typic Haplohumults, Typic Kandihumults, Umbric Dystrochrepts, Typic Palehumults, Aquic Eutrochrepts, Humic Hapludults, Umbric Dystrochrepts were interpreted as moderately suitable. While other soil unit like Typic Udorthents and Pachic Haplumbrepts, were diagnosed marginally suitable for citrus. Interestingly, soils qualifying for same sub-groups rated differently due to variations in land characteristics which affect the land use requirement for citrus, with Ultisol showing better suitability for citrus over Entisols or Inceptisols.

Investigation on healthy and declining *Khasi* mandarin orchards in the hill regions of Assam, India, by Dey and Singha (1998) showed that soils were acidic (pH 4.4-6.0) and deficient in available P_2O_5(1-16 kg ha^{-1}). The EC was low (0.030-0.406 dS m^{-1}). Most of the soils had high organic matter content to a depth of 45 cm (1.5-6.0%). Available N and K_2O were medium to high in the surface layer (220-568 and 246-820 kg ha^{-1}, respectively) and low to high in the sub-surface (112-517 and 122-651 kg ha^{-1}, respectively). Foliar K was regulated by the ratio of K : Ca + Mg or K : Mg in soils in the North Cachar Hills, and by N : Ca in Karbi Anglong. Foliar Ca was regulated by soil concentration ratio of K : Mg in both locations. Low Ca availability in soil (> 288 kg Ca ha^{-1}) and foliar Ca : Mg (ratio of > 8.70) were observed in healthy orchards in the North Cachar Hills. The nutritional survey carried out by Prasad and Ghosh (1976) and Ghosh *et al.* (1982) indicated nutrient deficiency of B, Fe, Zn and Ca.

On the basis of data recorded on leaf nutrient status of mandarin orchards located in important belts of states like Meghalaya, Sikkim and Arunachal Pradesh were observed to be low to deficient in Ca and Zn and sufficient in Fe (Ghosh and Singh, 1993). Analysis of leaf samples of Sikkim mandarin representing Bermiok, central Pandam, Nazitam, Namthang, Sang and Sumin of Sikkim state showed that 69% orchards were deficient in N, and concentration of P in most of the orchards was within optimum range with K being high in 57% orchards. As many as 80% orchards were optimum in Cu and Fe. According to Gupta and Prasad (1989), the soils of Sikkim are optimum in available micronutrients. While other studies by Patiram *et al.* (2000) reported that 30-35% orchards were deficient in Zn (< 25 mg kg^{-1}) and Mn (< 25 mg kg^{-1}). All the measured soil properties showed the negative relationship with leaf micronutrient cation which was significant for organic carbon (r = -0.269 to - 0.481) and Zn with pH only below 0-20 cm depth (r = - 0.352 to - 0.393). The values of R^2 improved substantially from 0.031 to 0.639, 0.137 to 0.647, 0.069 to 0.462 and from 0.130 to 0.657 when soil properties viz., clay, organic carbon, pH and exchangeable $Ca^{2+} + Mg^{2+}$ along with available micronutrient Zn, Cu, Mn and Fe of three depths, were taken into consideration for predicting the concentration of different nutrients in Khasi mandarin leaves.

A survey was conducted by Singh *et al.* (1998) to study the nutrient status of soil and leaves of the Khasi mandarin orchards in Meghalaya, India. Soil pH, organic carbon, available P, Ca, Mg, K, Cu and Mn were greater in the surface (0-15 cm) than in the subsurface (15-30 cm). Orchard soils were acidic with poor availability of cations (K^+ 0.09-1.02 me 100 g^{-1}, Ca^{2+} 0.20-7.00 me 100 g^{-1} and Mg^{2+} 0.10-4.50 me 100 g^{-1}) and P (1.0-8.4 mg kg^{-1}), an optimum level of micronutrients (DTPA Fe 4.0-63.0 mg kg^{-1}, Mn 0.5-68.3 mg kg^{-1}, Cu 0.1-8.0 mg kg^{-1} and Zn 0.5-14.0 mg kg^{-1}). Leaf nutrient status indicated that most of the orchards were low in N (2.19%) and Ca (2.33%) and a few were low in P (<0.11%) and Mn (<25 mg kg^{-1}), whereas the concentration of K (0.74-2.53%), Mg (0.30-1.59%), Zn (14.0-218.0 mg kg^{-1}), Cu (13.0-180.0 mg kg^{-1}) and Fe (15.0-182.0 mg kg^{-1}) were in optimum to excess range. Availability of nutrients in the soil did not bear any relation to their leaf status.

Recently, the entire stretch of northeastern citrus belts were surveyed. Using the soil/plant nutrient diagnostics developed earlier for soil fertility and leaf nutrient standards. Ca was observed low in as many as 85% orchards followed by Mg (83.3%), P (74.1%), Cu (33.3%), and K (20.3%). While using the leaf analysis norms, most of the orchards (79.7-82.4%) were low in Ca (1.82-2.42%) and Mg (0.22-0.42%) (Table 6). Phosphorus was low (0.09-0.10%) in as many as 81.5% orchards on account of most of the readily available P being fixed as Fe- and Al-phosphates. Soils in the region being highly acidic in nature, the slow release source of P like rock phosphate or basic slag hold promise.

Table 6. Frequency distribution (%) of nutrient constraints through analysis of soil fertility and leaf nutrient composition (n = 108) in 9 states of east/ northeast India

Nutrient	Soil fertility constraints			Leaf nutrient constraints		
	Low	Optimum	High	Low	Optimum	High
N	14.8	55.5	29.7	48.1	22.2	29.7
P	74.1	85.5	7.4	81.5	14.8	3.7
K	20.3	70.4	9.3	27.8	64.8	7.4
Ca	85.2	14.8	-	79.7	20.3	-
Mg	83.3	16.7	-	82.4	17.6	-
Fe	-	3.7	96.3	-	1.8	98.2
Mn	13.0	18.5	68.5	22.2	25.9	51.8
Cu	33.3	20.4	46.3	44.5	18.5	37.0
Zn	7.4	9.3	83.3	77.8	16.7	5.5

Source: Srivastava and Singh (2006)

Management of Nutrient Constraints

There are three approaches to fertilizer recommendations that are widely used: the deficiency correction approach (from research on crop response to nutrient additions to the point of maximum economic yield), maintenance concept (aims to maintain soil fertility level slightly above the point of maximum economic yield), and nutrient removal or balanced approach (tries to return to the soil what is removed by the crop to maintain productivity, but often over-recommends nutrient need, since it does not take into account of the soil's ability to supply available nutrients to plants over time). An optimum supply of nutrients is aimed to meet the conditions that all nutrients are available in quantities which exclude the possibility of absolute deficiency or excess as to exclude any deficiency as no nutrient works independent to each other.

Fertilizer programs for citrus are determined by several criteria. These are: surveys, growers' experience, following the fertilization program of high yielding orchards (Chundawat *et al.*, 1991), replacing the amount of nutrients removed in fruits, deficiency symptoms (Singh and Tripathi, 1985; Srivastava and Singh, 2003c), applying results from sand culture (Chapman, 1949) and field experiments (Srivastava and Singh, 2003c). Each one of these has certain advantages and limitations. But, common of all these studies is to address the balanced plant nutrition vis-à-vis sustained quality production.

There are two basic philosophies of fertilizer management, one is based on fertilizing the crop and other on fertilizing the soil.

Foliar fertilization

Foliar sprays are useful to maintain optimum nutrient concentration in the plant during the growing cycle by optimising the movement of nutrients. Foliar fertilization is better than conventional soil fertilization, (i) in soils having an acute shortage of nutrient supply, (ii) nutrients either due to their total absence or due to trace concentration, are immobilized on account of unfavourable soil conditions, (iii) under soil nutrient imbalances i.e. having an unfavourable influence on root absorption for an optimal growth and (iv) restricted nutrient uptake through the plant roots (Dixit *et al*., 1979; Srivastava and Singh, 2003a). All these advantages of foliar application of nutrients render it to be highly effective, quick in response, convenient in application and avoid any nutrient toxicity in soil. Some of the earlier work done on northwest citrus have revealed correction of chlorotic condition and dieback by spraying micronutrients as Zn and Cu (Dikshit, 1958), Zn Fe and B (Choudhary, 1954), Zn Cu and Fe (Kumar and Sharma, 1960) and Zn and Fe (Sandhu *et al*., 1970). Kanwar and Dhingra (1961) earlier observed that treatment with Zn followed by Zn + Fe or Mn was most effective in reducing the intensity of chlorosis, whereas Cu and Fe sprays without Zn were not so effective.

The disadvantage of foliar application is that the effects of sprays are temporary and are not carried forward into the next year. Maximum efficiency of foliar applied nutrients can be obtained only when there is a maximum concentration of root absorbed nutrients. For example, Swietlik and Zhang (1994) observed zinc foliar sprays less effective than Zn applications to the roots in alleviating severe Zn deficiency because foliar absorbed Zn was not translocated from the top to the roots. The study further suggested two mechanisms operating at two tiers of structural organisations viz. one in the roots and the other in the shoots.

There are certain nutrients whose demand in initial crop growth stages is high, e.g. K is one such nutrient. Studies have shown that maximum accumulation of K in leaf takes place by the end of fruit set stage, thereafter the rate of K accumulation in leaf is considerably slow (Srivastava *et al*., 1998), suggesting to continue foliar application of nutrients up to period, the wax deposition on leaf cuticle has not thickened enough to check absorption of nutrient by leaves. Various recommendations emerging out of foliar application of nutrients are reported in Table 7.

Table 7. Foliar spray recommendations of various macro- and micronutrients for various cultivars grown in northwest and northeast India

Foliar spray	Cultivar sp.	Source
N (1.5% urea)	Kinnow mandarin	Kannan *et al.* (2002)
Urea (2%) - KNO_3 (2.0 %)	Kinnow mandarin	Gill *et al.* (2005)
KNO_3 (2%)	Sweet orange	Feungchan and Sharma (1974)
$FeSO_4$ - $ZnSO_4$ (0.5% each)	Kinnow mandarin	Dixit *et al.* (1979)
$ZnSO_4$ (0.5%) - Borax (0.2%)	Kinnow mandarin	Singh and Misra (1980)
Zn (0.5%) - B (0.4%)	Kinnow mandarin	Mishra *et al.* (2003)
$ZnSO_4$ (0.5%) - $CuSO_4$ (0.25%)	Kinnow mandarin	Mann and Sidhu (1983)
$ZnSO_4$ (0.1%) - $CuSO_4$ (0.1%)	Kinnow mandarin	Sharma (1990)
$ZnSO_4$ (0.3 - 0.6%)	Kinnow mandarin	Mann and Takkar (1983)
B (0.2 - 0.6%)	Kinnow mandarin	Singh and Singh (1976)
$ZnSO_4$ (0.5%) - Borax (0.2%)	Kinnow mandarin	Singh and Misra (1980)
Zn - Cu - K (0.25% each)	Wilking mandarin	Singh and Chohan (1982)
$ZnSO_4$ (0.5%) - $MgSO_4$ (0.5%) - $MnSO_4$ (0.5%)	Khasi mandarin	Dhinesh Babu and Yadav (2005)
$FeSO_4$ (0.25%) - $MnSO_4$ (0.05%) - $CuSO_4$ (0.25%) - $ZnSO_4$ (0.05%) - $MgSO_4$ (0.05%)	Mosambi sweet orange	Desai *et al.* (1991)
Zn - EDTA (0.5%)	Mosambi sweet orange	Dube and Saxena (1971)
$ZnSO_4$ (0.3%) - $CuSO_4$ (0.6%)	Sweet orange	Anand *et al.* (1969)
$ZnSO_4$ (0.5% each) - urea (1%)	Mosambi sweet orange	Gupta and Prasad (1989)
$ZnSO_4$ (0.5%) - B (0.2%) - Fe (0.4%)	Sweet orange	Ghosh and Besra (2000)
$ZnSO_4$ (0.5%) - Borax (0.5%)	Sweet orange Jaffa	Kaur *et al.* (1990)
$ZnSO_4$ (0.6%) - 2, 4 - D (20 mg kg^{-1})	Kagzi lime	Singh and Misra (1986)
$ZnSO_4$ (0.5%) - K_2SO_4 (4%)	Kagzi lime	Singh *et al.* (1989)
$ZnSO_4$ (0.5%) - urea (1.5%)	Kagzi lime	Rathore and Chandra (2001)
Borax (0.2 - 0.6%)	Kagzi lime	Singh and Singh (1976)
$ZnSO_4$ (0.5%) - $CuSO_4$ (0.3%) - Borax (0.3%)	Kagzi lime	Singh *et al.* (1990)
Zn - EDTA (0.4%) - Cu - EDTA (0.2%)	Seedless lemon	Sharma *et al.* (1999)

Soil fertilization

The response of nitrogen fertilization in improving the growth, yield and quality of different citrus cultivars is well recognized under different agroclimatic regions of India (Table 8).

Table 8. Macronutrient recommendations for various cultivars of northwest and northeast India

Doses of application	Cultivar	Source
400 kg N - 200 kg K_2O ha^{-1}	Kinnow mandarin	Sharma (1990)
400 g N - 256 g P $tree^{-1}$	Kinnow mandarin	Shukla *et al.* (2004)
800 g N - 200 g P_2O_5 - 400 g K_2O $tree^{-1}$	Kinnow mandarin	Mann and Sandhu (1988)
600 g N - 200 g P_2O_5 - 200 g K $tree^{-1}$ (soil application) - 0.4% Cu - 0.5 % Zn (foliar spray)	Kinnow mandarin	Kar *et al.* (1988)
400 g N $tree^{-1}$ - urea (1.5% foliar spray) - $ZnSO_4$ (0.5% foliar spray)	Kinnow mandarin	Ram and Bose (1988)
400 g N - 100 g P - 200 g K $tree^{-1}$	Kinnow mandarin	Kumar *et al.* (1998)
450 g N - 300 g P - 300 g K $tree^{-1}$	Kinnow mandarin	Lal (1998)
1 kg N - 0.5 kg P - 0.5 kg K $tree^{-1}$	Kinnow mandarin	Gilani *et al.* (1989)
300 g N - 250 g P_2O_5 - 300 g K_2O $tree^{-1}$	Khasi mandarin	Ghosh *et al.* (1989)
600 g N - 300 g P_2O_5 - 600 g K_2O	Khasi mandarin	Borah *et al.* (2001)
N (400-800 g $tree^{-1}$)	Sweet orange	Govind and Mosambi Prasad (1976)
500 g N -100 g P_2O_5 - 400 g K_2O $tree^{-1}$	Sweet orange Mosambi	Ghosh (1990)
500 g N - 100 g P_2O_5 - 400 g K_2O $tree^{-1}$	Sweet orange	Ghosh (1990)
100 g N - 50 g P_2O_5 - 50 K_2O $tree^{-1}$	Sweet orange	Sharma and Azad (1991)
400-1200 kg N - 200 kg P_2O_5 ha^{-1}	Sweet orange	Sharma *et al.* (1993)
900 g N - 300 P_2O_5 - 300 g K_2O $tree^{-1}$	Sweet orange	Monga *et al.* (2002)

The researchers are not unanimous about the efficacy of soil versus foliar fertilization with reference to micronutrients. Elevating Zn concentration only in the tops of Zn-deficient plants with foliar sprays partially restored the normal root growth, but clearly was not as effective as the roots absorbing Zn directly from high Zn concentration solutions. This observation suggested the involvement of two mechanisms operating at different levels of structural organization: one in the roots and the other in the shoots (Swietlik and Zhang, 1994). The micronutrient-based Zn chelater complexes are poorly or not at all absorbed by plant roots, as demonstrated through water culture studies (Swietlik and Zhang, 1994). While, under field conditions, however, the addition of Zn micronutrient-chelate may elevate the amount of free nutrients in the soil solution due to adsorption and exchange properties of minerals present in soil. Soil application of micronutrient, e.g., Zn from $ZnSO_4$ is fixed in the surface soil, while the chelated-Zn remain soluble and get distributed evenly throughout the soil, as evident from 46-times higher uptake of Zn from Zn-EDTA than $ZnSO_4$ on sandy soils (Parker *et al.*, 1994). The studies carried out in the past have, shown some diversity in optimum dose of micronutrients due to difference in nutrient supplying capacity of soil conditioned by soil properties, nutrient requirement by specific crop, region specific cultural practices and the agro-climate (Table 9).

Table 9. Micronutrients recommendations as soil application for various cultivars of northwest and northeast India

Fertilizer dose	Cultivar	Source
$ZnSO_4$ (250 - 1000 g tree^{-1})	Kinnow mandarin	Nijjar and Brar (1977)
Borax or Boric acid (1 kg ha^{-1})	Coorg mandarin	Srivastava *et al.* (1977)
Fe - Zn (15-30 kg ha^{-1})	Sweet orange	Jadhav *et al.* (1979)
$ZnSO_4$ (500 g tree^{-1})	Blood red	Khera *et al.* (1985)
Fe - EDDHA - Zn - EDTA (35 g tree^{-1} each)	Trifoliate orange	Bakhshi *et al.*(1973)
$ZnSO_4$ - K_2SO_4 (0.5% foliar spray) - K_2O as K_2SO_4 (210 g tree^{-1} soil application)	Kagzi lime	Singh *et al.* (1989)
B (37.5-75.0 g tree^{-1})	Kagzi lime	Chanturiya (1972)

Fertigation

Low water (WUE) and fertilizer-use-efficiency (FUE) are amongst the major production related constraints (Srivastava and Singh, 2003a). Basin irrigation is widely used in citrus orchards, but it has several drawbacks in terms of conveyance, percolation, evaporation, and distribution losses, yet without much adverse impact on growth, yield and fruit quality. In light of growing scarcity of water and poor WUE under basin irrigation, micro-irrigation has gained wide application in citrus orchards, especially in kinnow orchards of northwest India. However, the efficacy of drip irrigation is often questioned, with respect to uniform development of root system within the rhizosphere.

Fertigation (application of nutrients through the irrigation) has produced better results in terms of improvement in tree growth, fruit yield, quality, the reserve pool of soil nutrients and consequently, the plant nutritional status (Shirgure *et al.*, 2003a). Besides the mobility of nutrients, fertigation has several advantages over broadcast application of granular fertilizers with respect to effective placement of nutrients and flexibility in application frequency, development of uniform root distribution in wetted zone, an important pre-requisite for better FUE, and improvement in fruit quality.

Irrigation at 20% depletion of available water content (AWC) combined with fertilizer treatment of 500 g N + 140 g P + 70 g K $tree^{-1}$ yr^{-1} produced a significantly higher magnitude of fruit yield per cubic metre of canopy in addition to higher nutrient status and fruit quality (Table 10) compared to other treatments involving irrigation either 10% depletion or 30% depletion of AWC with 600 g N + 200 g P + 100 g K $tree^{-1}$ yr^{-1} in 14-yr-old Nagpur mandarin (*Citrus reticulata* Blanco) on an alkaline calcareous Lithic Ustochrept soil type (Srivastava *et al.*, 2003). Field experiments on response of pre-bearing acid lime plants to differential N-fertigation versus circular band placement (CBP) method of fertilizer application showed superiority of former over latter treatments. The higher leaf N, P and K with 80% fertigation over 100% N through CBP further demonstrated that saving of N up to 20% can be attained (Shirgure *et al.*, 2001). In India the fertigation experiments on crop like citrus are very limited and most of the studies have emanated from National Research Centre for Citrus, Nagpur.

Table 10. Response of different drip irrigation and fertilizer treatments (fertigation) on Nagpur mandarin (*Citrus reticulata* Blanco) and Acid lime

Treatments				**Canopy Volume (m^3)	Yield (kg $tree^{-1}$)	Quality (%)			Leaf nutrients (%)		
Main	Sub										
	N	P_2O_5	K_2O			TSS	Acidity	Juice	N	P	K
Nagpur mandarin (1999-2002)											
Irrigation at 10% depletion of AWC* (I_1)	600	200	100	4.22	52.3	9.5	0.85	51.8	2.2	0.10	2.1
	500	140	70	4.38	57.5	9.7	0.87	52.2	2.2	0.14	2.1
	400	80	40	4.18	50.8	9.6	0.85	51.4	2.0	0.12	2.0
Irrigation at 20% depletion of AWC (I_2)	600	200	100	4.64	55.8	9.9	0.83	53.5	2.2	0.14	2.2
	500	140	70	5.12	74.2	10.2	0.72	55.5	2.5	0.18	2.4
	400	80	40	4.25	58.0	10.2	0.85	54.1	2.2	0.14	2.1
Irrigation at 30% depletion of AWC (I_3)	600	200	100	4.08	54.9	8.7	0.88	50.2	2.3	0.11	2.1
	500	140	70	4.15	65.7	8.9	0.85	52.3	2.2	0.12	2.2
	400	80	40	4.03	58.20	8.9	0.87	51.1	2.1	0.10	2.1
Irrigation at 40% depletion of AWC (I_4)	600	200	100	3.95	51.2	8.1	0.82	54.7	2.2	0.12	2.1
	500	140	70	4.02	61.2	9.2	0.84	52.0	2.1	0.10	1.9
	400	80	40	3.75	49.8	8.7	0.83	50.8	2.1	0.10	1.8
L.S.D.	Irrigation (I)			0.58	1.9	1.5	0.03	1.7	0.1	0.04	0.1
(0.05)	Fertigation (F)			0.23	3.2	NS	NS	1.2	0.1	0.02	0.1
	Interaction (I x F)			0.82	4.7	NS	NS	2.3	0.2	0.06	0.2
Acid lime (2000-2002)											
Irrigation at 10% depletion of AWC (I_1)	600	200	100	3.44	8.7	7.9	5.82	35.4	2.0	0.09	1.6
	500	140	70	3.56	9.7	7.9	6.11	36.3	2.1	0.10	1.8
	400	80	40	3.42	8.9	8.0	6.00	34.9	1.8	0.10	1.8
Irrigation at 20% depletion of AWC (I_2)	600	200	100	3.52	12.6	8.0	5.93	37.1	2.1	0.10	1.8
	500	140	70	3.78	11.3	8.0	6.26	38.1	1.9	0.14	1.9
	400	80	40	3.62	10.3	8.0	6.02	38.3	2.0	0.12	2.0

Irrigation at 30%	600	200	100	4.85	13.3	7.8	6.74	39.3	2.1	0.10	1.8
depletion of AWC	500	140	70	5.87	15.8	8.1	7.00	34.2	2.3	0.14	2.2
(I_3)	400	80	40	4.71	10.1	7.9	6.83	41.3	2.1	0.12	1.9
Irrigation at 40%	600	200	100	3.98	9.6	7.9	6.14	39.6	1.8	0.11	1.9
depletion of AWC	500	140	70	3.72	10.7	7.8	6.99	39.8	1.9	0.10	1.8
(I_4)	400	80	40	3.46	9.2	7.7	6.34	37.2	1.8	0.12	1.8
L.S.D.	Irrigation (I)			0.30	1.5	NS	0.11	1.5	0.1	1.53	0.2
(0.05)	Fertigation (F)			0.19	0.7	NS	0.05	0.5	0.1	0.48	0.1
	Interaction(I x F)			0.48	2.3	NS	0.21	2.3	0.2	2.32	0.2

*AWC stands for available water capacity of soil

**Canopy volume is expressed in increase over previous year

Source: Srivastava *et al.* (2003); Shirgure *et al.* (2003b)

Site Specific Nutrient Management

Knowing the required nutrients for all stages of growth and understanding the soil's ability to supply those needed nutrients are critical to profitable crop production. The recommendations on fertilizer application may not, however, produce the same magnitude of yield response when practised on an orchard of large area, because of its inability to accommodate variation in soil fertility status. Slight changes in the nature of soil, local climate and agronomic practices etc. may seriously affect the nutrient utilisation capacity of the plant. However, application of a single rate of nutrients may result in over-application of nutrients at some sites and under-application at others often lead to reduced FUE. Under such circumstances, site specific nutrient management is adopted in big orchards requiring variable precision application as per soil variability so as to improve the orchard efficiency (average yield of specified trees in relation to average orchard yield) in ultimate terms.

With new advances in technology, grid sampling for precision citriculture is increasing. The first step in the process is to divide large fields into small zones using a grid. Next, a representative location within the grid is identified for precision soil sampling. Grid sampling is integrated into commercial global positioning system (GPS) based soil sampling and nutrient-mapping that in turn uses a geographic information systems (GIS) to employ variable rate technology for fertilizer applications.

Variable rate fertilization

It is considered as a part of precision citriculture, and the most effective technique for rationale use of fertilizers, executed by matching the fertilizer rate with tree requirement on a per tree size basis. Site specific management of 17-year old Valencia grove (2980 trees) in Florida using automated sensor system equipped with differential global positioning system and variable rate delivery of fertilizers (135-170 kg N ha^{-1} yr^{-1}) on a tree size basis (0-240 m $tree^{-1}$), achieved 38-40% saving in granular fertilizers cost. While, conventional uniform application rate of 270 kg N ha^{-1} yr^{-1} showed that trees with excess nitrogen (>3%) had canopies less than 100 m^3 with lower fruit yield and inferior quality (Zaman *et al.*, 2005). In another long term experiment, the large fruit yield difference of 30.2 and 48.9 kg $tree^{-1}$ initially observed on shallow soil (Typic Ustorthent) and deep soil (Typic Haplustert) in an orchard size of 11 ha, reduced to respective fruit yield of 62.7 and 68.5 kg $tree^{-1}$ with corresponding fertilizer dose (g $tree^{-1}$) of 1200 N - 600 P - 600 K - 75 Fe - 75 Mn -75 Zn - 30 B, and 600 N - 400 P - 300 K - 75 Fe - 75 Mn -75 Zn - 30 B, suggesting the necessity of fertilizer application on variable rate application for rationality in fertilizer use (Srivastava *et al.*, 2006).

Analysis of tree size of 3040 trees space of 40-acre grove showed a skewed distribution with 51.1% trees having 25-100 m^3 $tree^{-1}$ size classes and a median size of 82 m^3 $tree^{-1}$. At a uniform fertilization rate of 240 kg N ha^{-1} yr^{-1}, the leaf N concentration of 12 trees with different canopy sizes that were randomly sampled in the grove showed optimal levels (2.4-2.6%) in the large trees and excess levels (> 3%) in the medium to small trees (Tucker *et al.*, 1995). From the regression line, trees with excess N had canopies < 100 m^3 $tree^{-1}$, and constituted 62% of the grove. Under such conditions, variable rate fertilization can, therefore, save production costs, reduce N leaching, and increase yields per variable acre (Schumann *et al.* 2003). A 30% saving in granular fertilizer cost was estimated for this 'Valencia' grove if variable N rates were implemented on a per tree basis ranging from 129 to 240 kg N ha^{-1} yr^{-1}. For comparison purposes, the eastern half of the grove received the full uniform rate of 240 kg N ha^{-1} yr^{-1}. No fertilizer was allocated by spreader to skips or resets of one-to-three year age. Due to a very restricted root system, new resets should be fertilized individually, usually by hand (Tucker *et al.*, 1995), ensuring that the granules are accurately placed adjacent to the tree. Application of variable fertilizer rate technology in this grove saved in nitrogen equivalent to the 32 to 43% reduction of N rates achieved through use of fertigation and foliar sprays of urea (Lamb *et al.*, 1999).

Integrated Nutrient Management

In the recent years, the nutrient additions have been exclusively in favour of mineral fertilizers. While the quick and substantial response of fruit yield to mineral fertilizers eclipsed the use of organic manures (Srivastava *et al.*, 2002; Srivastava and Singh, 2003b; 2005) the inadequate supply of the latter sources exacerbated this change. Integrated nutrient management (INM) is a comparatively recent concept which involves combined use of chemical fertilizers, organic manures and biofertilizers to achieve the sustainability in production from citrus orchards (Ghosh, 2000). The work on INM using citrus as test crop is very limited.

Maximum improvement in canopy volume, fruit yield and fruit quality were reported with 25 kg FYM + 400 g N + 150 g P_2O_5 + 300 g K_2O tree^{-1} yr^{-1} in Khasi mandarin on red acidic soil (Ghosh and Besra, 1997), 15 kg neem cake with 800 g N + 300 g P_2O_5 + 600 g K_2O tree^{-1} yr^{-1} in Sweet orange and by substituting, 50% of NPK with FYM in Coorg mandarin on red acidic soils (Mustaffa *et al.*, 1997). Huchche *et al.* (1998) observed that application of inorganic- N up to 800 g plant^{-1} yr^{-1} significantly increased the yield of Nagpur mandarin compared to farmyard manure alone in Typic Haplustert soil. Weight loss and decay during storage of Nagpur mandarin fruits for 12 days at 20-28^{0}C, 50-70% relative humidity and upto 80 days at 5-6^{0}C, 85-90% relative humidity further revealed no adverse effect of inorganic chemical-N upto 600 g plant^{-1} yr^{-1} supplemented with 200 g P_2O_5 and 100 g K_2O. Shelf life of fruits was not significantly better when fruits were grown with farmyard manure alone.

Cakes also serve to be a rich source of nutrients, both edible as well as non-edible cakes. Edible cakes seem to have much higher concentration of nutrients e.g. cotton seed or safflower cake. Combination of 15 kg neem cake and 800 g N + 300 g P_2O_5 + 600 g K_2O tree^{-1} year^{-1} proved most effective in improving various growth parameters, yield and cost-benefit ratio (1:2.14) in sweet orange (Tiwari *et al.*, 1997). The yield and quality of acid lime fruits were found to be significantly improved due to application of neem cake along with chemical fertilizers. Significantly higher yield with better quality fruits were obtained from the trees receiving 600 g N + 300 g P_2O_5 + 300 g K_2O 15 neem cake plant^{-1} yr^{-1} with maximum monitory returns per rupee investment than other treatment combinations (Ingle *et al.*, 2001). The application of 7.5 kg neem cake along with (g) 600 N + 300P + 600 K NPK plant^{-1} yr^{-1} produced the maximum yield and best quality of Khasi mandarin in the orchard of citrus growing belt of the Tinsukia district of Assam and sustained the soil productivity of the orchard at the optimum level (Borah *et al.*, 2001).

The response of 20 year old seedling trees of sweet orange cv. Sathgudi application of organic matter (castor cake) alone, inorganic alone and combination of both was studied by Seshadri and Madhavi (2001) in alkaline sandy loam soil. The results over a period of 6 years revealed that the maximum yield potential, cost benefit ratio with better fruit quality may be obtained by the balanced nutrition through organic (castor cake @ 7.5 kg) alongwith 400:150:300 g NPK plant^{-1} yr^{-1}. Application of pig manure at 110 kg tree^{-1} with urea-N 750 g tree^{-1} + K 650 g tree^{-1} recorded the highest fruit yield of Khasi mandarin (163.30 kg tree^{-1}) compared to control (91.80 kg tree^{-1}) on Alfisol (Dubey and Yadav, 2003).

Future Research

A strong urge is felt to explore the possibility of practising crop regulation through nutrient management to produce fruits throughout the year as per market requirements. An equally promising area is the improvement in post-harvest life of fruits by adequate fertilization, especially by K fertilization. Amongst different nutrients, Zn has attracted worldwide investigation from various angles. The role of Zn in flowering, fruit set, fruit quality and juice shelf life; models for predicting Zn-availability and its uptake for helping the management decision under different citrus-based cropping systems; and devising means for improved Zn-uptake efficiency through technology for application of nutrients to entire volume of roots in the soil and the foliage will further unravel many of the complexities involved with Zn-nutrition.

Impacts due to environmental changes and anthropogenic activity are the potential threats to the conservation of soil quality, while expanding the citriculture to marginal soils having a wide range of limitations. With the availability of more technical know-how on collective use of bulky organic manures, prolonged shelf life microbial bio-fertilizers, and chemical fertilizers coupled with information on substrate dynamics would ease out the intricacies involved with the nutrient acquisition and regulating the water relations to ultimately evolve a more effective integrated citrus production system in the background of effective citrus-based land use planning. The back-up support of modern tools of crop improvement like molecular biology and genetic engineering is equally imperative in developing the cultivar that would further maximise the quality production of citrus orchards on a sustained basis in terms of space and time. Open field hydroponic culture of citrus is gaining momentum where nature of soil as a growing medium has limited significance in crop raising in some of the countries like USA and Australia.

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Balanced Fertilization for Sustainable Yield and Quality in Tropical Fruit Crops

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Abstract

India needs to increase its fruit production and productivity which warrants judicious nutrient management. The need for balanced fertilization has been well documented in tropical fruit crops like mango, banana, citrus, papaya, pineapple and sapota. Integrated nutrient management studies conducted in these crops resulted in enhanced fruit yield and quality concomitant with saving nutrients also. Fertigation studies conducted in banana resulted in higher yield with quality fruit besides saving of nutrient, however, such studies are lacking in other fruit crops like mango, citrus, pineapple, sapota etc. The results of various studies on balanced fertilization in tropical fruit crops have been discussed.

Keywords: Tropical fruits, nutrition, balanced fertilization, yield, quality

India needs 92 million tonnes of fruits to have balanced nutrition for its 1000 million population. Although the country has achieved fairly good production level of fruits (43 million tonnes), it is hardly sufficient to meet only 46% of our country's requirement. This warrants increase in production and productivity of fruit crops in our country. Judicious nutrient management is often regarded as one of the important aspects to increase the productivity of horticultural crops particularly fruit crops. Efficient and rational use of the fertilizers is imperative not only for obtaining more yields per unit area on a sustainable basis, but also to conserve the environment.

The fruit plants generally need higher amount of potassium followed by nitrogen and a small quantity of phosphorus. Further, the nutrient requirement varies from fruit to fruit (Table 1). Banana may be considered as voracious feeder, whereas citrus as less voracious. The requirement of secondary elements like Ca, Mg and S ranges between 500 g to 1000 g $tonne^{-1}$ of the fruit and the micro-nutrients are required in a range of 2 to 50 g $tonne^{-1}$ of the fruits (Chundawat and Trivedi, 1998). However, for a precise estimate of the nutrient requirement in fruit trees, it is necessary to determine not only the quantities removed annually by the fruits and new shoots but also those accumulating over the years in other plant parts and proportion of the currently absorbed fertilizer nutrients moving into different parts. Studies have indicated that the bulk of nutrient requirement of the developing fruits and new growth is met by the endogenous reserves of the tree. It is, therefore, necessary to monitor the current status of tree for making meaningful fertilizer recommendation for which leaf analysis appears to be quite useful. The leaf nutrient levels required for the optimum production in some important fruit crops are presented in Table 2. Efforts in the nutritional management programme should be directed towards the maintenance of these levels in tree leaves before flowering.

Table 1. Nutrients removed by various fruit crops for one tonne fruit yield

Fruit	Nutrient uptake (kg t^{-1} of the fruit)		
	Nitrogen	Phosphorus	Potassium
Mango	6.7	1.7	7.3
Banana	5.6	1.3	20.5
Citrus	1.1	0.6	2.8
Pineapple	1.8	0.5	6.3
Papaya	2.8	0.8	2.3

Source: Iyengar (1993)

Table 2. Optimum leaf nutrient status of some important fruit crops

Fruit	Nutrient									
	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu
	(%)						(mg kg^{-1})			
Mango	1.23	0.06	0.54	1.71	0.91	0.12	171	66	25	12.0
Banana	3.29	0.44	3.11	2.12	0.24	-	-	-	-	-
Citrus	2.50	0.14	0.90	4.20	0.43	0.25	90	112	62	10.5
Sapota	1.66	0.08	0.80	0.83	0.48	0.07	100	39	15	06.7
Papaya	1.66	0.50	5.21	1.81	0.67	0.38	-	-	-	-
Pineapple	1.40	0.16	3.70	-	-	-	-	-	-	-

Knowledge on the active root zone is also essential for the efficient utilization of applied nutrients, so that the nutrients placed around this zone are made available to the plant. The active root zone as well as place of the application of fertilizers as summarized by Chundawat (1997) has been presented in Table 3.

Table 3. Active root zone of some important fruit plants and the place of fertilizer application

Fruit	Area of active root zone	Place of application
Mango	82 to 88.5% of the active roots are located within a radius of 300 cm with the highest activity at 120 cm from the trunk	One meter away from the main trunk under the drip and mix thoroughly
Citrus	Within a radial distance of 120 cm at the depth of 15 to 30 cm	30 to 45 cm away from the trunk under the drip followed by light working
Pineapple	Highly restricted	9 to 10 cm away in 10 to 15 cm deep strip around the plants
Sapota	Under the canopy within a depth of 0 to 30 cm	Under the canopy and mix in the soil up to 15cm depth

In the following text, the role of balanced fertilization for sustainable yield and quality in important tropical fruit crops is discussed.

Mango

Although mango grows well even in poor soils because of its deep and extensive root system, in view of the vegetative growth it makes annually and the removal of nutrients through the harvest, it needs regular fertilization for maintaining proper growth and heavy yield of crop every year. However, nutritional requirements vary depending upon the type and nutrient status of the soil and age of the tree etc.

Pre bearing trees

After planting the prebearing stage extends to 4-8 years depending upon variety and environment. Since the plants during this period continue to grow in size, manurial dose needs to be scheduled according to their age. The requirement of an year old mango plant can reportedly be met by applying 75 g N, 110 g P_2O_5 and 55 g K_2O (Singh, 1967). Munniswamy (1970) advocated application of 10 kg farm yard manure, 3 kg bone meal, 5 kg wood ash, 1.5 kg ammonium sulphate, 2.5 kg super phosphate and 0.5 kg muriate of potash (MOP) to one year old tree and that these doses should be increased annually up to 8 years by 5 kg farm yard manure, 0.5 kg bone meal and 1 kg wood ash. The Central Institute for Research on Subtropical Fruit Crops, Lucknow has recommended that during the non bearing stage the plants should be supplied with 73 g N, 18 g P_2O_5 and 68 g K_2O tree^{-1} year^{-1} of age. On the other hand Tamil Nadu Agricultural University recommended 10 kg farm yard manure, 20 g N, 20 g P_2O_5 and 30 g K_2O tree^{-1} year^{-1} for one year old tree with an annual increase respectively 10 kg, 0.2, 0.2 and 0.3 kg till it attains fifth year.

Bearing trees

In most parts of India, bearing mango trees are not at all manured, however, evidence indicates that regular manuring of bearing trees is essential to maintain the productivity of the trees. Most of the earlier manurial recommendation for mango consisted of applying farm yard manure, neem cake, bone meal, wood ash, ammonium sulphate, and super phosphate etc., the quantity varying from region to region. Subsequently, recommendations of inorganic fertilizers were made for different regions. The Tamil Nadu Agricultural University recommended 50 kg farm yard manure, 1.0 kg each of N and P and 1.5 kg K year^{-1} bearing tree^{-1} (Anon, 2004). Ladani *et al.* (2004) suggested application of 1.5 kg N, 0.5 kg P and 1.2 to 1.5 kg K tree^{-1} to get higher yield. The ratio of N and K is known to affect the growth and yield in mango. Higher N and low K (1.5 and 0.5 kg plant^{-1}, respectively) promoted vegetative growth, whereas higher N and K (both 1.5 kg plant^{-1}) promoted fruiting in mango cv. Fazli (Banik *et al.*, 1997).

Foliar sprays of macronutrients have been used to supplement their soil application and to obtain quick response and to correct deficiencies. Application of 1 kg N, 0.5 kg P_2O_5 and 1 kg K_2O through soil and 3% urea as foliar spray year^{-1} after pruning resulted in marked improvement in fruit yield in 60 year old declined Fazli tree.

Recently, Sulphate of Potash (SOP) has been tried as an alternate source of K in mango and the preliminary results indicated that when SOP was incorporated, there was an increase in fruit yield; however, the differences were not significant. Similarly, the fruit quality particularly the total sugars, ascorbic acid and carotenoid contents was also influenced by SOP application.

Banana

Banana generally requires high amount of mineral nutrients for proper growth and production. Nutrient uptake studies (Fig 1) reveal that most of the nutrient uptake occurs 4-6 months after planting, followed by fruit maturity phase. Studies on uptake of nutrients in tissue culture banana cv. Robusta (AAA) also revealed that N, P, K uptake increased linearly till shooting stage (Nalina, 2002). The distribution of N, P, and K within different organs of banana plant is found in the order of the bunch > leaves > pseudostem > corm for N and P, and pseudostem > bunch > leaves > corm for K.

Banana cultivation in India is polyclonal with an array of varieties under cultivation. The systems of culture are diverse; therefore, fertilizer recommendations are diverse (Table 4).

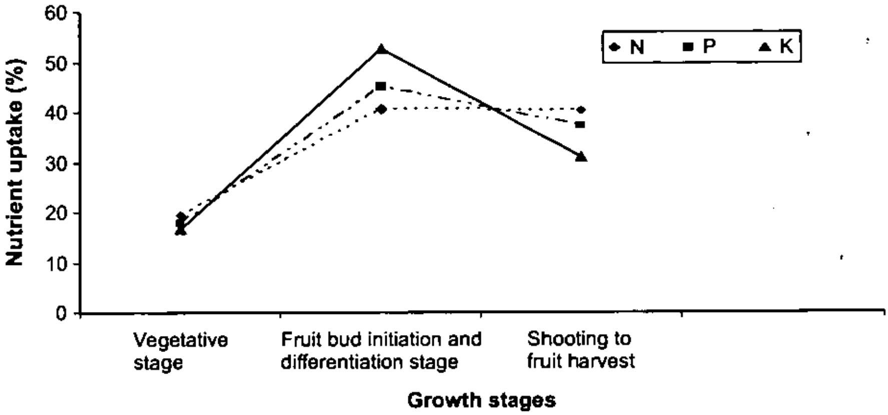

Fig 1. Nutrient uptake in banana at different growth stages

Table 4. Fertilizers recommendation in Banana (g plant $^{-1}$) in various states

States	N	P	K
West Bengal	240	45	240
Kerala	225	225	225
Tamil Nadu	110	35	330
Goa	75	75	240
Assam	110	35	330
Bihar	125	80	225
Orissa	80	32	90
Uttar Pradesh	200	100	250

Bellie (1987) obtained higher bunch yield, early shooting, harvest and higher net income per hectare in Nendran when a balanced fertilizer dose of 150:90:300 g NPK plant^{-1} was applied. In experiments at Ranchi (Bihar), application of 120 g K_2O to individual stools of Dwarf Cavendish banana along with 80 g N and 50 g P_2O_5 resulted in highest yield (35 t ha^{-1}) and number of hands per bunch (Pandit *et al.*, 1992). All India coordinated trials revealed that application of 200 g each of N and K_2O (6 split doses) starting from 60 days after planting at 30 days interval for Rajapuri banana, while 300 g each of N and K_2O plant^{-1} in three equal splits at 90, 120 and 150 days after planting for Gandevi selection continued to record higher yield. Efficiency of different source of nitrogen on banana cv. Ney Poovan (AB) revealed that combined application of 25% of N as Calcium Ammonium Nitrate + 25% of N as urea + 50% of N as ammonium sulphate is the best combined source of N for the banana cv. Ney Poovan (Keshavan, 2004).

Banana, being a potassium loving crop, the farmers in India are applying potassium @ 800 to 1600 kg ha^{-1} depending upon the available soil K status. As Muriate of Potash (MOP) is commonly used as the source of potassium, the chloride toxicity is often met in banana, hindering crop growth, yield and quality especially at amounts greater than 1200 kg ha^{-1} (Nalina, 2002). Hence, SOP has been tested as a substitute for MOP in banana. Ramesh Kumar (2004) tried various combination of SOP and KCl to supply the recommended dose of K_2O i.e 330 g of K_2O $plant^{-1}$ to cv. Robusta and found that soil application of SOP improved the bunch weight and quality (Fig 2 and 3) as compared to 100% through MOP. But the prohibitive cost of SOP is the limiting factor.

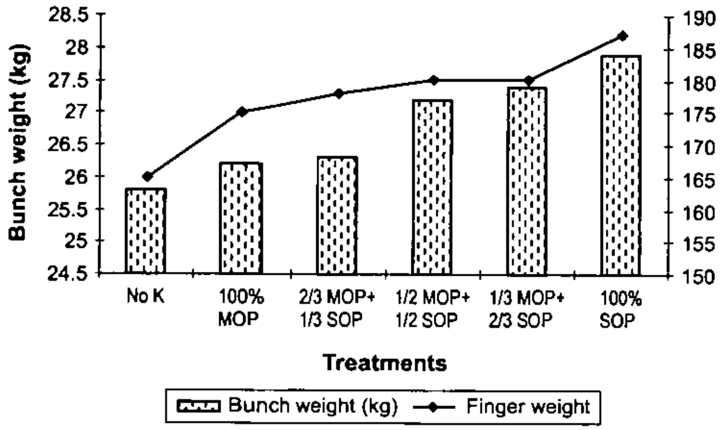

Fig 2. Influence of sources of potassium (SOP vs MOP) on bunch and fruit weight of banana (Source: Ramesh Kumar, 2004)

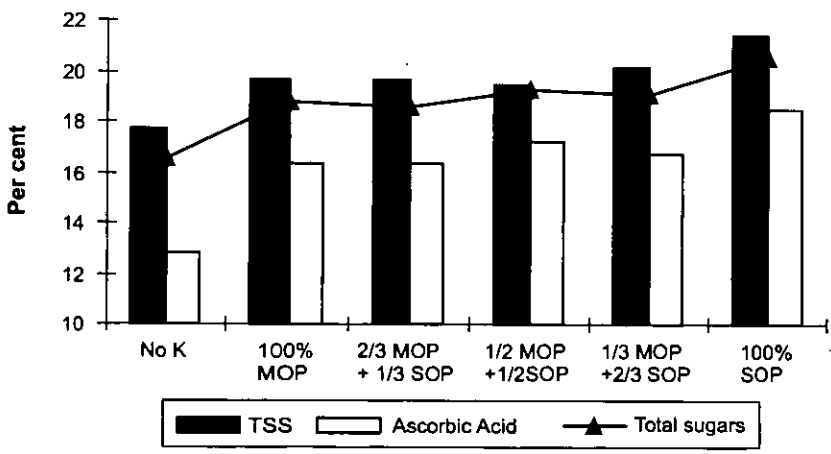

Fig 3. Influence of sources of potassium (SOP vs MOP) on quality traits in banana (Source: Ramesh Kumar, 2004)

Fertigation is particularly useful in improving yield and quality of banana besides improving the nutrient use efficiency. Experiments conducted at Coimbatore revealed that under both the normal and high density system of planting, fertigation was effective in improving the yield and maintaining fruit quality (Mahalakshmi, 2000) (Table 5). Other studies conducted at Tamil Nadu Agricultural University (Kavino, 2001) also indicated that conventional soluble fertilizers like urea and MOP were equally effective and cheaper sources for fertigation.

Table 5. Fertigation effect on banana cv. Robusta (AAA)

Water + Fertilizer	Bunch weight (kg)	Yield (t ha^{-1})	% increase over conventional	No. of hands	No. of fingers	TSS (%)
Normal planting system						
Plant crop 25LPD + 100:30:150 g NPK plant^{-1}*	38.0	95.0	61.1	9.3	163.9	19.3
Ratoon crop 25 LPD + 150:30:225 g NPK plant^{-1}**	44.4	111.0	61.1	13.5	261.3	20.1
High density planting system						
50 LPD + 450:90:675 g NPK plant^{-1}**	35.0	174.9	196.5	10.2	173.4	21.2
Conventional						
200:30:300 g NPK plant^{-1}	23.6	59.0	-	8.1	118.0	22.1

* 50 percent recommended dose

** 75 percent recommended dose

Tissue-cultured (TC) banana cultivation is expanding in India as farmers are now realizing its advantages due to its rapid growing, early and high yielding characters. Application of 150% of recommended NPK (i.e.165:52.50:495 g) in four splits was found essential to increase the plant's growth and development, yield and quality in the plant and ratoon crops of TC banana (Table 6) (Nalina, 2002). The dose of 300 g N and K_2O each and 100 g P_2O_5 plant^{-1} crop^{-1} was observed to be optimum for TC "Robusta" under irrigated, low fertility, lateritic soils of coastal Orissa (Pandey *et al.*, 2005).

Table 6. Response of Tissue culture derived banana to increased dose of nutrients

Treatments	Bunch weight (kg)			TSS in fruit (°Brix)			B/C ratio		
	PC	R_1	R_2	PC	R_1	R_2	PC	R_1	R_2
Recommended dose (110:35:330 g N, P_2O_5, K_2O) in 3 split doses	26.9	30.0	17.5	18.1	18.5	18.2	2.5	3.0	1.8
150% of recommended dose (i.e. 165:52. 5:495 g N, P_2O_5, K_2O) in 4 split doses	35.2	37.0	25.3	20.5	20.6	20.2	3.0	3.4	2.3
C.D. (0.05)	1.1	1.2	1.6	0.2	0.3	0.3	-	-	-

PC: Plant crop R_1: First ratoon R_2: Second ratoon

Further, fertigation experiments conducted at various parts in India revealed saving in the fertilizer requirement. Application of 75 per cent recommended dose of fertilizer (RDF-200 g each of N and K_2O plant^{-1} year^{-1}) at Arabhavi (Robusta), Gandevi (Gandevi selection), Jalgaon (Grand Naine) and Kannara (Robusta) and 50% recommended dose of fertilizres at Kovvur through drip was sufficient for Karpura Chakkerakeli (AAB, Mysore).

Foliar nutrition at post shooting stage is known to improve the fruit size and quality in banana. Ramesh Kumar (2004) found that post shoot application of SOP 1.5% twice, first at the time of last hand opening and second one month from first spraying helped to improve the bunch weight and quality of fruits in certain commercial varieties of banana (Fig 4 and 5).

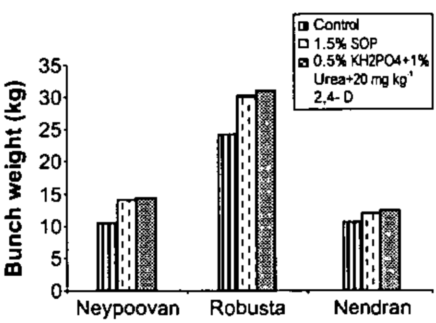

Fig 4. Influence of post shooting spray of certain nutrients on bunch weight of banana

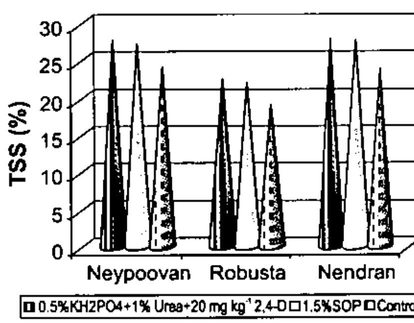

Fig 5. Influence of post shooting spray of certain nutrient on TSS of fruits

Citrus

Improper and inadequate nutrition is one of the major causes of citrus decline in India (Chadha *et al.*, 1970). Studies on the decline of mandarins in Kerala showed that poor nutrient status of soil (Iyer and Iyengar, 1956) and neglect and lack of manuring are the main causal factors. Thirty tonnes of citrus fruits remove 270 kg N, 60 kg P_2O5, 350 kg K_2O, 40 kg MgO and 15 kg S from the soil (Tandon and Kemmler, 1986).

Different states recommend different amounts of NPK for mandarin and other important citrus species (Table 7). Recently, integrated nutrient management (INM) is being advocated in citrus. Studies conducted at Tinsukia (Assam) by Borah *et al.* (2001) revealed that maximum yield with appreciable tree vigour and fruit quality of Khasi mandarin could be obtained from balanced nutrition of the plants through combinations of organic (neem cake) and inorganic fertilizers (Table 8). Results of a study (Seshedri and Madhavi, 2001) conducted on 20 year old seedling trees of sweet orange cv. Sathgudi revealed that the maximum yield, cost benefit ratio with better fruit quality could be obtained by the balanced nutrition through organic (castor cake @ 7.5 kg) along with 400:150:300g NPK plant^{-1} year^{-1} (Table 9). Similarly, integrated nutrient management studies conducted at Akola revealed that application of neem cake along with chemical fertilizers significantly increased the yield with better quality fruits (Ingle *et al.*, 2001).

Experiment conducted in Tamil Nadu revealed that application of P enriched farm yard manure (0.5 kg P_2O_5 tree^{-1} mixed with 20 kg farm yard manure) along with 700 g N and 600 g K_2O tree^{-1} recorded the highest yield and improved the fruit quality of mandarin. Ingle *et al.* (2003) found that in Nagpur mandarin, number and weight of fruits and total soluble sugars were highest with application of 800 g N, 300 g P_2O_5 and 600 g K_2O along with 7.5 kg neem cake plant^{-1} year^{-1}. Tiwari *et al.* (1999) also obtained maximum yield of sweet orange with the application of 800 g N, 300 g P_2O_5, 600 g K_2O + 15 kg neem cake tree^{-1} year^{-1}. Mycorrhizal association with citrus species has been well established. Shamshiri and Usha (2004) found that application of *G. manihotis, G. gigospora* and their combinations increased the trunk diameter, height and leaf area in Kinnow mandarin.

Fertigation has been recently introduced in citrus and varying response has been reported. Shirgure *et al.* (2001) found that fertigating Nagpur mandarin with 50:140:70 NPK kg ha^{-1} is good in improving the tree vigour, yield and quality of fruits. Application of 75% recommended amount of N and K through drip irrigation was found ideal for sweet oranges under Maharastra, Andhra Pradesh and Punjab conditions.

Secondary and micronutrient deficiencies are common in almost all citrus species. Each state has its own recommendations which involve application of $ZnSO_4$ (0.3 to 0.5 %), $MgSO_4$ (0.2 to 0.3%), $MnSO_4$ (0.1 to 0.3%), $CuSO_4$ (0.3%), $FeSO_4$ (0.2 to 0.3%) and Borax (0.05 to 0.1%) two to three times on the new flushes to get good yield and quality fruits (Bojappa and Bhargava, 1993).

Table 7. Fertilizer recommendation for optimum productivity of citrus cultivars grown in some states of India

Scion	Rootstock	Recommended fertilizer (g tree^{-1})		
		N	P_2O_5	K_2O
Punjab				
Kinnow mandarin	Jhatti Khatti	400	200	400
Jaffna Orange	Jhatti Khatti	400	200	200
Assam				
Khasi Mandarin	-	300	250	300
Maharashtra				
Nagpur mandarin	Jambhiri	600	200	400
Acid lime	-	800	200	100
Sweet Orange	-	800	100	400
Gujarat				
Acid Lime	-	900	250	500
Karnataka				
Coorg Mandarin	Rangpur lime	400	200	200
Andhra Pradesh				
Sathgudi	Rangpur lime	400	200	200
Tamil Nadu				
Acid Lime	-	600	200	300
Mandarin Orange	-	700	375	600
Meghalaya				
Khasi mandarin	-	300	250	300

Papaya

The nutritional demand of papaya differs from other fruit crops because of its tremendous yield potential due to its precocious bearing and indeterminate growth habit with simultaneous vegetative growth, flowering and fruiting. The uptake of

N, P, K, Ca and Mg on papaya is more between flowering and harvesting stages, but uptake is specifically higher between fruit development and harvest stages more so with potassium (Table 10) (Veerannah and Selvaraj, 1984).

Table 8. Effect of organic and inorganic nutrition on yield and quality of Khasi mandarin plants

Treatments	No. of fruits $plant^{-1}$	Yield (kg $plant^{-1}$)	Juice (%)	Ascorbic acid (mg $100g^{-1}$)	TSS (°Brix)
600:300:600 g NPK $plant^{-1}$	805	118.0	46.3	48.3	14.3
600:300:600 g NPK $plant^{-1}$ + Neem cake @ 15 kg $plant^{-1}$	1072	203.5	55.7	57.3	15.3
C.D. (0.05)	20	10.4	1.1	3.5	0.2

Table 9. Effect of organic and inorganic fertilizers on yield of sweet orange

Treatments	Fruit number $plant^{-1}$	Yield $plant^{-1}$ (kg)	Weight of fruit (g)	Juice (%)	TSS (°Brix)
T_1 (Inorganic fertilizers @800:300:600 g NPK $plant^{-1}$ $year^{-1}$)	1960	296.27	160.76	42.04	12.86
T_2 (Castor cake @ 7.5 kg $plant^{-1}$ $year^{-1}$ + 50 % of T_1)	2539	399.87	170.71	41.68	13.28
C.D. (0.05)	NS	NS	-	-	-

Table 10. Nutrient uptake by whole plant of papaya cv. CO 1 (kg ha^{-1})

Growth stage	N	P	K	Ca	Mg
Seedling	0.02	0.01	0.02	0.02	0.02
Vegetative	0.29	0.07	0.67	0.05	0.05
Pre flowering	9.04	0.81	18.58	1.46	0.99
Flowering	53.37	15.41	203.36	4.10	2.30
Fruit development	56.76	44.59	515.19	30.74	6.32
Harvest	305.58	103.68	524.02	327.40	183.34

In Solo variety, 250 g N, 250 g P_2O_5 and 200 g K_2O plant^{-1} year^{-1} applied in 6 split doses was the best when spaced at 2x 2 m (Sulladmath *et al.*, 1984). Results of experiments conducted at Tamil Nadu Agricultural University, Coimbatore reveal that split applications particularly six splits (Irulappan *et al.*, 1984) was found to be good while Ravichandrane *et al.*, 2002 recommended twelve splits instead of six as it resulted in higher yield and quality of fruits in CO 2 papaya (Table 11).

Table 11. Effect of split application of nutrients on yield and quality of papaya cv. CO 2

Treatment	Number of fruits	Yield of fruits (kg)	Fruit weight (kg)	TSS (° Brix)	Carotene (mg 100g^{-1} of pulp)	Enzyme activity (TU mg^{-1})
300 g each of NPK plant^{-1} year^{-1} in six split doses	86.6	167.0	1.97	12.25	3.39	231.5
400 g each of NPK plant^{-1} year^{-1} in 12 split doses	101.3	213.6	2.11	14.40	3.64	266.9
C.D. (0.05)	3.3	16.5	NS	NS	-	-

Papaya plants receiving inorganic nutrients alone (200 g each of N, P_2O_5, K_2O plant^{-1} year^{-1}) recorded the highest yield, but inclusion of an organic source of nutrient (farmyard manure/neem cake) produced better quality fruits. Tamil Nadu Agricultural University recommends application of 300g in each of NPK plant^{-1} year^{-1} at bimonthly intervals along with application of 20 g *Azospirillum* and 20 g Phosphobacterium at planting and again after six months.

Fertigation studies conducted at Tamil Nadu Agricultural University with CO 7 revealed that 75%of recommended does of fertilizers and soil application of super phosphate 278 g plant^{-1} at bimonthly intervals improve growth, yield and quality characteristics in papaya cv. CO 7 (Jeyakumar *et al.*, 2001).

In an experiment, graded doses of K (0,150, 300 and 450 Kg K_2O ha^{-1}) were applied with two cultivars (CO-2 and CO-7) at four locations of Tamil Nadu and found that potassium nutrition significantly influenced fruit weight, fruit yield plant^{-1} and the quality of fruits including the quality of latex (Fig 6 and 7).

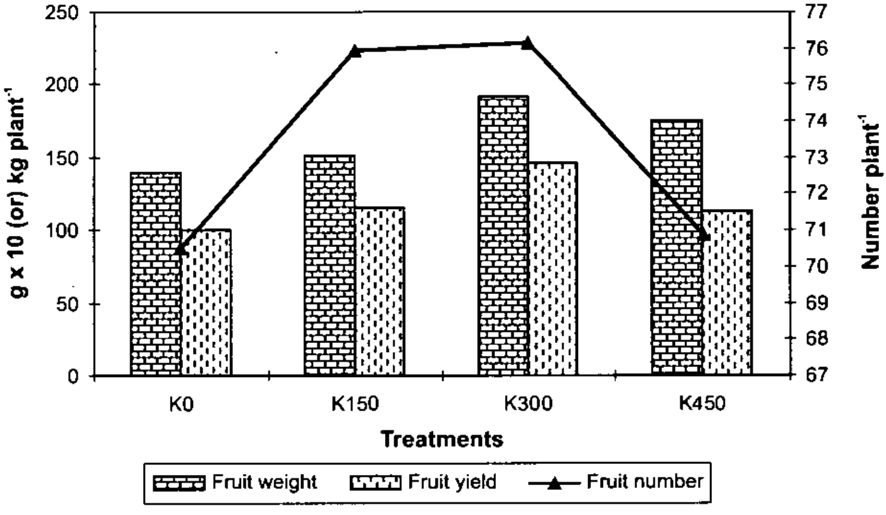

Fig 6. Effect of potassium on yield traits in papaya

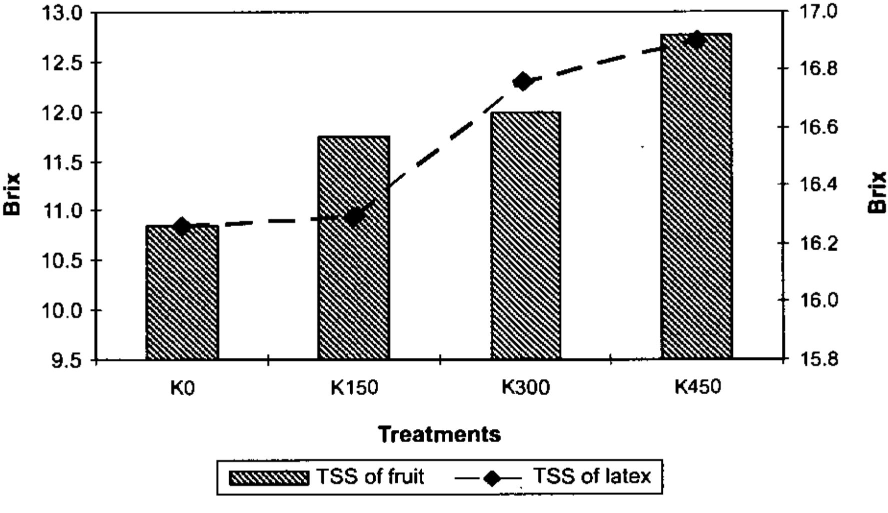

Fig 7. Effect of potassium on quality traits in papaya

Pineapple

Pineapple is cultivated in different types of soils but sandy loams and laterite soils of sub mountainous region are considered more suitable and favourable. Pineapple is a shallow feeder grown on loose and poor soils but has high N and K requirement.

Several nutrient removal / uptake studies have shown (Table 12) that pineapple requires large quantity of K followed by N and to give high yield. Ratio in which these nutrients are removed can be considered as basis of proportion in which nutrients can be applied.

Table 12. Nutrient removal by pineapple fruits

Yield (t ha^{-1})	Source	Uptake or removal	kg ha^{-1}				
			N	P_2O_5	K_2O	MgO	CaO
100	Cowie, 1951	Uptake	123	34	308	-	-
81	Stewart and Py, 1956	Uptake	574	126	631	-	-
		Removal	67	19	238	-	-
55	Martin-Prével, 1961	Uptake	205	58	393	42	121
		Removal	43	17	131	10	17

However, trials conducted in Assam (Mohan and Ahmed, 1987) and West Bengal (Sen, 1985) conditions stressed the importance of balanced nutrition to get higher yield.

Sapota

No systematic studies on the nutrient uptake or removal in sapota are available. However, Avilan *et al.*, 1980 reported from the analysis of fruits and seeds of 8 to 10 year old sapota trees that the plants required 1.69 kg K_2O, 1.16 kg N, 1.12 kg Ca, 0.17 kg P_2O_5 and 0.14 kg MgO to produce 1000 kg of fruits. Annapurna *et al.* (1988) reported that recently matured leaf which comes out to be 10^{th} leaf position should be utilized for diagnosis and such leaves on healthy trees indicated a levels of 1.66% N, 0.083% P, 0.80% K,0.83% Ca, 0.48% Mg and 0.066% S.

Sapota growing states like Andhra Pradesh, Karnataka, Maharastra and Tamil Nadu recommend different doses for obtaining higher yield (Table 13).

Integrated nutrient management has also gained popularity in many states. In Andhra Pradesh, sapota trees are fertilized with 100 kg farm yard manure, 6 kg caster cake and 2 kg super phosphate $tree^{-1}$ $year^{-1}$ (Narasimham, 1966); while in Maharastra, ten years old trees are fertilized with 40 kg farm yard manure and 6 kg of caster cake (Singh *et al.*, 1963). In Karnataka, the recommended dose for trees of 11 years and more is 40 kg farm yard manure, 400 g N, 160 g P and 450 g K $tree^{-1}$ (Anon., 1975). According to existing knowledge, a tree of 10 years and above age should be fed with 50 kg farm yard manure, 1000 g N, 500 g P_2O_5 and 500 g K_2O $annum^{-1}$.

Table 13. Fertilizer recommendation for sapota in certain states of India

States	Age	N	P_2O_5	K_2O	Farm Yard Manure
		(g tree^{-1})			(kg tree^{-1})
Andhra Pradesh	1-3 year	50	20	75	50
	4-6 year	100	40	150	50
	7-10 year	200	80	300	50
	11 & above	400	160	450	-
Karnataka	1-3 year	50	20	75	50
	4-6 year	100	40	150	50
	7-10 year	200	80	300	50
	11 & above	400	160	450	50
Maharashtra	1-10 year	50	-	-	-
	10th year	500	-	-	10-15
Orissa	Adult	45	150	-	15 kg farm yard manure + 250 g Stearameal
Tamil Nadu	Annual increase	30	30	50	10
	I year	30	30	50	10
	Adult	150	150	250	50

Application of 5 kg vermicompost with 150 g N, 40 g P_2O_5 and 150 g K_2O plant^{-1} year^{-1} for 9 year old trees of Kalipatti at Karnataka and PKM-1 at Tamil Nadu conditions recorded significantly higher growth and yield, while at Gujarat conditions, application of 25 kg farm yard manure per 5 kg vermicompost with 300 g N, 50 g P_2O_5 and 200 g K_2O plant^{-1} for 15 years old Kalipatti sapota recorded significantly higher growth.

Integrated nutrient management studies conducted at Andhra Pradesh revealed that 50% of the recommended dose of fertilizers besides 100g each of Azospirillum and Phosphobacteria + 5 kg of vermicompost resulted in higher fruit yield (15.48 t ha^{-1}) as against 13.98 t ha^{-1} with farmer's practice (Uma Jyothi *et al.*, 2004).

Future thrust

The future research on nutrition on tropical fruit crops should encompass

- Systematic long term experiments on major tropical fruit crops like mango, sapota, citrus need to be taken up with graded levels of N, P and K so as to assess the individual effect of these major nutrients and also their interaction on yield and quality.
- Considering the present situation of global warming, it is necessary to go for

integrated nutrient management, involving various sources of organic manures, organic cakes and biofertilizers including mycorrhiza besides chemical fertilizers in almost all tropical fruit crops.

- Fertigation is gaining popularity in all horticultural crops, however, research on these aspect in perennial fruit crops like mango, sapota, citrus is totally lacking. Liquid bio fertilizers are available now. Their effect on feeding the fruit crops through drip system has to be standardized for all the fruit crops.

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Balanced Fertilization for Spices and Plantation Crops

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Abstract

In India spices and plantation crops are grown in an area of 2.5 million ha with an annual production of 2.9 mt. Crop productivity-measured in terms of response to fertilizers-can only be sustained if soil fertility levels are maintained. The total fertilizer nutrient requirement of the plantation crops is estimated to be around 0.43 mt N, 0.24 mt P_2O5 and 0.62 mt K_2O. Successful balanced fertilization and soil fertility management are essential to improve the fertility, sustain the productivity and thereby enhance the food security of millions of small farmers.

Keywords: Balanced fertilization, spices, plantation crops

Balanced fertilization advocates use of mineral fertilizers combined with organic sources of plant nutrients, thus promoting effective management of plant nutrients. Balanced fertilizer management in spices and perennial plantation crops is a continuous battle against limiting soil (physical, chemical and physico-chemical) factors. It requires a constant watch to identify and rectify the series of limiting factors encountered for sustained productivity.

In India spices and plantation crops are grown in an area of 2.5 million ha with an annual production of 2.9 million tones (mt). During the year 2003-2004 India exported about 0.25 mt of spices especially large cardamom, ginger, fenugreek, cumin, minor seeds, garlic, chilli, turmeric, coriander, celery and fennel valued at US $ 415.15 million. (Fig 1). However, irrespective, whether spices and plantation crops are produced for export or for the domestic market, the quality determines the commercial success of the grower. Although quality of crop products such as oil, protein and sucrose content, fibre quality, taste and appearance are genetically controlled, the nutrition of plants can have a considerable impact on quality. It is therefore essential to take care of the nutrient supply to the plants.

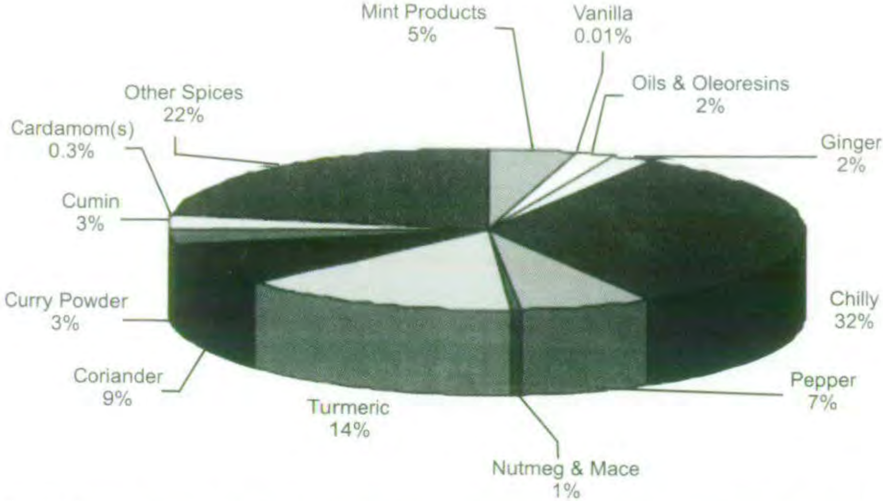

Fig 1. Share of major items in Indian spices exports (quantity %) during-2003-04

Present Scenario

Agriculture is advancing at a faster rate in India due to population pressure, globalization, industrialization and the need for quality food production. One of the major forms of land degradation is plant nutrient depletion, otherwise known as nutrient mining. Crop productivity - measured in terms of responses of fertilizers - can only be sustained if soil fertility levels are maintained. In India, farmers apply high amounts of nitrogen, but only small quantities of phosphorus and other nutrients such as potassium and micronutrients are hardly used. Under such conditions, the soil is depleted and more nitrogen has to be added every season to obtain the same crop yield.

Improvement in the N: P_2O_5; K_2O ratios in the developing countries from 6.2:6:1 in 1980 to 4.3:2.5:1 in 2002 reflects large potassium application rates, (Magen, 2006). The northern India with its food grain oriented cropping systems has an N: K ratio of 1:0.03 while south India with its high share of plantation crops uses N and K in the ratio of 1: 0.33 (Krauss, 2003). The southern region which is the biggest consumer of nutrients occupies 17 percent of the total cropped area in India (190.3 m ha). Its share is nearly 21, 25 and 44 percent of total N, P_2O_5 and K_2O consumed at the national level. Potassium consumption increased sharply (33%) followed by phosphorus (27%) and then nitrogen (14%) over previous year. These changes represent the balancing of high nitrogen rates with appropriate additions of phosphorus and potassium fertilizers, (Nagendra Rao, 2005). Some districts in the southern region exhibit narrow N: K_2O use ratio due to the fact that large areas are under banana, turmeric, vegetables, sugarcane, and plantation crops which require high potassium, still the region exhibits negative potassium balance warranting high nutrient use.

Balanced Fertilization in Spices and Plantation Crops

Balanced fertilization aids in the maintenance of proper nutrient ratios and abundant plant nutrient supply and is gaining importance in the recent years for spices and plantation crops to ensure soil fertility and sustenance of higher yield and quality.

Spices and plantation crops are grown mainly in the states of Kerala, Karnataka, Assam, Tamilnadu and Andhra Pradesh. These are mostly grown in humid tropical conditions between 20°N and 20°S of equator and their geographic distribution varies with the crop requirement. The spices, plantation crops being perennial and annual in nature remove nutrients from a limited volume of soil and hence, nutrients have to be replenished to maintain soil fertility. The average nutrient removal and fertilizer requirements of different spices and plantation crops are given in Table 1 and 2.

Although variations due to site characteristics may occur, and the nutrient removal at the highest reported yields may differ than those at average yield levels. The data illustrate the need for maintaining both a balanced nutrient supply and maximizing yields (Hamed Khan *et al.*, 2000).

The total fertilizer nutrient requirement of the plantation crops is estimated to be around 0.43 mt N, 0.24 mt P_2O_5 and 0.62 mt K_2O. However, only 22% of the fertilizer nutrient requirement of the plantation crops is being met through the use of fertilizers. Thus, there exists a huge gap between nutrient supply and crop requirement.

Table 1. Nutrient removal by spices and plantation crops

Crop	Production	Nutrient removal (000 tonnes)		
		N	P_2O_5	K_2O
Coconut	40 nuts palm^{-1}	56.0	27.3	84.0
Arecanut	173 palms ha^{-1}	79.0	28.0	79.0
Cocoa	1125 kg dried beans	25.5	11.5	60.0
Pepper*		53.3	8.1	61.6
Cardamon		25.9	9.9	62.5
Coffee	1125 kg coffee	40.0	16.7	60.4
Tea	1350 kg dried leaves	62.5	10.3	33.9
Rubber	1928 kg dry rubber	19.1	8.7	18.6
Cashew	1000 kg nut	88.0	25.0	42.0

*nutrient removal mg plant^{-1}

Table 2. Fertilizer requirement of spices and plantation crops

Crop	Fertiliser dose			Organic Manure
	N	P_2O_5	K_2O	
Group1 (g palm^{-1} year^{-1})				
Arecanut	100	40	140	12 kg
Coconut	500	320	1200	50 kg FYM in two split doses. Neem cake 5 kg tree^{-1} year^{-1} Micronutrients: Borax-50g, Gypsum-1kg, $MgS0_4$ - 0.5 kg
Cashew	500	125	125	
Cocoa	100	40	140	
Black pepper	100	40	140	10 t FYM ha^{-1}
Group 2 (kg ha^{-1})				
Cardamom	75	75	150	10 t FYM ha^{-1}
Coffee	140	90	120	
Tea	450	90	450	
Rubber	30	30	30	
Turmeric	125	60	90	FYM 30 t + Azospirillum 10 kg+ VAM 5 kg ha^{-1}

Source: Rethinam (1990)

Turmeric is an exhaustive crop and responds favorably to heavy manuring. Application of fertilizers results in enhanced tillering, luxurious foliage coupled and increased yield. The fertilizer effect is positive on turmeric and the response varies at different locations for different doses and sources of fertilizers (Rao *et al.*, 1975). Turmeric responds to balanced application of nutrients. Experimental evidences indicate the beneficial effect of balanced application of inorganic and organic fertilizers on growth, yield attributes, productivity and quality of turmeric (Manohar Rao *et al.*, 2005) Shanakaraiah and Reddy (1988) obtained the highest rhizome yield of 37.33 t ha^{-1} under balanced fertilization in Nizamabad at an NPK rate of 250:80:200 kg ha^{-1}

Cardamom is cultivated under rainfed conditions (75-80%), therefore, conservation of soil moisture and balanced application of fertilizers is essential. Cardamom plants fertilized with 32.5 g N, 25 g P_2O_5, and 50 g K_2O along with cattle manure/compost at 5 kg per clump recorded the highest dry matter production and yield over NPK treatments. In Cardamom, 140% increase in yield due to neem cake and vermicompost treatment has been reported over application of chemical fertilizers alone. A balanced dosage of 10 tones of FYM, 2 tones of leaf mulch, 75 kg N, 75 Kg P_2O_5, and 150 K_2O ha^{-1} to obtain a yield of 450 kg ha^{-1} $year^{-1}$ is recommended by the Indian Institute of Spices Research, Calicut.

Pepper, being a perennial vine, it is important that adequate and balanced amount of fertilizers are applied to maintain soil fertility and productivity of vines. Pepper is cultivated along with other plantation crops. In a mixed cropping system with coconut, manuring black pepper vines at 5 kg FYM, 0.5 kg each of neem cake and bone meal and 100, 40, 140 g N, P and K respectively $year^{-1}$ $vine^{-1}$ and manuring coconut palms at the rate of 50 kg green leaves, 25 kg FYM and 0.34, 0.17, 0.68 kg N, P, K $palm^{-1}$ $year^{-1}$, resulted in improved productivity of coconut and black pepper by 53 and 172%, respectively (Sadanandan *et al.*, 1991). Balanced application of organic and inorganic manures not only increased pepper yield but also enhanced curcurmin in turmeric (Table 3) (Sadanandan *et al.*, 2002).

Table 3. Effect of balanced fertilization on the yield and quality of pepper and turmeric

Treatment	Pepper		Turmeric	
	Yield (t ha^{-1})	Piperine	Yield (t ha^{-1})	Curcurmin
Control	2.33	6.94	2.60	6.00
NPK	3.62	6.74	3.85	6.20
FYM+CC+NPK	2.98	7.12	4.59	6.37
FYM+CC+1/2NPK+BF	4.03	6.99	3.78	7.26
L.S.D. (0.05)	0.41	0.15	0.90	0.42

Farm yard manure-10t ha^{-1}, Composted coir pith-2.5 t ha^{-1}, Biofertiliser-20 kg ha^{-1}

Source: Sadanandan *et al.* (2002)

Plantation crops occupy nearly four million hectares of area in India, which are about 2.3% of the total cropped area. India ranks fifth in production of plantation crops and it is estimated that plantation crops annually remove 149.7 ,52.4 and 218.9 thousand tonnes N, P_2O_5 and K_2O respectively (Biddappa *et al.*,1996).The plantation crops in general are grown on resource poor soils. The major soil types are laterite, lateritic, red and coastal sand. Apart from these, plantation crops are also grown in alluvial, coral and acid sulphate soils. The soils in general have poor physical properties and low native fertility. Proper on-farm management and adequate moisture availability go a long way in determining the productivity of the crops in these soils. Generally, soils under plantation and spice crops are acidic in reaction.

The desirable pH range is 4.5-5.0 for tea, 5.5-6.5 for coffee, 6.0-7.0 for rubber, wide pH range for coconut and for other crops; it is slightly acidic to near neutral in reaction. Some soils under plantation crops are very acidic, thereby toxicity of aluminum, manganese and iron poses problems in many situations (Hamed Khan *et al.*, 2000). Tea is tolerant to high levels of aluminum, manganese and iron. However, coffee and cardamom are sensitive to aluminum and manganese toxicity. In such conditions, liming is required. Being high rainfall tract and mainly light textured soils, leaching of nutrients takes place (Tandon and Ranganathan, 1988).

Arecanut is extensively used in India as a masticatory and is an essential requisite for several religious and social ceremonies. Annual application of 100 g N, 40 g P_2O_5, and 140 g K_2O through fertilizers and 12 kg each of green leaf manure or cattle manure for bearing palms is essential. Balanced application of green leaf manures along with the recommended dose of fertilizers enhanced the productivity of the nuts to the highest level of 21 kg palm^{-1} over control. Coconut Palms (Cv. West Coast Tall) under rain fed conditions in laterite soils exhibited that balanced application of NPK @ 0.50, 0.32 and 1.20 kg palm^{-1} year^{-1} with 25 kg green leaf and 10 kg FYM increased the yield up to 67 percent over normal NPK.

Tea is grown in high altitude followed by coffee in the valleys of mountainous terrain. The nutrients removed with the plucked leaves represent only 23% N, 41% P and 22% K (Krauss 2003) which is assimilated by the whole plant. Tandon (1993) also showed that for an overall production of 10.8 t made tea cycle of four year, the plant parts above the pruning cut need 1028 kg N, 357 kg P_2O_5 and 482 kg K_2O. The present manurial policy for tea in south India is based on balanced fertilization system where the rate of potassium application is linked to nitrogen dose and the organic matter status. A proper N: K_2O ratio is maintained depending on the height of the pruning in the pruned year and on the sources of nitrogen in the other years of pruning (Verma and Palani, 1997). A yield increase of 9% and 3% was recorded in plots with pruning buried and spread on surface respectively along with the recommended dose of fertilizers (Pandiaraj, 1991).

Coffee in India is a silvi-horticultural crop grown under shade of natural forests. Nutrient removal with the green berries in coffee represents merely 20% of N, 32% of P, 39% of K and 8% of Mg taken up by the whole coffee bush (Tandon, 1993).The recycling of nutrients and rich microbial population combined with balanced fertilizer application of inorganic fertilizers easily sustain a crop level of 325-500 kg clean coffee ha^{-1}. In an integrated measure to support large crops, application of FYM or farm compost at 1200 kg ha^{-1}, and based on soil test, liming, rock phosphate application, bone meal, wood ash etc. are emphasized (Hamed Khan *et al.*, 2000).

Conclusions

The benefits of balanced fertilization to spices and plantation crops are obvious: higher yields, profits, better crop quality, better resistance to pests and diseases, reduction in production costs. However, the quick turnover of nutrients requires judicious nutrient management to optimize the efficiency of the costly inputs and to minimize the environmental impact of fertilizers.

Application of integrated, sufficient, and balanced quantities of inorganic and organic fertilizers is necessary to make nutrient available for high yields in spices and plantation crops to combat nutrient mining.

Successful balanced fertilization and soil fertility management is essential to improve the fertility, sustain the productivity and thereby enhance the food security of millions of small farmers.

Future Strategies

Bench mark data on areas under cultivation, information/database pertaining to high yielding varieties needs to be established and finally soil nutrient balance sheet at the farm level needs to be calculated and maintained. With the depletion of soil nutrient pool, there is a need to emphasize on secondary and micronutrients and to maintain the suitable nutrient ratios.

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Balanced Fertilization for Sustainable Coconut and Coconut-Intercrop Systems in Sri Lanka

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Abstract

Coconut is commercially cultivated for more than 200 years in Sri Lanka. For the last few decades it is showing yield stagnation. The large scale depletion of nutrients from soils may be responsible for it. Apart from this, annual use of fertilizers has declined from 60,000 t in 1960 to 32,000 to 38,000 t in the first few years of this century (Anonymous, 2003). The nutrient balance sheet has always been negative for years, but may spiral into a disaster, especially in intensively depleted coconut-intercrop and coconut-integrate systems. The movement of all parts of coconut products likes shells, husks, and wood out of the eco-system has aggravated the situation.

On the other hand, merely 13 percent land under coconut plantations in Sri Lanka is fertilized. The Coconut Cultivation Board of Sri Lanka has launched a fertilizer promotion scheme for coconut by offering a subsidy to the tune of US $ 60.0 per t of fertilizer-mixture with an aim to shoot up annual fertilizer consumption to 50,000 t. Since 2005, International Potash Institute has assisted to establish demonstration trials and training extension staffs and planters. They have been sponsoring Growers' Awareness Programms for site-specific nutrient management in coconut-intercropping systems for small holders. Organic coconut farming is emerging as an alternate commercial venture.

Keywords: Coconut, coffee, pepper, plantation crops, plant nutrients

Cultivation of the coconut palms in Sri Lanka dates back to 200 years BC. Its commercial plantation started during the early twentieth century. At present, it occupies 430,000 ha in Sri Lanka. The plantations are mainly concentrated in the west coast. It is a livelihood for small and marginal planters and engages half a million people in the crop production, processing, and marketing. Its annual production in Sri Lanka is between 2.5 and 3.0 billion nuts.

Most of the coconut plantations are anchored in lateritic soils that are sandy to sandy loam in texture. These soils are dominated by the low activity clays, and thereby low in cation exchange capacity, and infertile. Light texture causes excessive leaching during rainy season. Coconut is a perennial crop, and requires large amount of plant nutrients. It is estimated that one hectare land that produces 7500 nuts year^{-1} removes about 50 kg N, 6 kg P, 106 kg K and 14 kg Mg from soils (Somasiri *et al.*, 2005).

Many planters prefer to grow cocoa, coffee, pepper, cinnamon, tea, cashew, and vegetables as intercrops in coconut plantation. The plantations are simultaneously used as pasture. Nutrient management in mixed plantations is particularly challenging, because nutrient fluxes for both coconut and intercrops becomes enigmatic. Balanced use of various nutrients to compensate loss from soil must be seen from this angle. In the present paper we concentrate to decipher a nutrient balance sheet taking into account nutrients lost from soils, nutrients exported from the production zone to consumer zone through various components of coconuts, and amount of fertilizer added to the plantations. We will not be covering transport of nutrients in soil-plant system, and in pedosphere, and between pedosphere and deep regolith and water bodies.

Fertilizer Equivalent of Coconut Products

Coconut has two biological components; kernel (e.g., copra, desicated coconut) and non-kernel (e.g., fiber, coco pith). Coconut shell removes least amount of nutrients. The amount of nutrients equivalent different coconut products is a useful index to understand coconut physiology and helps to plan nutrient management (Table 1).

Table 1. Fertilizer equivalent of coconut products

Product	Equivalent nuts	Urea (kg)	ERP[c] (kg)	MOP[d] (kg)	Dolomite (kg)
Coconut oil (1 tonne)	8000	46.1	22.4	22.3	14.1
DC (1 tonne)	6800	39.2	19.1	19.0	12
Copra (1 tonne)	4925	28.4	13.8	13.7	8.7
Poonac (1 tonne)	16000	92.2	44.8	44.6	28.2
Coconut shell and charcoal (1 tonne)	19700	10.4	2.4	16.2	4.3
Aetivated carbon (1 tonne)	65000	34.2	8.0	53.6	14.3
Coconut shell & shell flour (1 tonne)	7875	4.2	1.0	6.5	1.7
Mattress fibre (1 tonne)	11815	36.2	13.9	199.3	32.4
[a]Bristle fibre (1 tonne)	23625	72.5	27.7	398.4	64.8
[b]Coir fibire	7875	24.2	9.2	132.8	21.6
Fresh nuts	1000	9.5	4.2	21.4	4.9

[a]Bristle fibre = bristle fibre + twisted fibre ; [b]Coir fibre = coir yarn + coir twine; [c]Eppawele rock phosphate; [d]Muriate of potash

Nutrient Removal by Monoculture Coconut

All intensively cultivated soils would eventually require fertilizers to compensate the harvest removal of nutrients. The removal of N, P, K, and Mg by a hectare of exclusive coconut plantation that produces 7500 nuts is presented in Table 2. Potassium loss is largest amongst the nutrients, followed by N. Amongst the biological components, shell and kernel deplete high amount of N. A large amount of K is consumed by husks, fronds, kernel, and coconut-water, followed by leaf, shell and kernel. The fertilizer doses recommended by the Coconut Research Institute of Sri Lanka (CRIS) for N, P, and Mg are well below the amounts depleted from soils. Similarly, K removal is 265 kg ha^{-1}, but recommended dose is 240 kg. ha^{-1}. Unlike tea and rubber, coconut requires large amount of K, which is a crucial nutrient for yield of nuts and quality of kernel. Potassium also plays beneficial role for flower setting, and withstanding of drought situation. A part of the amount of K that is depleted from soils may be returned, if husk and leaves are incorporated and decomposed in soils. The leaves contain 45 percent mineral mass of N, therefore, recycling of leaves may partly compensate the N loss. Another source of N could be under-planting of legumes (e.g., *Puereria* spp.).

Amongst the coconut growing country, Sri Lanka is the only country where P application had significant effects on nut and copra yields. Because of the reason that most of the soils in Sri Lanka are deficient in P. Phosphorus is not a limiting nutrient in the plantations in Sri Lanka, because farmers are applying Eppawela Rock Phosphate, which is of native origin, and cheap. Magnesium deficiency is widespread in the coconut plantations in Sri Lanka, especially in the wet zones. Excessive use of K fertilizer may induce Mg deficiency. Application of 1.0 kg ha^{-1} yr^{-1} of dolomite is recommended for an adult palm to overcome it. Due to slow rate of solubility of dolomite, kieserite is recommended for a quick correction of Mg deficiency. It is advisable to analyze leaves to maintain a balanced Mg to K supply. Balancing of S, Zn, and B nutrition in plants are equally important, but growers concern for them is lacking.

Table 2. Nutrient removal by coconut monoculture (7500 nuts or 150 palms ha^{-1})

Part	Removal (kg ha^{-1})			
	N	P	K	Mg
Inflorescence	7.9	1.9	16.3	3.2
Fronds	33.4	3.3	43.6	20.3
Nuts				
Nut water	0.3	0.1	3.3	0.1
Shell	1.8	0.1	3.1	0.2
Kernel	19.9	2.8	10.5	1.6
Husk	10.6	1.2	63.2	2.5
Total	73.9	9.3	139.9	27.9
Equivalent to (kg)	Urea - 160	ERP - 71	MOP - 279	Dolomite - 232
Application (kg)	Urea - 120	ERP - 90	MOP - 240	Dolomite - 150

Annual Removal of N, P, K and Mg by Coconut (Nuts only)

Larger amounts of N, P, and K nutrients were removed from the coconut-growing soils than added, which led to a negative balance every year. The depletion may ultimately lead to an ecological disaster. Calculated values show that every year additional 28332 t of Urea, 8975 t of ERP, and 77318 t of MOP could have been applied to compensate the loss of nutrients from soils (Table 3). Sri Lanka produces 2600 million nuts annually. The fertilizer amounts equivalent to them are 25 000 t urea, 11000 t Eppawala Rock Phosphate, 5500 t MOP, and 13000 t Dolomite (Table 3).

Table 3. Removal of fertilizer amount equivalent to 2600 million nuts

Component of the nut	Urea (t)	Rock Phosphate (t)	MOP (t)	Dolomite (t)
Nut Water	237	343	2271	349
Shell	1369	320	2142	573
Kemel	14982	7285	7255	4575
Husk	7974	3049	43849	7130
Total	24562	10997	55517	12627

Export of Mineral Nutrients due to Export of Coconut Products

Twenty percent of the country's total annual production of the coconut is exported. In terms of fertilizer equivalence of nutrient loss from soils, it amounts to 7500 t urea, 320 t ERP, 19200 t MOP, and 4100 t dolomite. Perhaps, ERP and dolomite can be ignored, because they are locally produced. There is an opportunity to compensate N loss through the use of organic manures, and recycling of plant materials. The scenario for K is grim, because there is no indigenous source to manufacture it. The largest K-export occurred through mattress and bristle fiber, both of which use K-rich coconut husks as raw material. Coconut husk will unlikely to be recycled to the soils, because of its importance to the economy of the nation, and environmental security.

To and fro transport of mineral nutrients

There are two types of nutrient movements. One, when nutrients are moved from plantations to foreign countries (column 3, Table 5), and two when nutrients move from plantations to a place within the country (column 4, Table 5). Both these transports involve depletion of nutrients from soils of the plantations, and their arrival to consumer zone. When a balance is struck between total transport of N, P, and K to consumer zone and the nutrients retumed to soils of the estates and plantations of coconut in the form of fertilizer, a loss of nutrients from soil is observed. In terms of mineral fertilizer products, the deficits equal to 28332 t Urea, 8975 t RP and 77318 t MOP.

Table 4. Fertilizer equivalent of exported quantity of the coconut products (based on export data of 2004)

Product	Quantity (t)	Urea (t)	ERP (t)	MOP(t)	Dolomite (t)
Coconut Oil	2095	96	47	46	29
DC	54098	2119	1030	1026	647
Copra	15050	427	207	206	130
Poonac	10996	1013	493	490	309
Coconut Shell & Charcoal	5504	57	13	89	23
Activated Carbon	16008	547	128	857	229
Coconut Shell & Shell flour	1446	6	1	9	2
Mattress fibre	38355	1389	531	7642	1242
Bristle fibre [a]	18882	1368	523	7523	1223
Coir fibre [b]	4796	115	44	637	103
Fresh nuts [c]	41,356,000	390	174	883	200
Total		7532	3194	19412	4143

[a] Bristle fibre = Bristle fibre + Twisted fibre; [b] Coir fibre = Coir yarn +Coir twine
[c] In numbers

Table 5. To and fro transport of mineral nutrients (data pertain to 2004)

Fertilizer	Application through mixed fertilizer (t)	Export to other nations (t)	Transport to consumer zone within the country (t)	Total transport (3 + 4) (t)	Nutrient debit (t)
Urea	9333	7533	30132	37665	28332
ERP	7000	3195	12780	15975	8975
MOP	18667	19413	76572	95985	77318
Total	35000	30141	119484	149625	105075

Nutrient Management Programme for Monoculture Coconut

The objective of fertilizer recommendation to coconut plantation in Sri Lanka is maximizing profit, and environmental security. Therefore, the fertilizer doses are chosen on the basis of fertility status of the soils (Tennakoon, 2004). The soil fertility status is qualitatively grouped into good, fair and poor, and accordingly amounts of mixtures are prescribed (Table 6).

Table 6. Recommended doses of N, P, and K fertilizers to coconut for soils of varying fertility gradients

Soil fertility	Nutrient source and the rate (kg palm^{-1} year^{-1})		
	N Ammonium Sulphate (21.2% N)	P Super Phosphate (27.5 % P_2O_5)	K Muriate of Potash (60% K_2O)
Good	0.372	0.109	0.456
Fair	0.422	0.109	0.564
Poor	0.467	0.109	0.678

In 1967, urea (46% N) replaced ammonium sulphate (21% N) as a N source. In 1979, the recommended doses were revised, and N-dose was decreased and K-dose was increased. For easy handling, fertilizers were supplied by mixing required doses of fertilizers, and the mixtures are categorized as urea based (CU) Mixture, and ammonium sulphate based (CA) Mixture. The amount of nutrients in terms of N, P, and K applied through these mixtures are dependent on soil fertility status, and are presented in Table 7. The blanket recommendations of fertilizer mixtures are based on Agro-Climatic Zone (ACZ) and soil types. The recommended doses are given in Table 8. In 1985, a general fertilizer mixture, known as Adult Palm Mixture (APM) was formulated. The composition of APM is given in Table 9. It has to be applied in different doses to coconut plantations according to their location in the agro climatic regions and type of soils (Table 10).

Table 7. Amount of N, P, and K applied to soils through various CU and CA mixtures

Fertilizer mixture	Nutrient (kg palm^{-1} year^{-1})		
	N	P	K
CU1 or CA1	0.322	0.083	0.78
CU2 or CA2	0.230	0.072	0.44
CU3 or CA3	0.276	0.055	0.54

Table 8. The fertilizer recommendation for different soil and Agro-Climatic Zones

ACZ[a]	Soil type	Rate of fertilizer palm^{-1} year^{-1}
WZ	Lateritic loams	
IZ	Lateritic gravels	3 kg of CU - 1 or 3.75 kg of CA - 1
WZ	Coastal marine sands	
IZ	Cinnamon sands	
IZ	Deep reddish brown loams	2 kg of CU - 2 or 2.5 kg of CA - 2
IZ	Deep alluvial loam	
IZ	Estuarine and lagoon clay soils	
DZ	Coastal marine sand	2 kg of CU - 3 or 2.75 kg of CA - 3
DZ	Lagoon sandy deposits	

[a] WZ - Wet zone; IZ - Intermediate zone; DZ - Dry zone

Table 9. Composition of APM

Urea (46% N)	-	8 parts by weight
Saphos Phosphate (27.5% P_2O_5)	-	6 parts by weight
Muriate of Potash (60% K_2O)	-	16 parts by weight
NPK composition	-	12 - 6 -32

Table 10. Recommended APM rates for different soil types in Agro- climatic zones

Soil type & Agro-climatic Zone	APM (kg palm^{-1} yr^{-1})	Nutrient rates (kg palm^{-1} yr^{-1}) N	P	K
Gravel, cabook or sand in WX & IZ	3.0	0.368	0.078	0.796
Loam or clay in WZ & IZ	2.0	0.245	0.050	0.531
Sand in DZ	2.5	0.306	0.062	0.663

Recently, APM fertilizer has been modified to include two P sources; Eppawala Rock Phosphate (ERP), which is manufactured in the country, and Rock Phosphate (IRP), which is imported. The differences in their solubility is the basis of their mixture categorization (APM-W for wet region, and APM-D for dry region), and are prescribed to different regions. Their composition is given in Table 11.

Table 11. Mixture of the APM- W and APM- D

	APM-W	APM-D
Urea	8 parts by weight	8 parts by weight
Eppawala Rock Phosphate	9 parts by weight	-
Imported Rock Phosphate	-	6 parts by weight
Muriate of Potash	16 parts by weight	16 parts by weight
Composition N - P_2O_5 - K_2O	11-8-29	12-6-32

Nutrient Management Programme for Intercrop System

The majority of coconut growers of Sri Lanka do not use any fertilizer, while 13 percent use low doses. One of the best ways to encourage farmers to use fertilizer is to change monoculture land use to coconut-intercrop system. The later earns more profit as well. There is a wide choice of intercrops in coconut plantations, and thus fertilizer requirements vary widely. Some of the intercrops are seasonal, while others are perennials. Amongst the intercrops, fertilizer requirement for banana is the highest and cashew is the lowest (Table 12). Similarly, rambutan requires small quantities of N, P, and K, but no Mg, while, fertilizer requirements of pepper is quite high. For intercrop systems, integrated nutrient management schemes must be developed.

Table 12. Recommended fertilizer amounts for several intercrops under coconut cultivation

Crop	Scientific name	Plants ha^{-1}	Frequency of fertilizer application (times yr^{-1})	Fertilizer dosage (kg^{-1} ha^{-1} yr^{-1})						
				N Fertilizer	P Fertilizer			K Fertilizer	Mg Fertilizer	
				Urea	ERP	Super P	Saphos P	MOP	Dolomite	Kiserite
Cacao	*Theobroma cacao*	988	2	212	266			160		53
Coffee	*Coffea arabica*	1088	2	134			168	101		34
Pepper	*Pipper nigrum*	1235	2	532			665	399		133
Cinnammon	*Cinnamomum zeylanicum*	8151	2	90	67			67		22
Lime	*Citrus aurantifolia*	704	2	211		486		359		
Cashew Nut	*Anacardium occidentale*	80	1	28			107	26		
Rambutan	*Nephelium spp*	80	2	37			164	40	200	
Papaya	*Carica papaya*	741	4	177		118		370		
Banana	*Musa paradisiaca*	902	3	541		361		1128		

Balance fertilizer application for selected coconut plus intercrops system are described below.

Coconut-cinnamon intercropping system

The export earnings of cinnamon is US $ 50 million per year; the highest amongst all exportable farm commodities of the country. It is recommended to establish 8000 cinnamon trees ha^{-1} and production of quills (a product of bark) is approximately 200 kg ha^{-1} yr^{-1}. Cinnamon provides leaves for the extraction of oil, bark for culinary purposes, and wood for fuel. The total annual nutrient removal is 59 kg ha^{-1} for N, 5 kg ha^{-1} for P, and 20 kg ha^{-1} for K (Table 13). The applications of K and P through fertilizers are less than their removal from soils, but the application of N exceeds the amount removed from soils (Table 13). Out of the total nutrient uptakes, 73 percent of N, and 62 percent of K are taken up by leaves. Since earnings from leaves are less than 10 percent of the income from cinnamon, planters are advised to recycle cinnamon leaves.

Table 13. Nutrient removal by cinnamon in coconut-intercrop system

Nutrient	Removal ($kg\ ha^{-1}\ yr^{-1}$)	Application ($kg\ ha^{-1}\ yr^{-1}$)	Difference ($kg\ ha^{-1}\ yr^{-1}$)
N	50	41	- 9
P	5	9	+ 4
K	20	34	+ 14

Coconut-tea intercropping system

Tea is grown in the mid and up country areas in Sri Lanka. During last three decades, its cultivation is expanded to lower reaches, where coconut predominates. At present, generation of profit is more in tea than coconut, which makes tea a main crop in coconut-tea system. In it, coconut is used as a buffer crop to mitigate market fluctuation. Tea growing regions of Sri Lanka receive annual rainfall in the range of 1500 to 3500 mm. The soils of the regions are acidic, and red to yellow podzolic to reddish brown laterite. Leaching of bases and nutrient ions are very high. Tea grows well in slightly acidic soils (pH 4.4-5.5), while coconut grows well in neutral soils. In general, Mg deficiency in coconut is of common occurrence in tea-coconut system, because its loss from soils is never compensated (Table 14).

Table 14. Balance sheet of N, P, K, and Mg in coconut-tea intercropping system ($kg\ ha^{-1}\ yr^{-1}$)

Nutrient	Removal	Application	Difference
N	164.0	296.0	+132.0
P	12.3	12.4	+ 0.1
K	74.0	62.5	-11.5
Mg	12.3	0.0	-12.3

Coconut-gliricidia intercropping system

Gliricidia is the 4^{th} wide-spread plantation crop is Sri Lanka. It fixes atmospheric N, and mines P, Ca, and Mg from sub-surface soils. It is used for green manuring, and as raw material for bio-fuel. Gliricidia can be grown in coconut plantation with no adverse effect on coconut yield (Anonymous, 2000). Gliricidia produces 24.0 t $ha^{-1} yr^{-1}$ of leaf litter (Gunathilaka and Wasantha, 2004). It increases organic matter content in soils, improves plant nutrient retention, and facilitates soil microbial activity and root proliferation (Table 15).

Table 15. Nutrient level of 14th leaf of coconut

	N%	P%	K%	Ca%	Mg%
Coconut alone	1.68	0.11	0.91	0.35	0.39
Coconut + Gliricidia	2.18	0.12	0.84	0.33	0.54
Sufficiency range / level	1.9-2.1	0.11-0.13	1.2-1.5	0.25-0.35	0.35-0.50

Source: Gunathilake and Wasantha (2004)

Nutrient Management Programme for Coconut-Pasture Integrated System

The Government of Sri Lanka is keen to attain self-sufficiency in milk production, and therefore, there is a need to expand land under pasture and introduce foraging. Coconut plantation provides ideal space and sunlight requirements of pastures, for cultivation of forages. An important pasture species, *Brachaicia miliformis* produces 9000 kg ha^{-1} yr^{-1} of dry matter that amounts to total (N+P+K) depletion of 1395 kg ha^{-1} yr^{-1}, out of which K shares 77 percent (Table 16). The recommended dose of fertilizer is 52 kg ha^{-1} yr^{-1} N, 15 kg ha^{-1} yr^{-1} P, and 59 kg ha^{-1} yr^{-1} K. This indicates that removal of nutrients exceed the application. Current fertilizer application is mandated for low level, because it assumes incorporation of cattle dung/waste, although farmers often sell it to vegetable gardeners.

Table 16. Plant nutrient balance sheet in coconut-pasture integrated system (kg ha^{-1} yr^{-1})

Nutrient	Annual removal	Application as per the recommendation	Deficit
N	180	52	128
P	135	15	120
K	1080	59	1021

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Genetic Manipulation for Efficient Utilization of Nutrients

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Abstract

Increasing nutrient use efficiency is necessary due to reasons of increasing crop production to meet the demands of a growing global population as well as to minimize the environmental damage associated with the use of fertilizers. Besides, integrated nutrient management strategies, it is also necessary to develop nutrient-efficient cultivars. Hence, research efforts have focused on developing genotypes that use nutrients more efficiently. Two approaches have been used to increase nutrient use efficiency in crop plants. The first involves both traditional breeding and marker-assisted selection in an attempt to identify the genes. The second uses novel gene constructs designed to improve specific aspects of nutrient use efficiency. Knowledge of the basic physiological processes of uptake, distribution and storage at different stages of plant development can serve as a starting point for the biotechnological manipulation of crops. Genetic variability in relation to the components of nutrient use efficiency such as uptake, translocation and mobilization into grains need to be established. This review focuses on the various approaches to increase nutrient use efficiency for nitrogen and potassium at the physiological and molecular level. Improving nitrogen use efficiency (NUE) requires a better knowledge of the regulation of the plant N metabolism. Quantitative trait loci (QTL) analyses have led to the identification of loci common for yield and cytosolic glutamine synthetase (GS), both in maize and rice. Studies on transgenic plants overexpressing genes of nitrate transporters and enzymes of nitrogen metabolism have shown the effect of improved NUE by manipulation of genes for GS and glutamate synthase. In contrast to nitrogen, potassium is not an incorporated component of plant molecules and exists predominantly as a K^+ ion. Plants have evolved a sophisticated and highly specialized K^+ transport system to meet the different requirements for K^+ in various cells and tissues. However, the relative contributions of particular members of a gene family encoding K^+ transporters, to plant adaptive responses to the environment needs to be understood. QTL analyses for variation in shoot K^+ concentrations have been conducted in various crops such as rice and sugarbeet. These studies have demonstrated the presence of loci affecting K^+ concentrations coinciding with genes for K^+ transporters. Such studies have helped to further our knowledge to develop genotypes showing contrasting

behaviour in relation to the components of nutrient use efficiency, which in turn, can be used for studies on the mechanisms and inheritance of the trait.

Keywords: Efficient nutrient management, breeding, genetic manipulation, nitrate assimilation

The growing world population will require more intensive agricultural crop production. Higher yields will, in turn, increase the demand for, amongst others, nutrient inputs. The relative share of mineral fertilizers considering all sources of global nutrient inputs available for crop production, is projected to increase from 43% in 1960 to 84% in 2015. Growth in food and agricultural production will be largely dependent on land use intensification and on technologies that are increasingly focused on minimizing impacts on the environment and raising nutrient use efficiency (FAO, 2006). Agricultural intensification increases flow of plant nutrients to crops and results in a higher nutrient uptake. This in turn, results in the depletion of nutrient stocks in the soil, which is occurring in many developing countries and is a major but often hidden form of land degradation, making agricultural production unsustainable.

Enhancing nutrient use efficiency in plants is important for the transformation of agriculture. Improving nutrient use efficiency requires a combination of local/farmer and scientific knowledge to continuously adapt and improve crop, soil, and water and livestock management practices taking into account the socio-economic and environmental context. The current nutrient use efficiency is fairly poor, being 33% for N, 10-20% for P and 1-2% for K. Agronomically, nutrient use efficiency can be sub-divided into (i) uptake, or the ability of the plant to extract the nutrient from the soil, and (ii) ability of the plant to convert the absorbed nutrient into grain yield (Ortiz-Monasterio *et al.*, 2001). Hence,

Nutrient use efficiency = Uptake efficiency × Utilization efficiency

This includes processes such as uptake, assimilation, transportation and redistribution within the cell as well as homeostasis between storage and current use at the cellular and whole plant level (Abrol *et al.*, 1999).

Adoption of better crop management practices such as protection of soil, removal of weeds is an important aspect of nutrient use efficiency. Protecting and improving the soil increased the nutrient recovery by 2-3 times. There is a need to develop better cereal-legume rotations that cause less acidification and to better understand interactions (P, trace elements, etc.) and efficiency of fertilization and fixation, taking into account soil biological management. Two approaches have been used to increase nutrient use efficiency in crop plants. The first involves both traditional breeding and marker-assisted selection in an attempt to identify the genes involved. Identifying candidate genes and analyzing their expression patterns could help in improving nutrient use efficiency. The second uses novel gene constructs designed to improve specific aspects of nutrient use efficiency. There has been hardly any attempt to observe the effectiveness of the transgene expression in different genetic backgrounds. QTLs for nitrogen use efficiency have been identified in mapping populations of maize, rice, barley and Arabidopsis. Knowledge of the basic physiological processes of uptake, distribution and storage in plants, can serve as starting point for the biotechnological manipulation of crops (Grotz and Guerinot, 2002). Some of the nutrients for which these processes have been worked out include nitrogen, phosphorus, potassium, sulphur and iron. This review focuses on the various approaches to increase nutrient use efficiency for nitrogen and potassium at the physiological and molecular level.

Nitrogen

Nitrogen (N) most frequently limits agricultural production. The unaccounted 67% N represents a $15.9 billion annual loss of fertilizer (assuming fertilizer–soil equilibrium). To improve nitrogen use efficiency (NUE) in agriculture, integrated N management strategies that take into consideration improved fertilizer, soil, and crop management practices are necessary. This also includes growing of N-efficient cultivars, which serve as an important element of integrated nutrient management strategies in both low- and high-input agriculture. Hence, research efforts have focused on developing genotypes that use N more efficiently. This requires a thorough understanding of the mechanisms associated with higher uptake or utilization efficiency at different stages of plant development. Such genotypes can contribute to sustainable agriculture (Presterl *et al.*, 2002). Yield genes that have an improved capacity to assimilate nitrogen reduce environmental pressures by decreasing nitrogen leaching into groundwater. This means that sustained nitrogen losses in non-improved material are converted into higher yields by genetically improved material. Nutrient losses become lower and nutrient use efficiency thus increases.

Management practices for improvement in nitrogen use efficiency (NUE)

To identify the genotypes and management strategies, for better NUE, a thorough analysis of nitrogen uptake, assimilation of nitrate, storage and mobilization is necessary (Abrol *et al.*, 1999). The rice-wheat system in the Indo-Gangetic Plain often experiences low NUE as the soils cycle between anaerobic conditions during rice cropping and aerobic conditions during wheat cropping. These cycles combined with the often-high soil pH and soil permeability in this system can result in high losses of fertilizer N. An approach to N management has been the development of periodic monitoring of crop N status which is directly related to the intensity of the green color due to chlorophyll in the leaves (Bijay-Singh *et al.*, 2002). A leaf color chart (LCC) provides an inexpensive and simple tool for monitoring the relative greenness of plant leaves and thus providing a quick estimate of the leaf N status. However, deficiencies in K, S, and Zn must be overcome in order for farmers to achieve the full benefits of improved N management with the LCC (Alam *et al.*, 2006). Use of the LCC for N management has been incorporated as a key ingredient of the site-specific nutrient management (SSNM) approach for rice.

Rice is a very important and staple diet for more than two-fifths (2.4 billion) of the world's population, making it the most important food crop of the developing world. The challenge of feeding the growing population has to be met with in a sustainable as well as equitable basis. The natural process of biological nitrogen fixation (BNF) also constitutes an important potential source of nitrogen for crop growth in many soils and ecosystems. BNF- based farming systems would enhance agricultural production in the long term in a way that is economically viable and environmentally useful. Rice suffers from a mismatch of its N demand and N supplied as fertilizer, resulting in a severe loss of applied N fertilizer. In case of rice crop, N sources other than chemical fertilizers could be in the form of green manuring, free-living, associative exophytic, associative/symbiotic endophytic systems, and N autotrophic rice plant (Shenoy *et al.*, 2001).

Nitrogen uptake vs. utilization efficiency

In rice, breeders can select for genotypes that are efficient in N utilization and have elevated levels of grain protein without sacrificing grain yield as grain yield was positively correlated with NUE, N content, and N translocation ratio, which, in turn was correlated with grain protein concentration (Samonte *et al.*, 2006). *Indica* rice utilises nitrate better than ammonia (the form in which N is usually available to the plant in water-logged fields), and it could have a higher NUE and yield potential with nitrate fertilization (Kronzucker *et al.*, 2000). In wheat, genotypic variation for NUE and photosynthetic activity of flag leaves among old and modem cultivars of winter wheat was observed under varied N fertilization levels (110, 90 and 80 kg N ha^{-1}). Some modern cultivars exhibited an enhanced tolerance to N shortage and several attributes of efficient N utilization i.e. later senescing and more photosynthetically active flag leaves, increased ability to redistribute N into grains. Thus, evaluations under diverse fertilization regimes may be necessary when searching for improved wheat efficiency and adaptation to less favourable environments (Gómy *et al.*, 2006). With the adoption of the input-responsive and lodging tolerant semidwarf wheat cultivars that launched the green revolution in the 1960s, the amount of grain produced per unit of N applied has increased significantly (Ortiz-Monasterio *et al.*, 2001). Recent CIMMYT cultivars are better yielders than earlier semidwarfs and old tall cultivars at all nitrogen levels (Ortiz-Monasterio *et al.*, 2001). CIMMYT bread wheats do not require more N than the old tall cultivars; they often need less N to produce the same yield. In addition, since CIMMYT bread wheats are more responsive to N application, the optimum economic rate is higher than that for the old tall cultivars (Ortiz-Monasterio *et al.*, 2001).

It was observed that a combination of high uptake and utilization efficiency was needed to achieve a high agronomic N efficiency (yield at a given N supply) in maize, whereas, oilseed rape cultivars achieved high NUE exclusively by high uptake efficiency. N-efficient cultivars of both crops were characterized by maintenance of a relatively high N-uptake activity during the reproductive growth phase. In rape, this trait was found to be linked with leaf area and photosynthetic activity of leaves (Weisler *et al.*, 2001). It was seen that plant species with a higher specific leaf area, in general, allocated a larger fraction of organic nitrogen to thylakoids and Rubisco, which increased NUE (Poorter and Evans, 1998).

C4 plants are more efficient users of nitrogen than C3 species

Maize, a C4 plant is a high N efficient plant as C4 species make more efficient use of their nitrogen, soluble protein, and RuBP carboxylase protein than C_3 species such as wheat or rice under atmospheric CO_2 conditions. This may be due in part to the CO_2-concentrating mechanism in the bundle sheath around Rubisco in C_4 photosynthesis. However, CO_2 enrichment during CO_2 assimilation measurements increased NUE in the C_3 species as well (Oaks, 1994). In an experiment CO_2 assimilation measured under saturating CO_2 showed N, soluble protein, and RuBP carboxylase protein use efficiencies of wheat equal to or greater than that of the C_4 species (Schmitt and Edwards, 1981). In addition, the lower amount of Rubisco allowed a greater N investment in the thylakoid components in maize. This greater content of the thylakoid components in turn may support higher NUE for photosynthesis (Makino *et al.*, 2003). In another study, the C4 sub-types, NADP-malic enzyme (ME) and NAD-ME species were grown under adequate or deficient nitrogen (N) supplies and it was observed that NUE at both photosynthetic (assimilation rate per unit leaf N) and whole-plant (dry mass per total leaf N) levels were greater in NADP- ME than NAD-ME species (Ghannoum *et al.*, 2005). This was attributed to NADP-ME species having less leaf N, soluble protein, and Rubisco having a faster kcat i.e. faster turnover rate, than NAD-ME species.

Genetics of NUE using QTL analysis

Evaluating the genetic basis of NUE in plants has been made possible with the development of molecular markers. Quantitative trait loci (QTL) mapping consists of identifying (through linked genetic markers) the individual genetic factors influencing the value of a quantitative trait. Understanding the complexity of the N metabolism network through QTL analysis could lead to the cloning of regulatory loci or factors interacting with them. In maize, when the variation in physiological traits and yield components were compared, a positive correlation was observed between nitrate content, glutamine synthetase (GS) activity and yield (Hirel *et al.*, 2001). The results suggested that increased productivity in maize genotypes was due to their ability to accumulate nitrate in their leaves during vegetative growth and to efficiently remobilize this stored nitrogen during grain filling. Loci that appeared to govern quantitative traits were identified on the maize genome map and the positions of the QTLs for yield components and the location of the genes for cytosolic GS were shown to coincide. This was true for rice as well (Obara *et al.*, 2001). These results suggested that GS might be a key component of NUE and yield (Gallais and Hirel, 2004). It appears that the GS locus on chromosome 5 is a good candidate gene that can, at least partially, explain variations in yield or kernel weight. Similarly, identifying candidate genes and analysing their expression patterns could help in improving NUE. Hence, marker-assisted selection can play an important role along with classical breeding.

Improving plant NUE or controlling soil N requires a better knowledge of the regulation of plant N metabolism. Hence, *Arabidopsis* has been used as a model genetic system, due to the natural variation amongst its ecotypes (Loudet *et al.*, 2003). A large number of QTLs were identified representing potentially at least 18 genes that are polymorphic between Bay-0 and Shahdara recombinant lines. Candidate (structural) genes from N metabolism were assigned to some of these loci. *AAP5*, an amino acid transporter, and *GLN1.2*, a gene coding for cytosolic GS, colocalize with L1 locus; *NRT2.6*, a putative high-affinity nitrate transporter, colocalizes with L4 locus.

Nitrate assimilation

Nitrate uptake and transporters

Inorganic N is available to plants in both anionic and cationic forms (NO_3^- and NH_4^+, respectively). The relative abundance of these two ions in natural soils is highly variable and to a large degree depends on the relative rates of two microbial processes: mineralisation (the release of NH_4^+ from organic N) and nitrification (the conversion of NH_4^+ to NO_3^-) (Marschner, 1995). In well-aerated soils nitrification is rapid, so that NH_4^+ concentrations are low and NO_3^- is the main N source, but in waterlogged or acidic soils nitrification is inhibited and NH_4^+ accumulates. Most plants are able to use either form. The first step in nitrate assimilation is uptake of nitrate from the soil solution. Nitrate concentrations vary widely with typical levels in agricultural soils ranging from 1-10 mM. Uptake occurs in the outer cell layers of the root by active transport processes. Various environmental and internal signals influence the rate of uptake into roots. NO_3^- itself acts as an inducer. NO_3^- uptake is also subject to feedback inhibition and responds to signals from the shoot. The uptake system is mediated by transporters located on the plasma membrane of the epidermal and cortical cells (Crawford and Forde, 2002). Two such transport systems; low affinity transport systems (LATS), and high affinity transport systems (HATS) have been identified in wheat, rye and triticale (Abrol *et al.*, 1999) (Fig 1).

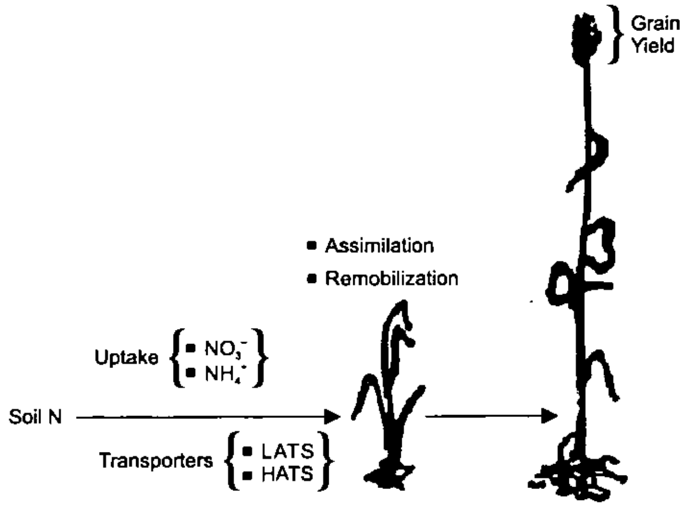

Fig 1. A schematic representation of the flow of nitrogen into the plant involving both uptake and utilization processes. LATS - Low affinity transport system; HATS - High affinity transport system

The genes encoding nitrate transporters have been found in both prokaryotes and higher plants. The Arabidopsis nitrogen (nitrate) transporter gene *AtNRT1.1* was originally isolated in screens for chlorate resistance and then cloned by T-DNA tagging (Crawford and Forde, 2002). This gene is part of the PTR family (short for peptide transporters). *AtNRT1.2* is a low affinity NO_3^- transporter that is constitutively expressed in root epidermal and root hair cells (Crawford and Forde, 2002). High affinity nitrate transporters such as *AtNRT2.1* and *AtNRT2.2* have also been found to be NO_3^- inducible and NH_4^+ repressible. NRT2 family of transporters have been proposed to be a components of HATS in plants (Crawford and Forde, 2002). However, the overexpression of nitrate transporters has been shown to affect NO_3^- influx but no phenotypic effect on NUE has been seen to date (Raghuram *et al.*, 2006).

Nitrate and nitrite reductase

Two successive enzymatic steps in the nitrogen assimilation pathway reduce nitrate to ammonia. Nitrate is first converted to nitrite by nitrate reductase (NR) and then nitrite is translocated from the cytoplasm to the chloroplast, where it is reduced by nitrite reductase (NiR) to ammonium (Fig 2). The expression of the NR genes is influenced by several endogenous and environmental factors in plants and is highly regulated at the transcriptional, translational and post-translational levels (Good *et al.*, 2004). *Nia* gene, which encodes NR in higher plants, is conserved among plants and is present in multiple copies per haploid genome. Transgenic plants overexpressing NR activity in tobacco showed no differences in chlorophyll, proteins or amino acid accumulation and reduced levels of nitrate (Table 1). Overexpression of nitrite reductase (NiR) genes in Arabidopsis and tobacco showed no phenotypic differences between the control and transgenic plants (Cre'te' *et al.*, 1997). However, the NiR activity was found to be higher in transgenic *Arabidopsis* (Table 1; Takahashi *et al.*, 2001). Thus, overexpression of either the NR or the NiR genes in plants has been shown to increase mRNA levels, and often affects N uptake but this does not seem to increase the yield or growth of the plants regardless of the nitrogen source available. This is believed to be partly due to the complex regulation of the nitrogen assimilatory pathway.

$$NO_3^- \xrightarrow{NR} NO_2^- \xrightarrow{NiR} NH_4^+$$

$$NH_4^+ + \text{glutamate} + ATP \xrightarrow{GS} \text{glutamine} + ADP + Pi$$

$$\text{Glutamine} + \alpha\text{- ketoglutarate} + NAD(P)H \xrightarrow{GOGAT} 2\ \text{glutamate} + NAD(P)^+$$

Fig 2. Nitrogen assimilation pathway. NR - nitrate reductase; NiR - nitrite reductase; GS - glutamine synthetase; GOGAT - glutamate synthase

Table 1. Transgenic plants overexpressing genes involved in nitrogen uptake and assimilation

Gene	Gene Action	Plant species	Phenotype
Nrt1.1	Nitrate transporter	*Arabidopsis*	Nitrate uptake
Nrt2.1	Nitrate transporter	*Nicotiana tabaccum*	Nitrate content
Nia2	Nitrate reductase	*Solanum tuberosum*	Reduced nitrate levels
Nia	Nitrate reductase	*Lactuca sativa*	Nitrate content, nitrate levels
NR	Nitrate reductase	*Nicotiana tabaccum*	Biomass, NR activity, drought stress
NiR	Nitrite reductase	*Arabidopsis*	NO_2 assimilation
GS1	Glutamine synthetase (cytosolic)	*Triticum aestivum*	Enhanced capacity to accumulate nitrogen
NADH-GOGAT	NADH-dependent glutamate synthase	*Oryza sativa*	Enhanced grain filling
NADH-GOGAT	NADH-dependent glutamate synthase	*Nicotiana tabaccum*	Higher total carbon and nitrogen content in shoots, dry weight

Source: Good *et al.* (2004)

Ammonium assimilation

Ammonium uptake and transporters

Ammonium uptake is also mediated by LATS and HATS (Rawat *et al.*, 1999). The LATS only becomes evident at external NH_4^+ concentrations above 1 mM (Rawat *et al.*, 1999). However, the precise mechanism of NH_4^+ influx across the plasma membrane is still not fully resolved. It has been established for a wide range of plant species that the HATS for NH_4^+ (but not the LATS) is highly regulated according to the N nutrition of the plant (Crawford and Forde, 2002). This is true in Arabidopsis as well (Crawford and Forde, 2002). The Arabidopsis AtAMT1.1 gene was the first NH_4^+ transporter gene to be cloned from higher plants. Subsequently, two closely related cDNAs (AtAMT1.2 and AtAMT1.3) were isolated by homology. The AMT genes encode hydrophobic proteins of 475-514 amino acids and belong to a probably ubiquitous gene family (the AMT/MEP family), which has known members in bacteria, archaea, fungi, plants and animals (Saier *et al.*, 1999). Most of the members of this gene family has been characterized in terms of function and regulation. However, there have been few studies that report the overexpression of these genes in plants and, to date, the consequences of the overexpression of ammonium transporters on NUE or other growth parameters has not yet been established.

Glutamine synthetase and glutamate synthase

The generation of mutants or transgenic plants with altered levels of GS/GOGAT have been used to determine the effects of these proteins on plant development and to study the expression of the different members of the GS multigene family (Good *et al.*, 2004). The two GS isoforms are located either in the cytosol (GS1) or in the plastids (GS2) and have specific functions in assimilating or recycling ammonium. Although several studies have demonstrated an increase in GS transcripts in transgenic plants, many have been unable to show any direct increase in activity or phenotype associated with this trait (Raghuram *et al.*, 2006) which indicated post-transcriptional regulation. Increases in plant biomass have been shown in GS overexpressing pea and tobacco plants (Fei *et al.*, 2003; Oliveira *et al.*, 2002). However, in pea, the results were not consistent for a second transgenic line (Fei *et al.*, 2003) suggesting that overexpression of GS does not always lead to an increase in GS activity and biomass accumulation. Several studies have demonstrated a direct correlation between an enhanced GS activity in transgenic plants and biomass or yield (Oliveira *et al.*, 2002). These studies suggest that the overall level of nitrogen assimilation can be enhanced using the GS1 genes.

GOGAT catalyses the reductant-dependent conversion of glutamine and 2-oxaloglutarate to two molecules of glutamate and occurs as two distinct isoforms, ferredoxin dependent (Fd-GOGAT) and NADH dependent (NADH-GOGAT)

(Fig 2). Yamaya *et al.* (2002) overexpressed NADH-GOGAT in rice under the control of its own promoter and found that transgenic rice plants showed an increase (up to 80%) in grain weight (Table 1). This study showed that overexpression of NADH-GOGAT can be used as a key step for nitrogen use and grain filling in rice and other cereal crops. Hence, transgenic plants over-expressing transferred GS or GOGAT genes could be used to improve NUE in agronomic crops.

Thus, even though map-based cloning is labour intensive, identifying candidate genes and analysing their expression patterns will allow us to focus more quickly on genes that improve NUE. However, for complex metabolic traits such as NUE, there is need for the use of transgenics in tight coordination with classical breeding and marker-assisted selection if these introduced genes are to provide the maximum benefit (Good *et al.*, 2004). Improving NUE in plants by overexpressing individual enzymes of nitrate and ammonia assimilation has not been so successful indicating that there is no single point rate limiting regulation (Andrews *et al.*, 2004; Raghuram *et al.*, 2006). This is especially true for enzymes of primary nitrate assimilation, while, enzymes of secondary ammonium assimilation seem to hold more promise, especially in cereal crops (Andrews *et al.*, 2004).

Potassium

Globally the application of potassium has decreased since the late 1980's although this decrease includes substantial variation across countries (FAOSTAT, 2002). In many developing African countries, the use of inorganic fertilizers is very low which causes nutrient depletions. On poorer soils withholding K^+ fertilizer will eventually lead to yield reductions. In the Indo-Gangetic plains of south Asia the rice-wheat cropping system removes the highest amount of potassium as very little or no potassium fertilizers are being applied and thus most of it comes from the potassium reserves of the soil (Bijay-Singh *et al.*, 2003). Each harvest leaves the soil poorer with respect to potassium. Imbalance in the use of nitrogen, phosphorus and potassium is further creating situations which may lead to reduced sustainability of the rice-wheat cropping system. Hence K may be a limiting resource under high cropping intensity.

Potassium is one of the major essential elements required by plants and is present in cells exclusively as its monovalent ion. Potassium is not an incorporated component of plant molecules as opposed to N and P, which are constituents of proteins, nucleic acids, phospholipids, ATP etc. K^+ predominantly exists as a free or absorptive bound cation and can therefore be displaced very easily at the cellular level as well as in the whole plant. K^+ plays an important role in metabolism, growth and stress adaptation. These functions can be classified into those that rely on high and relatively stable concentrations of K^+ in certain cellular compartments and those that rely on K^+ movement between different compartments, cells, or tissues. The first class of functions includes enzyme activation, stabilization of protein synthesis, and neutralization of negative charges on proteins (Marschner, 1995). The second class of functions of K^+ is linked to its high mobility. This is particularly evident where K^+ movement is the driving force for osmotic changes as, for example, in stomatal movement, light-driven and seismonastic movements of organs, or phloem transport. In other cases K^+ movement provides a charge-balancing counter-flux essential for sustaining the movement of other ions. Thus, energy production through H^+-ATPases relies on overall H^+/K^+ exchange. The most general phenomenon that requires directed movement of K^+ is growth. Accumulation of K^+ (together with an anion) in plant vacuoles creates the necessary osmotic potential for rapid cell extension. Optimal growth, as measured by fresh or dry weight, occurs when K^+ is present in shoots at concentrations of at least 1-2 % in dry matter (Leigh and Wyn Jones 1984), although most plants accumulate K^+ to much higher concentrations (Broadley *et al.*, 2004). These supra-optimal concentrations reflect the large proportion of total K^+ that is located in the vacuole while growth limitations at lower concentrations are thought to indicate the point at which K^+-dependent processes in the cytosol are compromised (Leigh and Wyn Jones, 1984). Accumulation of K^+ to concentrations in excess of those needed for maximal growth is termed luxury uptake and is agronomically wasteful because it results in a decrease in the amount of dry matter produced per unit amount of K^+ absorbed (K^+- use efficiency; Marschner, 1995). Optimal concentrations of K^+ in crops are usually maintained by the addition of fertilizers, but it might be possible to breed more K^+-efficient crops if the genes determining K^+ concentrations in plants were known.

Genetic variability in KUE

The ability of plants to uptake and efficiently use potassium varies within and across species within a wide range. Varietal differences have been observed in rice, barley, tomato, Arabidopsis etc. Differential genotypic requirements for K^+ and the underlying causes of differences in K^+ utilization need to be understood. Three barley varieties selected according to their relative growth and utilization efficiencies when grown at low (10 mmol m^{-3}) and high (100 mmol m^{-3}) external K^+ concentrations were analyzed for subcellular compartmentation between vacuole and the cytoplasm in the roots (Memon *et al.*, 1985). At low K^+ concentration the inefficient variety exhibited typical K^+ deficiency symptoms and failed to mobilize vacuole K^+ into the cytoplasm compartment although it had high K^+ in shoots and roots. The efficient variety which demonstrated pronounced growth responses to increased K^+ showed significant increases of cytoplasm K^+ in this range. By contrast, the efficient non-responder variety whose growth is not stimulated by increased K^+ showed virtually no increase in cytoplasm K^+. These results highlight (1) the importance of subcellular distribution of K^+ between cytoplasm K^+ and vacuole and indicate that (2) critical cytoplasm requirement for optimal growth may be significantly lower in some efficient cultivars. It seems that this level of K^+ in the cytoplasm is adequate for maintaining the biophysical and biochemical processes especially protein synthesis for maximum biomass production in these varieties (Memon *et al.*, 1985).

Potassium uptake by the plant involves absorption by the root, mobilization from root to shoot and also the utilization. Hence, differences in KUE have been analysed in relation to the component processes. Tomato cultivars differing in KUE showed similar potassium transport rates from root to shoot (Chen and Gabelman, 1999). Transgenic Bt cotton showed premature senescence and K^+ deficiency symptoms more often than the conventional cultivars in the fields in China. Cotton requires K^+ at the late growing stage and K^+ deficiency can reduce cotton yield quality and results in premature senescence (Zhu *et al.*, 2000). Studies on the response of transgenic and conventional cultivars to K^+ deficiency were examined in terms of growth and K^+ absorption rates. (Zhang *et al.*, 2004). Seedling growth of transgenic cottons was reduced more under low K^+ than conventional cultivars. K^+ absorption and K^+ content in leaf and root of transgenic cotton were higher than conventional cultivars under low K^+. Hence growth differences between transgenic cultivars and conventional cultivars may be the result of the efficiency with which K^+ is utilized in these cultivars.

Efficient uptake of nutrients contributes significantly towards higher NUE. The size of the root system, the physiology of uptake and the ability of plants to increase K^+ solubility in the rhizosphere are important components of uptake efficiency. Steingrobe and Claassen (2000) compared wheat, sugarbeet and potato for K^+ uptake efficiency both in solution culture and field conditions. They observed that wheat and sugarbeet were more K^+ efficient than potato because wheat had a large root system and both species had an efficient uptake physiology. In soil also wheat was more efficient because of a large root system where as the efficiency of sugarbeet was caused by the ability to increase K solubility. Høgh-Jensen *et al.* (2003) examined the ability of several crops including cereals, pulses, oil seed and perennial ryegrass to adapt to low potassium conditions with respect to root surface and root volume. The legumes (pea, red clover, Lucerne) accumulated larger amount of nitrogen but lower amount of potassium than rye, ryegrass, barley and oil seed rape. The differences in K^+ accumulation correlated with root hair length (Fig 3). Rye had an outstanding root surface, which in total and per unit root matter was twice that of other crops. The ranking in decreasing order was rye, ryegrass, oil seed rape, Lucerne, barley, pea and red clover. Hence crops modify their root hair length as response to low potassium conditions and maintain the uptake from soluble potassium sources.

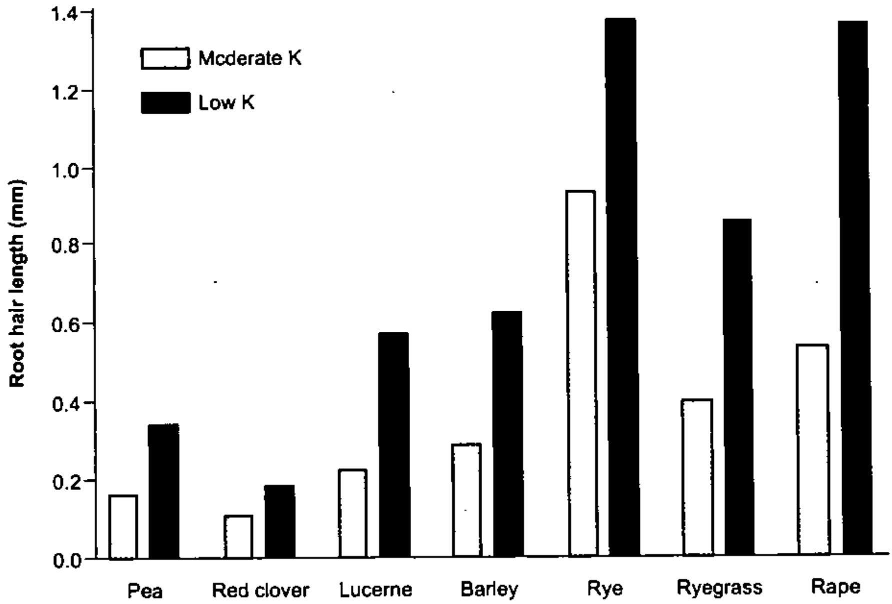

Fig 3. Root hair length (mean ± SE; n = 3) of roots per container for seven different crops grown in soils with moderate (60 mg K kg-1 soil) or low (26 mg K kg-1 soil) potassium levels (Source: Høgh-Jensen *et al.*, 2003)

K^+ transporters and their role

Plants have multiple mechanisms for K^+ uptake from soil and translocation to various plant tissues to help them respond to changing environmental conditions and the varying K^+ requirements in different tissues. The high and low affinity K^+ uptake system proposed by Epstein and colleagues have now been investigated using biophysical methods and subsequently analyzed at the biochemical and molecular level.

There are five major families of K^+ transporters that have been identified in Arabidopsis (Table 2; Véry and Sentenac, 2003). These are (i) Two families of K^+ channels i.e. Shaker-type and KCO channels; 15 genes in total (ii) Trk/HKT transporters [Na^+/K^+ Symporter]; one gene (iii) KUP/HAK/KT transporters [H^+/K^+ symporters]; 13 genes (iv) K^+/H^+ antiporter homologs; 6 genes (v) cyelic-nucleotide-gated channels (CNGC); 20 genes. The Shaker-type channels are further subdivided into SKOR, GORK, KAT and AKT channels.

Table 2. Some members of the cloned K^+ transporters in Arabidopsis and various crops

Family	Group	Members	Plant Species	Organ
Shaker	KAT1	KAT1, KAT2	Arabidopsis	Leaf
		KST1	Potato	Leaf, flower
	AKT1	AKT1, AKT6	Arabidopsis	Flower
		LKT1	Tomato	Root, leaf
		SKT1	Potato	Leaf
		TaAKT1	Wheat	Root
		ZMK1	Maize	Root
	AKT2	AKT2	Arabidopsis	Leaf
		ZMK2	Maize	Leaf
	AtKC1	AtKC1	Arabidopsis	Root, leaf
	SKOR	SKOR, GORK	Arabidopsis	Root
HKT		HKT1	Arabidopsis,	Root
			Barley, Rice, Wheat	Root
		HKT2	Rice	Root
KUP/HAK/KT		KUP1, KUP2, KUP3, KUP4	Arabidopsis	Flower, leaf, root, stem
		KT1	Cotton	Fibre
		HAK1	Barley, rice	Root
		HAK2	Barley	Root
		HAK7, HAK10	Rice	Root, shoot
KCO		KCO1, KCO6	Arabidopsis	Root, flower, leaf

Source: Véry and Sentenac (2003)

The largest gene family of K transporters in *Arabidopsis* is the AtKT/KUP family. These transporters were originally identified in *E. coli* as KUPs (K^+ uptake permeases) and only recently in plants. Studies in plants show that these transporters are involved in both high and low affinity K^+ transport. KT/HAK/KUP gene expression is often found in all tissues in wide range of species (Kim *et al.*, 1998). The transcript levels of several KT/HAK/KUP were up-regulated in roots and shoots of Arabidopsis, rice and tomato in response to K^+ deprivation (Kim *et al.*, 1998).

Detailed spatial and temporal expression patterns of each AtKT/KUP genes in Arabidopsis has been examined and their K^+ transport function was demonstrated using *E. coli* (Ahn *et al.*, 2004). Ten AtKT/KUP genes expressed in root hairs while only 5 genes expressed in root tip cells. This suggests an important role for root hairs in K^+ uptake. Root hair mutants of Arbidopsis exhibited lower uptake rates for K^+ but showed decreased plant biomass only when K^+ concentrations were low. Only one gene At/HAK.5 was upregulated under K^+ deficiency and was shown to function as a high affinity transporter. Characterization of some transport systems is providing exciting information at the molecular level on functions such as root K^+ uptake and secretion into the xylem sap, K^+ transport in guard cells or K^+ influx into growing pollen tubes.

Plant shaker channels share similarities, both at the sequence and structure levels, with animal voltage-gated K^+ channels forming the so-called Shaker family. Animal Shaker channels are made up of four subunits arranged around a central pore. The hydrophobic core of each subunit consists of six transmembrane segments (TMS), the fourth one with repetition of basic residues acting as a voltage sensor. A highly conserved membranar loop, located between the fifth and the sixth TMS and called the P (pore) domain, forms part of the selectivity filter of the ion-conducting pore. This loop contains a TxxTxGYGD motif, the hallmark of K^+-selective channels. The plant Shaker cytosolic C-terminal region harbors regulatory domains comprising a putative cyclic nucleotide-binding site and, at the extreme C terminus, the so-called KHA region (rich in hydrophobic and acidic residues), which might be involved in subunit tetramerization and/or channel clustering in the membrane. An ankyrin domain, hypothesized to be a site of interaction with regulatory proteins, is present in most channels (e.g., in six of the nine Arabidopsis Shakers) between the putative cyclic nucleotide-binding site and the KHA region (Véry and Sentenac, 2003).

Most plant Shakers identified so far have been successfully expressed and characterized in heterologous systems i.e. *Xenopus oocytes*, insect and mammalian cell lines, or yeast (Table 3). Like their animal counterparts, they form K^+-selective channels strongly regulated by voltage. They are active at the plasma membrane and mediate K^+ transport at millimolar concentration. The Arabidopsis shaker family is the best-characterized family of plant transport systems. In the root AKT plays a role in K^+ uptake from soil solution and SKOR in K^+ release into the xylem sap. KAT1 takes part in guard cell K^+ uptake but is not essential for stomatal opening. SPIK is involved in K^+ uptake in pollen and is required for optimal pollen tube development. AKT2 is involved in long-distance K^+ transport via the phloem sap. AKT2 and AKT1 are important for mesophyll cell permeability while GORK mediates K^+ release from guard cells during stomatal closure (Shabala, 2003). AKT6 has been shown to be localized in flowers.

Table 3. Candidate K^+ and cation transporter genes with loci that coincide with the QTLs for K^+ concentrations

QTL (and position in cM)	Candidate genes and positions in cM[a]
KFM2.1 (40)	*AtAKT1* (51), *AtAKT6* (47), *AtCNG6* (40), *AtCNGC14* (40)
KFM4.1 (43)	*ATHAK5* (46)
KFM5.1 (82)	*AtKAT1* (97), *AtTPK2* (98), *AtKCO3* (98)
KFM5.2 (106)	*AtKTPK1* (112), *AtCNGC1* (109), *AtCNGC5* (113), *AtKEA5* (109), *AtNHX3* (112)
KDM3.1 (0)	*AtSKOR* (7)

[a]Positions are those in the AGI (Arabidopsis Genome Initiative) map (http://www.arabidopsis.org/servlets/mapper)

Among the KCO channels KCO1 is expressed throughout plant and is localized at the tonoplast. The channels have a hydrophobic core and have putative Ca^{2+} binding sites in their cytosolic C-terminal region. As more K^+ channels and transporters are identified K^+ transport in plant appears to be much more complex than originally thought in 1980's. Most types of K transport systems are encoded by large gene families and systems from the same family are expressed differentially in various tissues. Large variations in transcript levels have been found for both K channels and transporters in the course of plant development and in response to environmental changes. Studies on K^+ transporters have been mainly concerned with transcriptional regulation in response to K^+ starvation, salt stress and hormones. Upregulation of HAK transcripts in common ice plant upon salt stress could be an adaptation limiting Na^+ accumulation and favouring K^+ selective uptake (Su *et al.*, 2001). In Arabidopisis, ABA, cytokinins or auxin have been shown to strongly affect K^+ channel expression providing the first molecular clues regarding hormonal control of K^+ transport. Expression analysis of shaker channels localized in phloem indicating regulation by light and sugars have advanced molecular analysis of the coupling between phloem K^+ transport and sugar production and allocation.

QTL's for variation of K^+ concentration in shoots

Genotype dependent variation of K^+ concentration in shoot has been reported in forage grasses (Vogel *et al.*, 1989), wheat (Zhang *et al.*, 1999) and maize (Harada *et al.*, 2001). In forage crops the genotypic variation in K^+ concentrations is important for identifying lines that will reduce the occurrence of hypocalcaemia (milk fever) and hypomagne sacmia in dairy cows, syndromes that are related to the mineral balance of plants. Other crops research is aimed at identifying the basis of K^+-use efficiency or increasing the discrimination of K^+ over Na^+ for salinity resistance

(Mathuis and Amt Mann, 1999). QTL analyses for variation in shoot K concentrations have been conducted in rice (Wu *et al.*, 1998; Koyama *et al.*, 2001; Ren *et al.*, 2005), sugarbeet (Schneider *et al.*, 2002) and *Miscanthus*. These studies have demonstrated the presence of loci affecting K^+ concentrations although the identity of the underlying genes remains largely unknown. In rice a QTL SKCI that maintained K^+ homeostasis in the salt tolerant variety under salt stress was cloned and shown to express in the parenchyma cells surrounding xylem vessels. SKCI protein was shown to be coincident with OsHKT8, a Na^+ transporter and is involved in regulating K^+/Na^+ homeostasis under salt stress, thus providing a potential tool for improving salt tolerance in crops (Ren *et al.*, 2005).

Natural variation in K^+ concentration in shoots of *Arabidopsis thaliana* accessions and a cape Verdi Island/Landsberg erecta recombinant inbred line population expressed on the basis of fresh matter (KFM) or dry matter (KDM) was mapped for QTLs. Four QTLs were identified for KFM and three for KDM located on chromosome 2, 3, 4 and 5. *In silico* analysis helped in identifying known or putative K^+ and cation transporter genes whose loci overlapped with the QTLs (Table 3). These include important genes such as AtAKT1, AtSKOR, AtKAT1, AtHAK5 etc. AKT1 is responsible for passive uptake of K^+ in roots and is localized in the plasma membrane of root epidermal and cortical cells and mesophyll cells. Plants with disrupted AKT1 or AtSKOR have lower K^+ concentrations than the wild type and do not grow as well (Broadley *et al.*, .2001). These genes are expressed in many plant parts including roots, xylem, flower stalks, hypocotyls and stomates etc. This is understandable as K^+ concentration in shoots of plants is affected by multiple processes including uptake and efflux by roots, storage in root cell vacuoles, loading into the xylem, uptake and storage in leaf cells and recirculation to the roots via phloem. Each step is managed by multiple transporters of varying specificity (Shabala, 2003; Véry and Sentenac, 2003) and hence the number of genes that can potentially influence natural variation in K^+ concentrations in shoots is large. Interestingly most of the K^+ transport genes that coincided with QTLs overlapped with the peaks for KFM rather than KDM thus justifying the osmotic role of K^+ dependent on tissue fresh matter. Further studies are needed to unravel the relative importance of each gene at each QTL.

Potassium plays an important role in contributing to the survival of crop plants under environmental stress conditions. Improvement of K^+ nutritional status of plants can greatly lower the ROS production under environmental stresses by reducing the activity of NAD(P)H oxidases (Cakmak, 2005). Conversely potassium deficiency is an important nutritional problem affecting crop production and quality. K-deficient plants are very sensitive to high light intensity, rapidly becoming chlorotic and necrotic. Photooxidative damage to chloroplasts is a major contributing factor in the development of K-deficient syndrome. The larger K requirement of plants under different abiotic stresses appears to be related to the inhibitory role of K against ROS production during photosynthesis and NADPH oxidase.

Under K^+ deficiency conditions plants enhance their capability of K^+ uptake by activating some K^+ transporters (Véry and Sentenac, 2003). A signaling process exists for the plants to "monitor" external K^+ concentration and respond to the low K-condition by enhancing the capability for K^+ acquisition. This signaling pathway represents a typical nutrient sensing and response process in plants about which information is now being generated (Armengaud *et al.*, 2004). Low K-status in the soil triggers elevated production of H_2O_2 in root hair cells that serves as a signaling molecule and alters the expression of K^+ transport gene AKT1 in a Ca^{++} dependent manner (Li *et al.*, 2006). More studies are needed to unravel the mechanism of K^+ ion channels so that this knowledge can be used for increasing the K^+-use efficiency of plants.

Conclusions

NUE is important to control the escalating costs of fertilizers along with the environmental damage. There have been a few successes in manipulating N metabolism in plants such as tobacco or Arabidopsis using specific genes involved in nitrate uptake and assimilation such as nitrate transporter genes *Nrt1.1*, *NRT2.1*, nitrate reductase genes *Nia*, *NR* etc. However, there is a need to evaluate these traits in economically important crops, as this has not been translated in terms of enhanced NUE. On the other hand, enzymes of secondary ammonium assimilation (cytosolic GS1 and NADH-GOGAT) seem to hold more promise in cereal crops and thus, can be used as targets for metabolic engineering.

Potassium is a major inorganic osmolyte, which is crucial for cell osmoregulation and turgor maintenance and, hence, for cell expansion, stomatal function, tropisms and leaf movement. Plants have evolved a sophisticated and highly specialized K^+ transport system to meet the different requirements for K^+ in various cells and tissues. A large number of genes encode proteins involved in K^+ transport in plants. Despite the tremendous progress in our knowledge of genes encoding K^+ transport systems in plants, understanding has not developed of coordinated functioning and operation of these genes or proteins in the context of whole plant physiology and plant-environment interaction. There is a need for functional studies of specific mutants to quantify the relative contributions of particular members of a gene family to plant adaptive responses to the environment.

Overall, a multidisciplinary approach in relation to nutrient use efficiency in crops is important. Genetic variability in relation to the components of nutrient use efficiency such as uptake, translocation and mobilization into grains need to be established. The genotypes showing contrasting behaviour in relation to the components of nutrient use efficiency can be used for further studies on the mechanisms and inheritance of the trait. Molecular techniques can help to identify the role of ion transporters/ channels in model systems as well as crops.

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Fertigation in the Arava Region – Nutrient Uptake and Farmers' Practice

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Abstract

The Arava is the most intensively cultivated and the most advanced agricultural region in Israel. Pepper is grown in more than 50% of the 2,000 hectares of agricultural fields in the Arava. The fertigation technique that is widely used in the region enables the growers to meet the needs of the plant and to maximize the yield (and profit). At the same time, once the farmer is aware of and cares about the environmental effects of his growing practices, he can apply precise fertigation management and so minimize problems like leaching of various nutrients below the root zone and into the groundwater. Growing on detached media combined with a system of recycling the fertigation water can be a sustainable solution.

In this paper, we present the results of measurements of nutrient uptake by pepper in four field experiments: two experiments with pepper grown in soil and two in detached media. In three of the four experiments the nutrient uptake was measured during the growing season and was separated between canopy and fruits. This separation allows us to better understand the uptake process during the growing season and to adjust the fertigation scheme to the crop and stage.

It can be concluded that NPK uptake by pepper ranges from 200 to 400 kg ha^{-1}. Potassium uptake is dominant during the reproductive stages, when adding too much N might impair the fruit yield, in both quality and quantity. We compared the measured uptake data with the recommendations of the Extension Service, and found quite large differences. These differences represent "lost" nutrients that might permeate into and pollute the groundwater aquifer.

In conclusion, it is recommended to follow the uptake curve functions as closely as possible, and fertigation is probably the best means to achieve this.

Keywords: Fertigation, nutrient uptake, farmers' practice, Arava region

The Central Arava Region measures 70 km in length and 25 km in width, and covers an area of about 150,000 ha, which is about 6% of the total area of Israel. There are five agricultural settlements (known as Moshavim), with a total of 2,700 residents.

The climate is arid, with only about 30 mm of rainfall annually. In the summer, temperatures regularly exceed 40°C and humidity is fairly low. Winter temperatures are mostly mild with few frost events every year.

The Arava is not connected to the national water system, and irrigation water is obtained from local wells. There are three main aquifers at varying depths that yield water of differing quality. In this region, where water availability is the most limiting factor for crop production, microirrigation (mostly drip irrigation) is a must, along with fertigation, which implements the simultaneous use of irrigation and fertilization.

The advantages of the Arava region include long hours of sunshine and relatively high temperatures, which lead to earlier crop ripening. This makes it possible to grow for export to Europe during the winter months - October through March - when prices are highest, with less expenditure of energy than required elsewhere.

Because of the harsh natural conditions, agriculture in the Arava is difficult. However, application of scientific and technological developments have overcome the natural limitations. Arava farmers provide nearly half of all Israel's vegetable exports and about 15% of its flower exports. Sophisticated agricultural techniques, computerized irrigation, and climate-controlled greenhouses are in common use. Advanced technologies used in protected agriculture include synthetic fabrics, cooling and heating devices and mechanisms, drip irrigation and fertigation, growth substrates, and insect pollinators.

Most of the 2,000 ha of agricultural area in the Arava is operated under protected conditions, mainly for growing vegetables (pepper, tomato and melon) and flowers. This intensive type of agriculture offers a relatively high level of control over the process: the use of detached growth media, which currently involves 3 to 5% of the region, together with recycling systems for water and nutrients, offers the possibility of almost complete control over the environmental aspects of the regional agriculture, by minimizing pollution of the aquifers.

The most desirable agricultural practice is one that is not only profitable but also sustainable, and, in most cases, sustainability relates to the impact on the environment. However, in intensive-growing systems such as those in the Arava region the costs of fertilizers and water are virtually negligible compared with the total costs. Therefore, savings on these items do not generally serve as an incentive to implement concepts and measures for maintaining sustainability. Nevertheless, fertigation is an environmentally sound practice that enables the production of high yields to be combined with careful and economical use of water and nutrients, so as to satisfy plant demands while maintaining sustainability.

The quality of soils, ground and surface waters is especially vulnerable in climatic regions where agricultural production is possible only through the use of irrigation. Such regions include the Arava and many other arid regions worldwide.

The regular excessive application of nitrogen fertilizers with the irrigation water is probably responsible for the increases in nitrate concentrations in the groundwater resources in these areas. The recent rise of chloride and nitrate concentrations (Fig 1) in several of the 54 wells used by the Arava farmers should be of concern. Precise fertigation practices are needed to allocate water and fertilizers so as to maximize their application efficiency, by minimizing fertilizer losses through leaching towards the groundwater.

Water and fertilization are interlinked in the fertigation practice that was first reported on field experiment of tomatoes performed in 1969. Adequate supplies of nutrients and water to satisfy plant demands from a limited soil root volume can only be achieved by synchronizing the water and nutrients supplies with the varying plant needs during the successive growing stages.

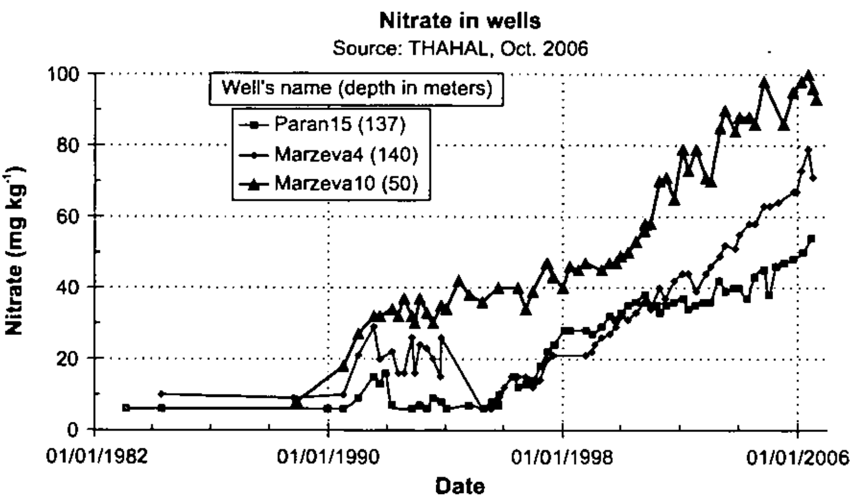

Fig 1. Nitrate concentration versus time (1982-2006) in the Arava region of Israel. All three wells are very close to fields used for intensive agriculture, on which large amounts of N are applied (Personal communication)

A fertigation management scheme is shown in Fig 2. It can be divided to three main areas: the plant, the growing media and the irrigation water. The uptake process is a surface phenomenon and these three areas are interrelated as is shown in the Michaelis-Menten model that can be used to quantify the uptake process (Bar Yosef, 1999):

$$U \quad U_{max} \frac{C_r}{K_m + C_r} \qquad [1]$$

in which U is the uptake rate per unit length of root (g cm^{-1} sec^{-1}), U_{max} is the maximal possible uptake rate, C_r (g L^{-1}) is the concentration of the nutrient in the soil or more precisely in the rhizosphere, and K_m is a plant coefficient (g L^{-1}). Since U is based on the root dimensions, the plant uptake will increase with increasing root surface area participating in the uptake process. The same applies to the dependence of the uptake on the concentration of the nutrient in the soil solution.

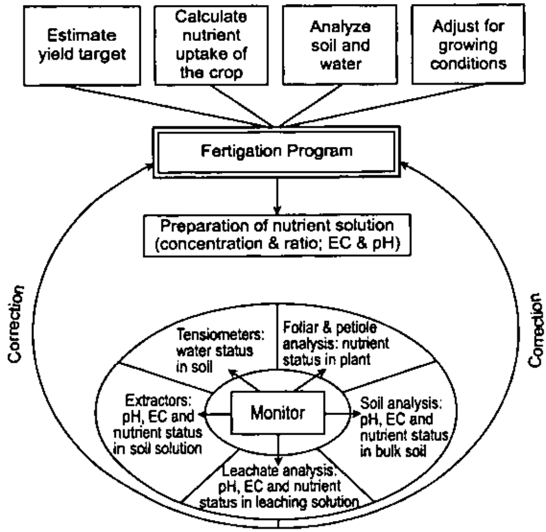

Fig 2. Fertigation management scheme

Fertigation enables the amount and concentration of the applied nutrients to be adjusted to match the actual nutritional requirement of the crop throughout the growing season. In order to correctly plan the nutrients supply to the crop according to its physiological stage, we must know, throughout the growing cycle, the optimal daily nutrient uptake rate that results in maximum yield and highest product quality. Knowledge of the nutrient uptake rates (or amounts) during the various stages of the growing season is essential for the farmer to achieve the appropriate practice. Also, one has to take into account the efficiency of the fertigation process, in order to supply nutrients to the crop in accordance with the optimal amounts, concentration, timing, etc.

This paper focuses on the plant aspect of fertigation planning, as illustrated by measurements of the nutrients uptake of pepper in four different experiments: Bar-Yosef *et al.* (1980), Scaife and Bar-Yosef (1995), Tzipilevitch *et al.* (1994) and Gantz *et al.* (2004). Pepper was chosen as the plant model because it is the major vegetable grown in the Arava, where it occupies more than 1,000 ha out of the total 2,300 ha of agricultural land. Bar Yosef *et al.* (1980) and Scaife and Bar Yosef (1995) addressed pepper growing on soil in the Arava region; the other two experiments addressed growing on detached media in the northern Jordan valley and the western

Negev of Israel, respectively. We will compare these data with fertigation recommendations of the Israeli Extension Service (2006).

Nutrient Uptake

Nutrient uptake data are specific for each crop and climate, and can be either estimated or measured in field experiments. Scaife and Bar-Yosef (1995) measured the N, P, and K uptakes of the main crops in Israel, i.e., peppers, tomatoes, cucumbers, melons, maize, etc.

Daily and accumulated N, P, and K uptakes of bell pepper cv. Maor are shown in Table 1 (Scaife and Bar-Yosef, 1995). The peppers were planted on July 14th, at a density of 100,000 plants ha^{-1} in sandy soil, and were harvested selectively to obtain a total marketable yield of 75 t ha^{-1}. Table 1 shows four stages of the growing season, which are the same as those used by the Extension Service in its fertigation recommendations: initial establishment (~ 2 weeks); vegetative to fruit set (3-4 weeks); fruit set to first harvest (5-6 weeks); and harvesting, that can last up to 20 weeks. The main purpose of such data is to enable the supply of the different nutrients to be matched to the plant demand, thus maximizing nutritional efficiency. The direct outcome of maximizing nutritional efficiency is minimization of leaching of nutrients out of the system.

Table 1. Daily and accumulated NPK uptake of bell pepper planted in sandy soil in the Arava on July 14th; marketable yield of 75 tonne ha^{-1}

Plant Stage	Days after emergence or planting	Daily uptake ($kg\ day^{-1}\ ha^{-1}$)			Accumulated uptake ($kg\ ha^{-1}$)		
		N	P	K	N	P	K
Initial establishment	1 - 10	0.1	0.01	0.1	1	0.1	1
	11 - 20	0.5	0.10	0.9	6	1.1	10
Vegetative to fruit set	21 - 30	1.5	0.10	1.25	21	2.1	22
	31 - 40	1.6	0.20	1.25	37	4.1	35
	41 - 50	1.7	0.25	2.5	54	6.6	60
Fruit set to first harvest	51 - 60	1.6	0.35	4.5	70	10.1	105
	61 - 70	1.7	0.45	5.0	87	14.6	155
	71 - 80	2.6	0.35	4.5	113	18.1	200
First to last harvest	81 - 90	2.8	0.35	3.5	141	21.6	235
	91 - 100	2.5	0.35	5.0	166	25.1	285
	101 - 110	2.5	0.25	5.5	191	27.6	340
	111 - 120	1.5	0.25	3.0	206	30.1	370
	121 - 130				206	31.1	370
Total ($kg\ ha^{-1}$)					206	31.1	370

Source: Scaife and Bar-Yosef, 1995

As seen in Table 1, when the crop was first seeded/transplanted, small amounts of nutrients were taken up as the crop was growing slowly and its root volume (more accurately, its root surface area) was small. The amounts increased as the growth rate and root density increased. As the crop matured and growth slowed, the nutrients uptake rates decreased accordingly. The ratio (N:P:K) between the nutrient uptakes also varies through the season. Early in the season the uptake includes high proportions of P and K, for best rooting and plant establishment. When the plants become vegetative, N uptake is relatively high, for best leaf growth and development. As the fruit load grows, the proportion of K increases to ensure the best fruit setting, development and quality. High K uptake is associated with heavy fruit loads of vegetable crops and massive stalk development of flower crops. At the same time, the proportion of N should be reduced, to prevent lush growth, soft fruit and pest problems.

In the second experiment (Bar Yosef *et al.*, 1980), 90,000 plants ha^{-1} were seeded on August 26, 1978, after application of methyl bromide at 300 kg ha^{-1}, as soil disinfectant, and 95 mm of sprinkled water for leaching. Two irrigation levels and four fertilization levels were studied in this experiment. In the present paper we present and compare the high levels of irrigation and fertilization with the normal and recommended levels of irrigation and fertilization (designated below as "high" and "recommended"). In both experiments, the N:P:K ratio was kept constant at 1.46:0.1:1 during the first 50 days of the season and at 0.83:0.1:1 afterwards. The fertilizers used were ammonium nitrate, potassium nitrate, and phosphoric acid. The NO_3^-/NH_4^+ ratio was 3:1. The irrigation rate was based on the following equation:

$$I = E_0 \cdot F \cdot P \cdot R \qquad [2]$$

where I is the irrigation amount (mm), E_0 is pan A evaporation (mm), P is the vegetal coverage of the field, R is the fruit-fill factor and F is the experimental factor.

The main characteristics of the two treatments are shown in Table 2:

Table 2. The main characteristics and yields of the "High" and "Recommended" treatments

Treatment	F (Eq. 2)	Irrigation amount (mm)	Fertilization factor	Applied N (kg ha^{-1})	Total yield, exportable yield and SD (t ha^{-1})
High	1.1	887	1.5	800	128, 69.5 (10.9) *
Recommended	0.8	683	1.0	380	80, 62.1 (15.0)

* Figures in parentheses are standard deviation (SD)

Source: Bar-Yosef *et al.*, 1980

Accumulation of fresh matter in the "High" treatment is shown in Fig 3, in which canopy and fruits are shown separately. The unexpected dips in the accumulations are due to fall of leaves and fruits. The accumulation of N in both plants and soil (Fig 4) can throw some light on what happened during some crucial period of the growing season. The reduction of soil-N between days 75 to 95 was probably due to an earlier intensive uptake by the plants that was not fully replaced by the fertigation regime. The total uptake of N was 435 kg ha^{-1} whereas 800 kg ha^{-1} were applied (Table 2). This is very significant in relation to the rise of NO_3^- concentration in the shallow aquifer beneath the fields of the Arava (Fig 1).

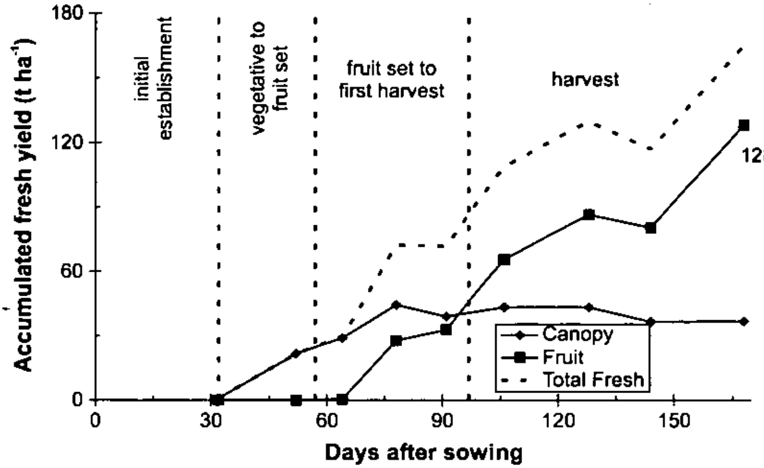

Fig 3. Accumulated fresh organic matter of canopy and fruits of the "High" treatment (Bar-Yosef *et al.*, 1980)

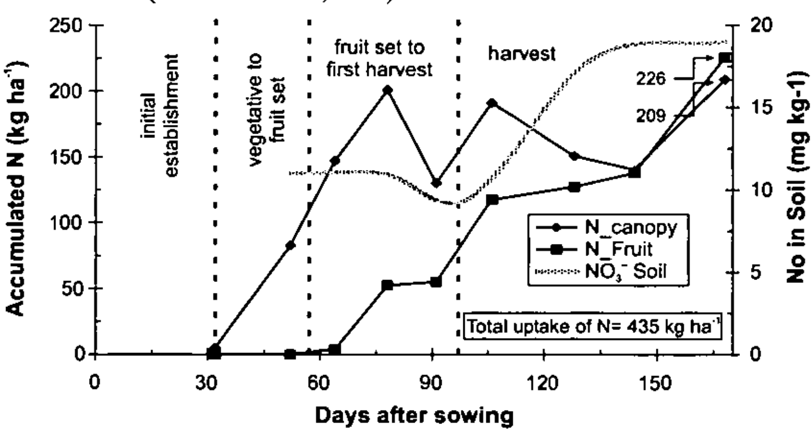

Fig 4. Accumulated N in canopy and fruits (left y-axis) and soil-NO_3^- concentration (right y-axis) of the "High" pepper treatment (Bar-Yosef *et al.*, 1980)

Bar Yosef et al. (1980) also collected the corresponding data for K and P (Fig 5). A reduction in soil-K, similar to that in soil-N, is evident during days 60 to 100, and application of larger amounts of K and/or a higher K:N ratio during this period probably would have resulted in a better total yield or a greater export-quality yield.

Similar results were observed in the "Recommended" treatment. The main point in comparison between these two treatments is that the exportable yields - 62.1 and 69.5 ton ha^{-1} - for the "recommended" and "high" treatments, respectively, did not differ statistically, although the amounts of applied N were 380 and 800 kg ha^{-1} and those of irrigation water were 6,830 and 8,870 m^3 ha^{-1} for the "recommended" and "high" treatments, respectively (Table 1).

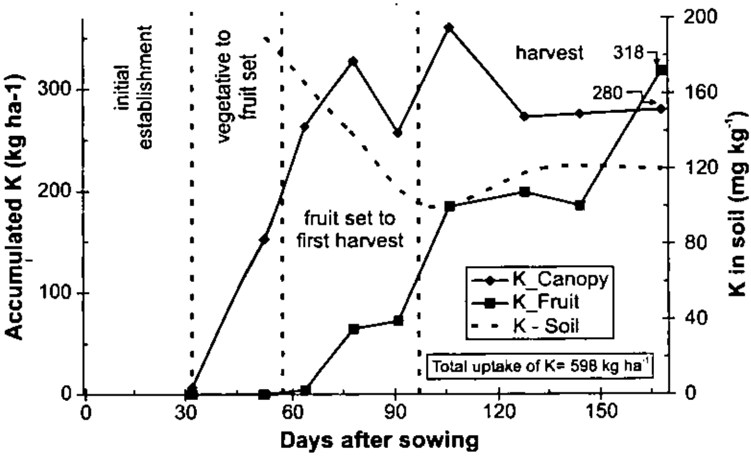

Fig 5. Accumulated K in canopy and fruits (left y-axis) and soil-K concentration (right y-axis) of the "High" pepper treatment (Bar-Yosef *et al.*, 1980)

In the third experiment, 3,300 pepper plants were planted on detached tuff medium in the northern Jordan valley (Tzipilevitch *et al.*, 1994). Fertigation was applied twice a day in the summer and once a day during the winter. Drainage was controlled to dispose 50% of the irrigation water. Concentrations of nutrients in the irrigation water were set to different levels at different stages of the growing season, their concentration in the drainage were measured, and the differences between the concentrations were used as a first estimation of nutrient uptake by the plants. These data will be compared with measurements of actual nutrient uptakes based on their concentrations in the plants.

The fresh matter accumulated during the 240 days of the growing season and its sharing between canopy and fruits are shown in Fig 6. In contrast to the findings of Bar-Yosef *et al.*, 1980, the canopy continued to grow, and even at an enhanced rate during the author-defined last stage of the season (Tzipilevitch *et al.*, 1994).

The amounts of accumulated, applied, and drained, i.e., collected N are shown in Fig 7, along with the estimated N uptake by the plant (difference between N applied and N drained). From these data we get a total N application of 1,882 kg ha^{-1} and a total estimated N uptake of 774 kg ha^{-1}. Accumulated uptakes of NPK, as divided between canopy and fruits, are shown in Fig 8. Note that the measured total N uptake was 443 kg ha^{-1}, compared with the estimated 774 kg ha^{-1} based on water-balance considerations. The P and K uptakes were found to be 43 and 624 kg ha^{-1}, respectively.

To get a better understanding of the uptake process in pepper, we compared the N uptake in the fruits, as measured by Bar-Yosef *et al.* (1980), with the measurements of Tzipilevitch *et al.* (1994) (Fig 9). We suggest that the N uptake was higher (and fruit yields smaller) in the shorter Arava experiment because K acted as a limiting factor for N uptake in the other experiment.

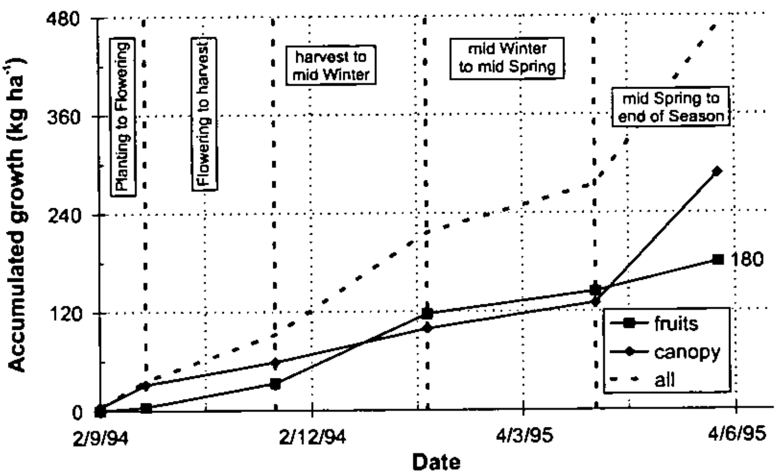

Fig 6. Accumulated fresh matter in fruits (red), canopy (green) and whole plant (broken line) in the pepper experiment in the northern Jordan valley (Tzipilevitch, 1994). The growing season lasted ~240 days and was divided into five stages

In the fourth experiment, (Gantz *et al.*, 2005), two varieties of pepper ('Silika' and 'Rafsoda') were grown on perlite medium in the northern Negev in Israel. The plants were planted on Sept. 4, 2004, at 28,800 plants ha^{-1} and two levels of NPK were applied: "high" and "low" (Table 3). Irrigation was based on "pan A" evaporation data and crop coefficients, according to the various growth stages during the nearly 300 days of the growing season. Drainage was kept at about 30-40% of the irrigation water supply. The total and exportable fruits yields are shown in Table 3.

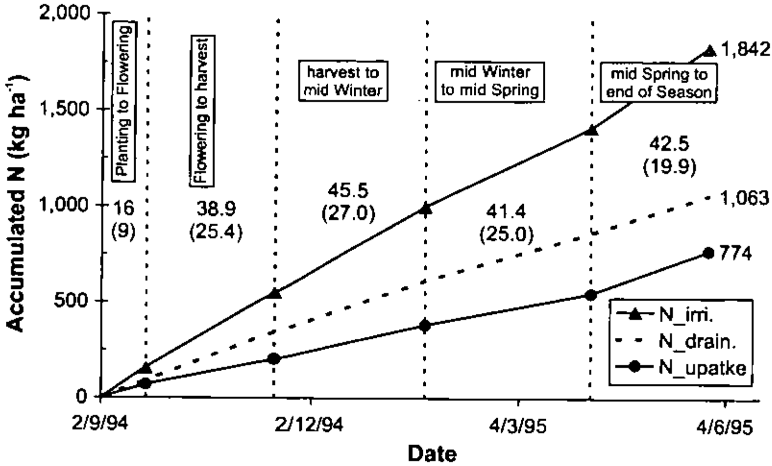

Fig 7. Accumulated N in the irrigation water (solid), drainage (dashed) and estimated N uptake (w/symbols) by the plants in the pepper experiment in the northern Jordan valley (Tzipilevitch *et al.*, 1994). The numbers on the graph are NO_3^- concentrations (mg kg^{-1}) in the irrigation (top) and drainage (bottom in parentheses) water. The numbers at the right-hand end of each line are the accumulated totals in kg ha^{-1}

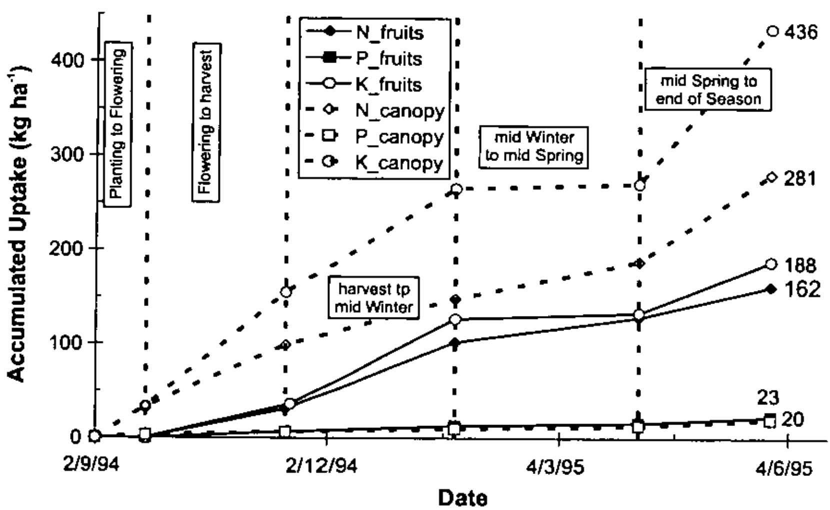

Fig 8. Accumulated N, P, and K (green, red and brown respectively) in the fruits and canopy (solid and dashed lines, respectively) in the pepper experiment in the northern Jordan valley (Tzipilevich *et al.*, 1994). The numbers at the right-hand end of each line are total uptakes (kg ha^{-1})

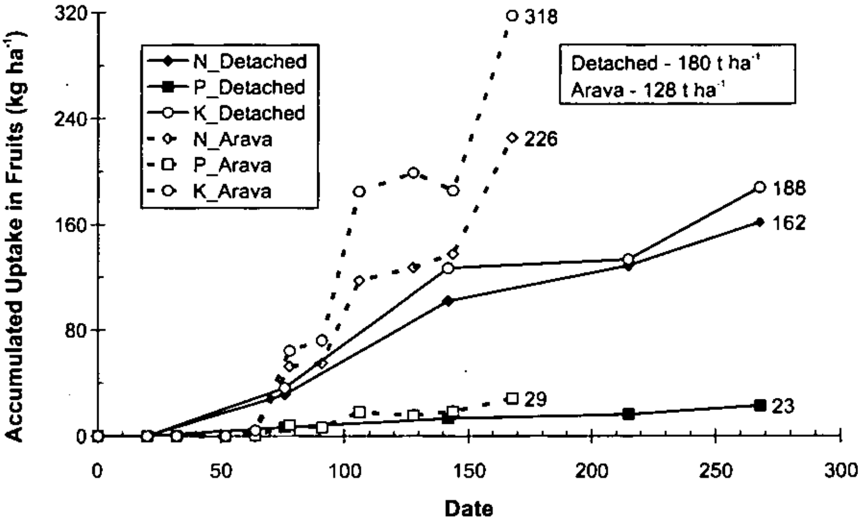

Fig 9. Comparison between the measurements of N uptake in the fruits in the Arava experiment (Bar-Yosef *et al.*, 1980) (Arava) and the northern Jordan Valley experiment (Tzipilevitch *et al.*, 1994) (Detached). The numbers at the right-hand ends of the lines are the total accumulated N uptake (kg ha^{-1}). Total fruit yields are shown in the upper right side of the graph

Table 3. NPK levels and fruit yield in the "High" and "Low" fertilization treatments (Gantz *et al.*, 2005). Different superscript letters within a column indicate significant differences

Fertilization treatment	N	P_2O_5	K_2O	Total fruit yield (t ha^{-1})		Exportable fruit yield (t ha^{-1})	
	(mg kg^{-1})			Silika	Rafsoda	Silika	Rafsoda
Low	60	39	90	225^{a}	236^{a}	123^{ab}	135^{a}
High	120	74.4	180	221^{a}	216^{b}	120^{b}	133^{ab}

Nutrient concentrations in the leaves were measured on March 7, 2005 (Table 4). These data are good indicators of total uptake. The main observation is the similarity between the different fertilization levels - the authors concluded that low concentrations of NPK could and should be applied.

In contrast to the similarity observed between the nutrients data in the various fertilization treatments, significant differences were observed between the nutrient concentrations in the drainage (Table 5).

Table 4. Nutrients concentration in the leaves as measured on March 7, 2005

Cultivar	Fertilization level	N	K	P	Cu	Mn	Zn	Fe	Cl	B	Na	Ca	Mg
		(%)			(mg kg^{-1})				(%)	(mg kg^{-1})	(%)		
Silika	Low	5.38	5.60	0.35	11.2	191	64	171	0.72	25.0	0.02	2.88	0.83
	High	5.58	6.90	0.40	12.4	228	86	247	0.85	26.9	0.02	2.46	0.66
Rafsoda	Low	5.32	6.00	0.38	11.4	171	60	173	0.53	21.9	0.02	2.81	0.88
	High	5.30	6.00	0.34	16.5	281	95	243	0.65	25.8	0.02	2.89	0.79

Source: Gantz *et al.*, 2005

Table 5. Nutrient concentrations in the drainage as measured on March 7, 2005

Cultivar	Fertilization level	N-NH_4	N-NO_3	P	K	Mn	Zn	Fe	B	Mg	Ca+Mg	Na
		(mg kg^{-1})			(meq l^{-1})	(mg kg^{-1})						
Silika	Low	1.0	12.0	3.2	0.10	0.01	0.32	0.28	0.27	6.1	12.9	9.0
	High	1.1	132.3	9.3	2.57	0.04	0.36	0.96	0.42	8.0	17.2	10.4
Rafsoda	Low	1.0	12.0	4.0	0.10	0.01	0.20	0.24	0.25	5.4	11.3	7.8
	High	1.0	99.0	7.5	2.15	0.04	0.28	0.72	0.36	6.4	15.0	9.0

Source: Gantz *et al.*, 2005

The seasonal average NO_3^- concentration in the drainage of the "high" treatment was measured as 150 ppm; the applied irrigation amount was 1,200 m^3 ha^{-1}. On the assumption of 35% drainage, the NO_3^- loss in this season was 630 kg ha^{-1}. If this had not been on a detached medium, with the possibility to control (and recycle) the drainage, large amounts of NO_3^- would have been added to the groundwater.

Fertigation Recommendation

To complete the account of this study, we present the recommendations for irrigation and fertilization of pepper issued by the Extension Service in the Arava in 2006. These data comprise "pan A" evaporation data (Table 6), crop factors at different stages of the season, and N, P and K concentrations in the irrigation water (Table 7). The N, P and K applications based on these recommendations are shown in Fig 10.

Table 6. Multiyear averages of daily "Pan A" evaporation in the Arava (mm day^{-1}) within 1st, 2nd, and 3rd third of each month

	1-10	11-20	21-31
January	3.0	3.2	3.4
February	3.8	4.4	4.6
March	5.5	6.6	7.8
April	8.8	10.5	10.1
May	10.8	11.7	12.7
June	12.8	14.0	13.6
July	13.7	13.4	13.0
August	13.7	13.2	12.4
September	11.5	10.3	9.4
October	9.1	8.4	7.4
November	6.8	5.7	4.6
December	4.0	3.8	3.4
Accumulated yearly			3066

Table 7. Different stages of the growing season, their duration, irrigation factor and N, P and K concentrations in the fertigation water

Stage	Planting to fifth leaf		Fifth leaf to vegetative		Vegetative to start of harvesting		Harvesting
Duration	2-3 weeks		3-4 weeks		6 weeks		
Pan A irrigation factor	0.4	0.4	0.5	0.8	0.9 (*)	1.1 (*)	1.0
N (mg kg^{-1})	70	70	80	80	100	100	60.0
P (mg kg^{-1})	10	10	6	6	6	6	6.0
K (mg kg^{-1})	40	40	60	40	40	40	20.0

(*) - with shades: can be reduced by 30%
- in the winter, irrigation can be performed once in 2 days

Conclusions

It is reasonable to assume N, P and K uptakes of 400, 40 and 500 kg ha^{-1}, respectively, by the pepper plants during a 240-day growing season (September to April). The differences between the recommended applications and the assumed uptakes result in an N excess of ~610 kg ha^{-1}, a K deficit of 50 kg ha^{-1}, and the required amount of P. These calculations regarding N bring us back to Fig 1, which shows the recent and constant increase of NO_3^- in the shallow aquifers of the Arava.

A more precise fertigation scheme is needed to ensure high and profitable yields, accompanied by minimal environmental pollution. It is recommended to further develop protocols for the use of plant and soil sensors as part of the regular growing practice. These protocols should be specific for each combination of growing bed, plants and climatic conditions. It is important to note that although such devices are available on the market, there is still a need for improvements to make their use part of the daily practice for all growers.

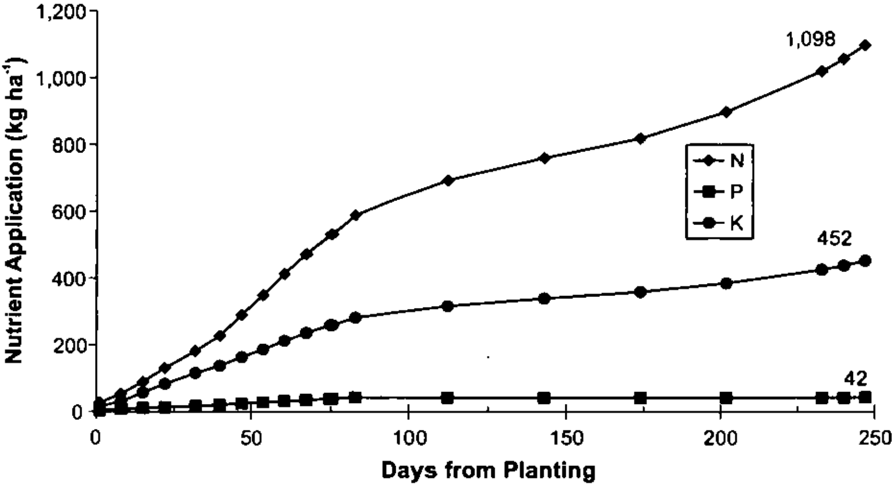

Fig 10. Simulations of NPK applications as recommended by the Extension Service for the Arava Region, 2006. The numbers at the right-hand end of each line are annual accumulated amounts in kg ha^{-1} (Extension Service, 2006)

Acknowledgments

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Role of Mineral Nutrients in Tolerance of Crop Plants to Environmental Stress Factors[1]

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Abstract

Around 60% of cultivated soils worldwide have plant-growth-limiting problems caused by mineral nutrient deficiencies and toxicities. Therefore, improving the mineral nutritional status of plants under marginal environmental conditions is of great importance for maintenance of crop productivity. In most cases plants growing under marginal environmental conditions (e.g., salinity, low and high temperatures, and drought) receive much more sunlight than they can utilize in photosynthetic electron transport and CO_2 fixation. This causes excessive accumulation of absorbed light energy and of photoreductants in the chloroplasts, which leads to activation of molecular O_2 to reactive oxygen species (ROS). When ROS are not adequately scavenged, photooxidative damage occurs in the chloroplasts, and leads to chlorophyll damage, lipid peroxidation and, consequently, cell death. By limiting the utilization of absorbed light energy in photosynthesis, environmental stress factors increase the potential for photooxidative damage in chloroplasts. Because an adequate supply of mineral nutrients is indispensable for maintenance of photosynthetic electron transport and carbon metabolism, impairment of the mineral nutritional status of plants under marginal environmental conditions can exacerbate photooxidative damage and limit plant performance. In the present study, several examples are given, which show that plants exposed to environmental stresses require additional supplies of mineral nutrients, particularly nitrogen (N), potassium (K), magnesium (Mg), calcium (Ca) and zinc (Zn) to minimize the adverse affects of stresses. Enhanced production of ROS in plants under marginal conditions is not caused only by impairment of photosynthetic electron transport. It appears likely that an NADPH-dependent oxidase is another important source of ROS, that is stimulated by drought, chilling, and/or salinity. Of the mineral nutrients, K and Zn seem to interfere with the NADPH-oxidizing enzyme and thus to provide additional protection against damaging attack of ROS under salinity, drought and chilling stress. It is concluded that improving the mineral nutritional status of crop plants is of great importance for minimizing detrimental effects of environmental stress factors on their growth and yield.

Keywords: Mineral nutrients, tolerance, environmental stress factors, crops

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Crop plants are often exposed to various environmental stress factors, such as drought, soil acidity, salinity and extreme temperatures, which severely affect soil productivity and crop production, worldwide. Bray *et al.* (2000) estimated that the contribution of environmental stress factors to global losses in crop production is becoming increasingly important. Figure 1 shows that the relative decreases from the record yield capacity (maximum yield under ideal growth conditions) caused by abiotic stress factors vary between 60 and 82% for corn, wheat and soybean. In the case of wheat and soybean, record yields are 14.5 and 7.4 t ha^{-1}, respectively, but the current worldwide average yields are 1.9 and 1.6 t ha^{-1}, respectively (Fig 1).

In comparison with the yield capacity losses of wheat and soybean caused by biotic stress factors, those caused by abiotic stress factors are much greater. Most of the yield losses caused by abiotic stresses are attributed to drought, salinity, extreme temperatures, acidity, and impairments of the mineral nutritional status of plants, i.e., deficiencies and toxicities. Recently, Cakmak (2002) reported that at least 60% of cultivated soils worldwide have growth-limiting problems arising from mineral nutrient deficiencies and toxicities. Combinations of such soil nutritional problems with other environmental stress factors such as drought, salinity, chilling, etc. are responsible for severe losses in crop production worldwide.

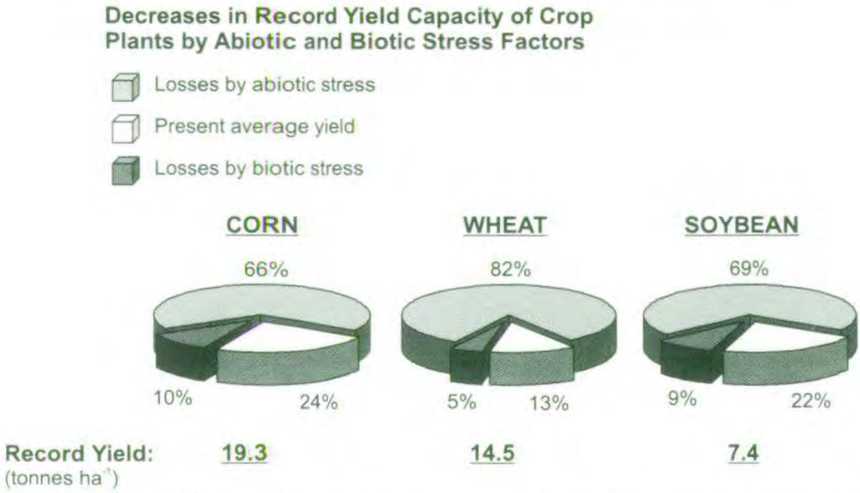

Fig 1. Record yields (yields under ideal conditions) and decreases from the record yield capacities of corn, wheat and soybean plants, caused by abiotic and biotic stress factors (Bray *et al.*, 2000)

Survival and productivity of crop plants exposed to environmental stresses are dependent on their ability to develop adaptive mechanisms to avoid or tolerate stress. Accumulating evidence suggests that the mineral nutritional status of plants greatly affects their ability to adapt to adverse environmental conditions. In the present paper the role of the mineral nutritional status of plants in their adaptation to environmental stress conditions will be discussed, with emphasis on abiotic stress factors. Of the mineral nutrients affecting plant adaptation to stress conditions, nitrogen (N), potassium (K), magnesium (Mg), calcium (Ca), zinc (Zn) and boron (B) are the most extensively studied, therefore, special attention will be paid to them.

High-Light Stress and Photooxidation

Photooxidative damage, i.e., light-dependent generation of reactive oxygen species (ROS) in chloroplasts, is the key process involved in cell damage and cell death in plants exposed to environmental stress factors (Foyer *et al.*, 1997; Asada, 2000; Foyer and Noctor, 2005). As shown in Fig 2, chloroplasts are the main sites of ROS formation, and photosynthesis electron transport provides the main means of formation of ROS such as superoxide radical ($O_2^{\cdot-}$), hydroxyl radical ($OH^{\cdot}$), and singlet oxygen ($^1O_2$). ROS are highly toxic to vital cell constituents and are responsible for destruction of chlorophyll, DNA, membrane lipids and proteins. Formation of ROS is particularly prolific when absorption of light energy exceeds the capacity of photosynthetic electrons to transport it. Environmental stress factors diminish photosynthetic electron transport and CO_2 fixation at various stages of the photosynthesis process (Fig 2). Therefore, a combination of an environmental stress with high light intensity may induce severe photo-oxidative damage to chloroplasts, and consequently cause decreases in the yield capacity of plants. The mineral nutritional status of plants greatly influences photosynthesis electron

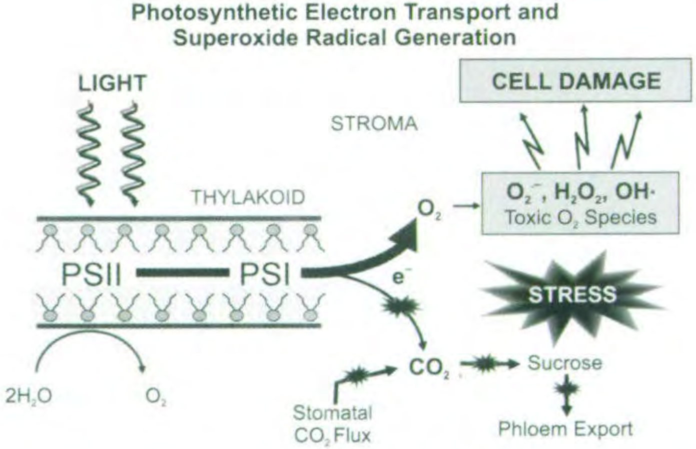

Fig 2. Schematic representation of ROS formation in chloroplasts under environmental stress conditions. [symbol] : indicates inhibition of the corresponding reaction by stress (Cakmak, 2003, 2005)

transport and CO_2 fixation in various ways (Marschner, 1995; Cakmak and Engels, 1999; Mengel and Kirkby, 2001). Impairment of the mineral nutrition of plants can, therefore, be accompanied by an enhanced potential for photo-oxidative damage, and this threat can be especially serious when plants are simultaneously exposed to an environmental stress.

Nitrogen

Of the mineral nutrients, nitrogen plays a major role in utilization of absorbed light energy and photosynthetic carbon metabolism (Kato *et al.*, 2003; Huang *et al.*, 2004). An excess of non-utilized light energy can be expected to occur in N-deficient leaves, where it leads to a high risk of photo-oxidative damage. In rice plants under high light intensity, N deficiency is associated with enhanced lipid peroxidation (Huang *et al.*, 2004), and Kato *et al.* (2003) recently showed that plants grown under high-intensity light with a high N supply had greater tolerance to photo-oxidative damage and higher photosynthesis capacity than those grown under similar high light with a low N supply. Utilization of the absorbed light energy in electron transport was also much higher in N-adequate than in N-deficient plants. These results indicate that N-adequate plants are able to tolerate excess light by maintaining photosynthesis at high rates and developing protective mechanisms. To avoid the occurrence of photo-oxidative damage in response to excess light energy, the thylakoid membranes have a protective mechanism by which excess energy is dissipated as heat. Dissipation of excess light energy is associated with enhanced formation of the xanthophyll pigment zeaxanthin, which is synthesized from violaxanthin in the light-dependent xanthophyll cycle (Demmig and Adams, 1992, 1996):

In plants suffering from N deficiency, the conversion of xanthophyll cycle pigments and formation of zeaxanthin were enhanced, and were accompanied by chlorophyll bleaching, particularly under high light intensity (Verhoeven *et al.*, 1997; Kato *et al.*, 2003). In spinach, N-deficient plants dissipate a greater fraction of the absorbed light energy than N-adequate ones: up to 64% and only 36%, respectively. This difference was associated with corresponding changes in xanthophyll cycle pigments: about 65% of the total xanthophyll pigments were present as zeaxanthin and antheraxanthin in N-deficient plants compared with 18% in the N-adequate plants (Verhoeven *et al.*, 1997). These results indicate impaired use of the absorbed light energy in photosynthetic fixation of CO_2, with consequently enhanced demand for protection against excess light energy, in N-deficient plants. Certainly, the reduction in the utilization of light energy and the consequently elevated need for protection against photo-oxidative damage in N-deficient plants can be more marked when the N deficiency stress is combined with an environmental stress.

The form in which N is supplied affects plant tolerance to photodamage. The light-induced conversion of violaxanthin to zeaxanthin, as a means to dissipate excess light energy was found to be stronger in bean leaves supplied with nitrate than in those supplied with ammonium (Bendixen *et al.*, 2001). In good agreement with these findings, Zhu *et al.* (2000) demonstrated that nitrate-grown bean plants had higher tolerance to photodamage than ammonium-grown ones. Under very high light intensity ammonium-grown plants had, therefore, higher levels of lipid peroxidation and higher contents of antioxidative enzymes.

Potassium, Magnesium and Zinc

Similarly to N deficiency, deficiencies of K, Mg and Zn also enhance the sensitivity of plants to photo-oxidative damage. When supplies of these nutrients are low, leaf symptoms of chlorosis and necrosis, and disturbances of plant growth become more severe when plants exposed to high light intensity (Marschner and Cakmak, 1989; Cakmak and Marschner, 1992; Cakmak *et al.*, 1995; Polle, 1996).

Deficiencies of K and/or Mg cause marked decreases in photosynthetic C metabolism and utilization of fixed carbon (Marschner, 1995; Cakmak and Engels, 1999; Mengel and Kirkby, 2001). Consequently, their deficiencies cause massive accumulation of carbohydrates in source leaves, with consequent inhibition of photosynthetic C reduction (Fig 3). Consistent with these changes in photosynthetic C metabolism, an excess of non-utilized light energy and photoelectrons is expected in K- and Mg-deficient plants, which leads to photoactivation of molecular O_2 and the occurrence of photo-oxidative damage (Fig 2). This is the main reason why Mg- and K-deficient leaves are highly light sensitive. Partial shading of K- or Mg-deficient leaves delayed or eliminated the occurrence of leaf chlorosis and necrosis (Marschner and Cakmak, 1989; Cakmak, 1994). These observations strongly suggest that photo-oxidative damage to chloroplasts is a key process in the occurrence of leaf symptoms under conditions of Mg or K deficiency. In contrast to Mg and K deficiency, P deficiency had no effect on sucrose transport from source leaves, and there was no accumulation of photosynthates in leaves (Fig 3). Leaf chlorosis, such as is found in K- and Mg-deficient plants, is not typical of P-deficient plants (Cakmak, 1994). Because of the distinct effects of Mg and K on photosynthetic carbon metabolism and on ROS formation in chloroplasts, photo-oxidative damage in plants grown under marginal conditions, such as drought, chilling and salinity can be exacerbated when the soil supply of Mg or K is low.

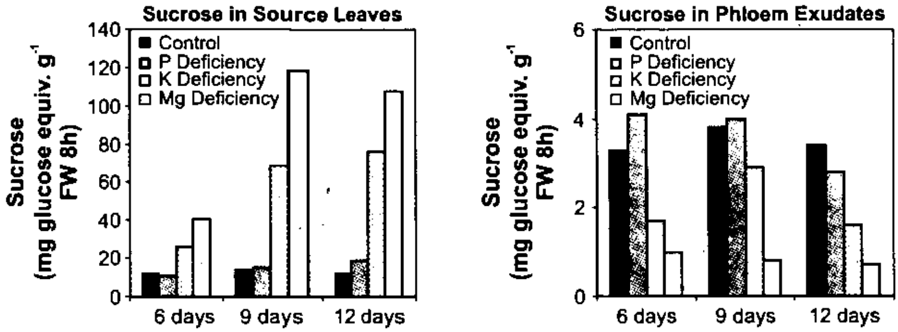

Fig 3. Effect of insufficient supplies of P, K and Mg on sucrose concentration in source leaves, and on the export of sucrose from source leaves of bean plants via the phloem during 12 days of growth (Cakmak *et al.*, 1994)

As reviewed by Cakmak (2000) and Cakmak and Romheld (1997), Zn and B deficiencies also affect the photosynthetic activities of plants in various ways. Both micronutrients exert marked effects on photosynthetic CO_2 fixation, and the translocation of photosynthates. Therefore, any interruption of the adequate supply of Zn and B to plants can potentiate photo-oxidative damage. Indeed, Zn- and B-deficient plants are highly photosensitive and rapidly develop chlorosis and necrosis when the light intensity increases (Marschner and Cakmak, 1989; Cakmak and Römheld, 1997).

Salinity

Evidence is accumulating that reactive O_2 species are major mediators of salt-induced cell damage in crop plants. In several plant species, application of NaCl, even at low concentration, stimulated the activities of antioxidative enzymes, which suggests a role of salt stress in ROS formation (Comba *et al.*, 1998; Tsuage *et al.*, 1999; Wang *et al.*, 2005). On the basis of inhibitor studies and measurement of production of $O_2^{\cdot-}$ it has been shown that a plasma membrane-bound NADPH oxidase is involved in the generation of $O_2^{\cdot-}$ following salt treatments (Kawano *et al.*, 2002; Aktas *et al.*, 2005). Accordingly, salt stress-induced cell damage could be prevented by overexpression of superoxide dismutase (SOD) in chloroplasts of rice plants (Tanaka *et al.*, 1999).

Zinc ions are known to be strong inhibitors of NADPH oxidase. In bean and cotton root cells Zn deficiency caused a significant increase in activity of NADPH-dependent $O_2^{\cdot-}$ production, and a resumed supply of Zn to Zn-deficient plants for 12 or 24 h caused a distinct reduction in the activity of $O_2^{\cdot-}$-generating enzymes (Cakmak and Marschner, 1988a; Pinton *et al.*, 1994). Similarly, in tobacco cell cultures salt-induced $O_2^{\cdot-}$ generation by NADPH oxidase was strongly inhibited by Zn (Kawano *et al.*, 2002). Previously, it has been often hypothesized that improving the Zn nutritional status of plants growing in saline conditions was critical for protection of plants against salt toxicity. This protective role of Zn was ascribed to its role in maintenance of the structural integrity of the plasma membrane and thus controlling the uptake of Na and other toxic ions (Welch *et al.*, 1982; Cakmak and Marschner, 1988b). In light of the protective roles of Zn against ROS it can be suggested that Zn ions protect salt-stressed plants not only from uptake of toxic ions across plasma membranes but also from damaging attack of ROS.

Like Zn, K, too, is a critical mineral nutrient that protects plant cells from salt-induced cell damage. Impairment of the K nutritional status of plants by increased Na uptake is a well-known phenomenon (Liu and Zhu, 1997). The K/Na ratio in plant tissue is, therefore, considered to be a reliable indicator of the severity of salt stress, or for screening plant genotypes for high Na tolerance. In studies with *Arabidopsis* mutant lines Zhu *et al.* (1998) showed that mutant lines showing very high sensitivity to NaCl were also highly sensitive to low K supply, and exhibited a poor capacity for taking up K from a growth medium. As discussed above, salt stress represents an oxidative stress, and causes activation of $O_2^{\cdot-}$-generating NADPH oxidase. Recently, we found that K deficiency resulted in a remarkable increase in NADPH oxidase activity in bean, with concomitant production of $O_2^{\cdot-}$ (Cakmak, 2003; 2005). Shin and Schachtman (2004) also reported that ROS production was an early root response to K deficiency, which was catalysed by $O_2^{\cdot-}$-generating NADPH oxidase. These results suggest that salt stress-induced $O_2^{\cdot-}$ generation by NADPH oxidase could be aggravated by a lack of K. As Na toxicity causes K deficiency at cellular levels, the increase in NADPH-dependent $O_2^{\cdot-}$ generation under salt stress (Kawano *et al.*, 2002) might be the result of an impaired K nutritional status of the plants. This point seems to be important, and should be elucidated in future studies.

Drought

In plants exposed to high light intensity at very low temperature or under drought stress, development of photo-oxidative damage and generation of ROS is very common (Foyer *et al.*, 1997; Jiang and Zhang, 2002a, b; Wang *et al.*, 2005). As discussed above, most mineral nutrients are a basic necessity for maintenance of photosynthetic electron transport. Therefore, the occurrence of photo-oxidative damage in plants stressed by drought or low temperature can be more dramatic when the plants also suffer nutrient deficiencies. Of the mineral nutrients, K plays a critical role in the stomatal activity and water relations of plants (Marschner, 1995; Mengel and Kirkby, 2001). Decreases in photosynthesis caused by drought stress in wheat become particularly high in plants growing under K deficiency, but are only minimal when the K supply is adequate. The capacity of plants to maintain high concentrations of K in their tissues seems to be a useful trait to take into account in breeding genotypes for high tolerance to drought stress. In *Hibiscus* *rosa-sinensis* plants grown under various K treatments, the root survival rate was strongly reduced when the water supply was limited, especially at the lowest K supply (Egilla *et al.*, 2001); an adequate supply of K was essential for enhancing the drought resistance of the plants and improving their root longevity. The beneficial effect of an adequate K supply was ascribed to the role of K in retranslocation of photoassimilates in roots, which contributed to better root growth under drought stress (Egilla *et al.*, 2001; Fig. 3).

As in salt-stressed plants, also in plants exposed to drought stress, ROS formation by $O_2^{\cdot-}$-generating NADPH oxidase was enhanced (Zhao *et al.*, 2001; Jiang and Zhang, 2002a, b). It appears that, in addition to ROS formation by photosynthetic electron transport, ROS production by NADPH oxidase activity is involved in cell damage and plant growth depression under drought stress. As indicated above, Zn and K strongly influence NADPH oxidation and NADPH-dependent $O_2^{\cdot-}$ generation. Under deficiency of these nutrients, especially of K, the capacity of root cells to oxidize NADPH is markedly increased, with concomitant production of $O_2^{\cdot-}$. In light of these results it may be suggested that the protective roles of Zn and K against drought stress seem also to be related to their inhibitory effects on NADPH-dependent $O_2^{\cdot-}$ generation. Therefore, in case of deficiency of these nutrients, plants become more sensitive to drought stress.

Chilling

Formation of ROS by NADPH oxidase and weakening of the antioxidative defensive systems are also important in chilling-induced cell damage (Shen *et al.*, 2000; Aroca *et al.*, 2005; Wang *et al.*, 2005). Since insufficient supplies of K and Zn lead to significantly increased NADPH oxidase activity, ROS formation in plants grown at low temperatures can be additionally exacerbated under deficiencies of these nutrients. Production of ROS in chilling-stressed plants can also be expected, in parallel with impaired photosynthetic electron transport and CO_2 fixation (Wise and Naylor, 1987; Asada, 2000). There are several examples from field experiments that demonstrate a role of K and Zn in protection of plants under low-temperature conditions: frost damage and related decreases in potato plant yields were alleviated by application of large doses of K (Grewal and Singh, 1980); during winter, citrus trees were found to be more vulnerable to low temperatures and peroxidative damage when grown under Zn-deficient conditions (Cakmak *et al.*, 1995). N, too, is involved in protection of plants against chilling stress; in studies with Eucalyptus seedlings it was found that seedlings with impaired N nutritional status were less susceptible to photo-oxidative damage in winter (Close *et al.*, 2003). Like low N supply, also excess N results in high sensitivity to environmental stress: stress tolerance of plants can be diminished because of modified root and shoot growth. Marschner (1995) found that a very high supply of N often led to a reduced root-to-shoot ratio that, in turn, impaired the support of shoot biomass with mineral nutrients and water. Also, in plants receiving a high N supply, most parts of the roots may grow near to the soil surface, with consequently higher sensitivity to frost and drought damage (Gordon *et al.*, 1999; Saebo *et al.*, 2001). Saebo *et al.* (2001) showed that tolerance to frost damage was very low at the highest N supply rate, which led to the suggestion that the tissue N status should not be very high during winter.

Generally, plant genotypes that tolerate low-temperature stress are able to maintain high leaf water potential by closing their stomata and preventing transpirational water loss (Wilkinson *et al.*, 2001). Calcium has been shown to be an essential requirement for chilling-induced stomatal closure in chilling-tolerant genotypes. Increasing the Ca supply induces stomatal closure, and this effect is most distinct in plants grown at low temperatures. It is also believed that ABA-induced stomatal closure is partially mediated by Ca released from internal guard cell stores or the apoplast (Wilkinson *et al.*, 2001), and this function seems to make Ca a major contributing factor to chilling tolerance and protection of leaves from dehydration.

Conclusions

The existing data indicate that it is essential to improve the mineral nutritional status of plants under marginal environmental conditions, in order to sustain their survival and to maintain high yields. Plant requirements for mineral nutrients increase with increasing severity of the environmental stresses imposed by drought, heat, salinity, chilling, or intense light. Impairment of the mineral nutritional status of plants, therefore, exacerbates the adverse effects of environmental stress factors on plant performance. The present paper has focused on one of the major reasons for the aggravation of the adverse effects of stresses by an insufficient supply of mineral nutrients, namely, the enhanced production of highly toxic ROS and the resulting photo-oxidative damage to chloroplast pigments and lipids. The production of ROS during photosynthesis, which is normally an unavoidable process, is intensified because of the limited and diminished utilization of absorbed light energy in photosynthetic electron transport and CO_2 fixation, which results from environmental stresses such as drought, salinity and chilling. Mineral nutrients, such as N, K, Mg, Ca and Zn, supplied at adequate levels are an essential requirement for the maintenance of photosynthesis activities and utilization of light energy in CO_2 fixation. Therefore, the improvement of mineral nutrition of plants becomes a major contributing factor in protecting them from photo-oxidative damage under marginal environmental conditions. Further challenges include the gaining of better understanding of the roles of mineral nutrients in: i) ROS formation during photosynthesis and formation of plasma membrane-bound NADPH oxidase; ii) signaling pathways that affect the adaptive responses of plants to environmental stresses; and iii) expression and regulation of stress-induced genes that contribute to stress tolerance.

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Balanced Chloride, Potassium and Silicon Nutrition for Plant Disease Management

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Abstract

Balanced plant nutrition is important since essential and even non-essential elements play key roles in the function, development and growth of plants. This fact becomes even more apparent when the plants are under some environmental stress, and the element in question is either low or limiting. As such, the plant may become even more susceptible to disease caused by a number of microorganisms. Chloride, potassium and silicon have been shown to reduce a number of plant diseases in a wide variety of crops. Each element has a different mode of action for plant disease suppression. Chloride appears to reduce the cell osmotic potential, increase manganese uptake, and enhance the activity of beneficial microbes via altered root exudation. Potassium acts on a number of processes that include alterations in protein or amino acid availability, decreased cell permeability, or decreased susceptibility of tissue to maceration and penetration. Silicon affects plant disease resistance by either an accumulation of absorbed silicon in the epidermal tissue, or expression of pathogenesis-induced host defense responses. This paper provides a general overview on the nutrient/host relationships of chloride/wheat, potassium/rice and silicon/rice, and how each influences plant disease development.

Keywords: Nutrients, plant diseases, plants-nutrition, silica minerals

Mineral nutrition plays a number of essential and functional roles in the development and growth of plants (Datnoff, 1994). They are involved in many physiological and biochemical processes that include enzyme activators, structural components, metabolic regulators, and substrates (Huber, 1990). These nutrients are supplied to the plant in organic or inorganic forms, and their availability to the plant depend on a number of factors such as soil texture, pH, moisture, temperature, mineral solubility, soil retention, soil microbial activity and the ability of the plant to use each nutrient efficiently. As such, the nutritional status of a plant will affect its inherent disease resistance, and the ability of the pathogen to infect and survive. This becomes even more apparent when the plant is under an environmental stress and the nutrient in question is low or limiting. This paper provides a general overview of the influences of chloride on diseases of wheat, and potassium and silicon on diseases of rice.

Chloride

In nature, chlorine exists mostly as chloride in rock salt (common salt, halite, NaCl), carnallite ($KMgCl_3.6H_2O$), and sylvite (KCl), which is mined and marketed as muriate of potassium. It was not until the late 1940's when the essentiality of chlorine as a micronutrient in photosynthesis was conclusively shown (Arnon and Whatley, 1949; Broyer *et al.*, 1954). Since then a number of studies have suggested that the benefits of chloride applications may be maximized when plants are under stress by disease or drought (Trolldenier, 1985). In fact, most of the reported benefits of chloride application on crop production have been made in environments where considerable environmental stress or disease pressure was present. Such observations suggest that chloride fertilization may improve defense mechanisms against stress factors and may explain the lack of response when disease or stress factors are absent. Although reports of growth enhancement in asymptomatic non-stressed plants have been made, it may not rule out the suppression of minor pathogens or a correction of chloride deficiency.

The majority of reports demonstrating disease suppression with chloride fertilization have been made on monocots such as asparagus, barley, corn, coconut, date palm, millet, and wheat (Table 1). However, dicots like beets, celery, cotton, potato, and soybean have shown considerable benefit from chloride fertilization (Maas, 1986; Fixen, 1993). All plants that show growth responses to chloride nutrition are usually ranked as moderately tolerant/tolerant to both chloride and salinity (Maas, 1986). These plants have acquired a high level of tolerance or even preference for chloride in their nutrition.

Effect of chloride on controlling wheat diseases

The effects of chlorides on wheat diseases have been studied more thoroughly than on any other crop. Both root and foliar disease suppression has been documented along with reports that found no response to chloride. Powelson and Jackson (1978) first demonstrated the effect of chloride on take-all root disease caused by *Gaeumannomyces graminis* (Sacc.) Arx & D. Olivier var. *tritici* J. Walker. Banding wheat at planting with chloride fertilizers led to increased vigor and less take-all. Their findings stimulated many other studies on take-all of wheat (Christensen *et al.*, 1981; Christensen *et al.*, 1982; Engel and Mathre, 1988; Powelson, *et al.*, 1985; Taylor *et al.*, 1981; Trolldenier, 1985). Rates of approximately 350 kg Cl

Table 1. Host plants, diseases, and pathogens suppressed by chloride[a]

Host plant	Disease	Pathogen(s)
Asparagus	Fusarium crown and root rot	*Fusarium oxysporum, F. proliferatum*
Barley	Common root rot	*Bipolaris sorokiniana, Fusarium culmorum*
Barley	Powdery Mildew	*Erysiphe graminis* f. sp. *hordei*
Barley	Rust	*Puccinia hordei*
Beets	Rhizoctonia root and crown rot	*Rhizoctonia solani*
Celery	Fusarium yellows	*Fusarium oxysporum* f. sp. *apii*
Coconut	Leaf spot	*Bipolaris incurvata*
Corn	Stalk rot	*Gibberella zeae, G. fujikuori*
Corn	Smut	*Ustilago maydis*
Cyclamen	Fusarium wilt	*Fusarium oxysporum* f. sp. *cyclaminis*
Date Palm	Fusarium wilt	*Fusarium oxysporum* f. sp. *albedinis*
Pearl Millet	Downy Mildew	*Sclerospora graminicola*
Sorghum	Stalk rots	*Gibberella thapsinum, Gibberella zeae, Macrophomina phaseolina*
Soybeans	Soybean cyst nematode	*Heterodera glycines*
Soybeans	Sudden death	*F. solani* f. sp. *glycines*
Wheat	Take-all	*Gaeumannomyces graminis* var. *tritici*
Wheat	Root rot	*Fusarium culmorum, Gibberella zeae Bipolaris sorokinian*
Wheat	Stripe (yellow) rust	*Puccinia striiformis*
Wheat	Leaf rust	*P. recondite* f. sp. *tritici*
Wheat	Powdery mildew	*Erysiphe graminis* f. sp. *tritici*
Wheat	Tanspot	*Pyrenophora tritici-repentis*
Wheat	Glume blotch	*Septoria tritici*
Wheat	Stagonospora blotch	*Phaeosphaeria avenaria*

[a]See Elmer (2006) for more inclusive information

ha^{-1} as NH_4Cl were shown to increase grain yield from 11% to 40% over using NH_4SO_4 in plots where take-all disease had been confirmed. In another report, Christensen and Brett (1985) found chloride applied as NH_4Cl did not affect disease incidence, but disease severity was significantly reduced in acid soils. In contrast, Gardner *et al.* (1998) compared chloride application to several other treatments for reducing take-all disease in South Australia and found chloride was ineffective. Gardener *et al.* (1998) suggested that the naturally high chloride concentration in the soil and the late application led to its ineffectiveness. Trolldenier (1985) demonstrated that take-all disease suppression observed with chloride was influenced by drought stress. Wheat grown in pot experiments under low soil moisture conditions and inoculated with *G. graminis* var *tritici* grew better when fertilized with KCl rather than K_2SO_4. However, when sufficient moisture was added and/or the plants were not inoculated, the ameliorating effects of chloride were marginal.

Other root rot diseases on wheat have been investigated as well. Engle and Grey (1991); Engel *et al.* (1994) evaluated whether chloride could increase yield of wheat and affect root disease caused by *Fusarium culmorum* (W.G. Smith) Sacc. Chloride applied under NH_4-N regime increased yield of hard spring wheat, but chloride had no effect on root rot severity rating when wheat cultivars were artificially inoculated with *F. culmorum*. Subsequent studies confirmed these findings at six different sites in Montana, where an average 7% increase in yield was recorded following chloride application without significant reductions in disease severity (Engle *et al.*, 1994). Alternatively, Tinline *et al.* (1993) found chloride reduced the severity of common root rot (*Bipolaris sorokiniana* (Sacc.) Shoemaker) without affecting yield. In a series of chloride experiments conducted in Saskatchewan, Canada, (4 out of 11 trials) chloride applied as KCl or NaCl significantly reduced the severity of common root rot. No yield benefits were noted. Buchenau and Rizvi (1990) found that wheat seedlings grown in sand infested with *Gibberella zeae* (Schwein) Petch had significantly less root lesions when irrigated with water containing 60 mg liter^{-1} chloride. Windels *et al.* (1992), however, found no association between chloride applications and common root rot or wheat yields over five separate trials in Minnesota.

Before Powelson and Jackson (1978) had made their report on chloride suppression of take-all, Russell (1978) had demonstrated in greenhouse pot trials in England that applications of KCl and/or NaCl reduced the severity of stripe (yellow) rust of wheat caused by *Puccinia striiformis* Westend. In field plots, Russell (1978) found that application of KCl and NaCl at 1130 kg ha^{-1} reduced disease incidence by an average of 63%. The effect was observed on six cultivars of wheat. Christensen *et al.* (1981; 1982); Scheyer *et al.*, 1987) also noted that application of chloride salts reduced the apparent infection of stripe rust in chloride-treated plots in Oregon. Accordingly, Rizvi *et al.* (1988) found potted wheat plants had 42% less wheat leaf rust than untreated controls when treated with $CaCl_2$. Reductions in both powdery mildew and leaf rust in chloride-treated plots were observed by Engel *et al.* (1994), but the effect was dependent on the location. Grybauskas *et al.* (1988) observed on winter wheat treated with KCl, but not with $CaCl_2$ marginal reductions in the severity of powdery mildew (*Erysiphe graminis*

DC. f. sp. *tritici* Em. Marchal). Yields were greater in chloride treated plants, but yield increases were not associated with reduction in powdery mildew. In studies from 1984-1987, Buchenau *et al.* (1988a) recorded reductions in the number and pustule size of leaf rust (*P. recondita* Roberge ex Desmaz. f. sp. *tritici* (Eriks. & E. Henn.) D.M. Henderson) following applications of KCl and $CaCl_2$. They also noted chloride-treated plants had less tan spot (*Pyrenophora tritici-repentis* (Died.) Drechs. and Stagonospora blotch (*Phaeosphaeria avenaria* (G.F. Weber) O. Eriksson). Controlled pot studies with $CaCl_2$ with wheat seedlings inoculated with *P. tritici-repentis* revealed smaller and fewer lesions than on nontreated seedlings (Buchenau *et al.*, 1988b). Gelderman *et al.* (1999) reported chloride applied as KCl had marked effects in reducing tan spot and rust on 15 spring wheat cultivars. Chloride decreased the diseased portion of the flag leaf from 25% to 13%, and reduced the mean decrease in leaf rust infection from 33 to 12%. Chloride did not affect scab caused by various species of *Fusarium.* Findings by Sweeney *et al.* (2000) were in agreement with those above and found KCl reduced leaf rust severity and increased yield. Miller and Tucker (1999); Miller and Jungman (1998) in Texas explored the option of reducing costly fungicide sprays to reduce leaf rusts caused by *P. recondita* f. sp. *tritici* by integrating chloride nutrition on wheat. After demonstrating that KCl significantly reduced overall injury from leaf rust in six wheat cultivars, studies were initiated to include the fungicide propiconazole with KCl. Interestingly, the fungicide offered no added benefit indicating the chloride applications might replace costly fungicides at a fraction of the cost.

Several workers such as Kettlewell *et al.* (1990; 2000); Cook *et al.* (1993); Mann *et al.* (2004) have explored the use of spraying chloride salts on wheat to suppress leaf diseases. Field studies were established in Shropshire, England. Late-season application of KCl suppressed glume blotch of wheat caused by *Septoria nodorum* (Berk.) Berk. in Berk. & Broome. Kettlewell *et al.* (1990) reported leaf blotch (*Septoria tritici* Roberge in Desmaz) and powdery mildew (*E. graminis* sp. *tritici*) were similarly suppressed by late season foliar sprays of KCl.

How chloride suppresses plant diseases?

A complete understanding of how chloride affects disease has not been resolved, but there have been many attempts to decipher its role in suppressing plant disease (Elmer, 2006). With a few exceptions, a general consensus is that chloride provided suppression of plant disease because it has a minor toxic effect on the pathogen. However, most soilborne pathogens grow better in culture as chloride concentrations are increased to 0.5-1.0% (Firdous and Shahzad, 2001; Suleman *et al.*, 2001). Although it is conceivable that soil application of granular NaCl or KCl would initially cause a concentrated and perhaps inhibitory plume to percolate through the soil system, this effect would likely be short lived and could not explain the long lasting suppression observed in many of the host-pathogen systems listed in Table 1.

The major overall influence of chloride fertilization on plant disease appears to be related to a reduction in cell osmotic potential, increased manganese uptake, and enhancement of beneficial microbes via altered root exudation (Elmer, 2006). While the reduction of cell osmotic potential would be a direct physiological result of chloride uptake, there are chemical and/or microbial methods for achieving a chloride-mediated increase in manganese uptake. Soil pH may have a governing effect on whether manganese uptake is mediated chemically or microbiologically. In acid soils (<pH 6.6), chloride suppresses nitrification. The persistence of nitrogen in the ammonical form facilitates the chemical reduction of manganese oxides, whereas in neutral to alkaline soils, chloride may enhance manganese by altering nutritional composition of the root exudates that, in turn, favors microbes that possess the manganese reduction trait. Chloride acts as a nitrification inhibitor that forces the wheat plant to take-up more of the nitrogen as ammonium than as nitrate when ammonical fertilizers are applied. The plant roots then give off hydrogen ions that result in an increase in acidity at the root surface. As a consequence, disease severity decreases due to inhibition of the take-all pathogen by microorganisms which thrive in a more acidic root zone environment.

At present, the current understanding would implicate these two processes, the reduction in cell osmotic potential and the increased uptake of manganese, as acting in concert to suppress disease. These mechanisms would seemingly have far-reaching effects on both foliar and root diseases. Furthermore, one should recognize that the root-mediated alteration in the rhizobacteria that occurs may also include added benefits delivered by these microbes in conferring biological control, plant-growth-promotion and systemically-acquired-resistance.

Potassium

Potassium (K) plays many essential roles in plant nutrition Although K is not structurally bound in the plant, it increases root growth, improves water and nutrient uptake, increases cellulose and protein content, reduces lodging, enhances and regulates at least sixty different plant growth enzymes, and can affect plant disease (Ishizuka, 1978).

Plants readily absorb available K in the soil and once inside the plant, K moves readily from older to younger tissue so that its deficiency first appears in older leaves and can be easily confused with nitrogen deficiency. The difference between rice plants deficient or not in K is the color of the lower leaves. Symptoms of K deficiency include stunting with little or no reduction in tillering, droopy and dark green upper leaves and chlorosis of interveinal areas and margins of the lower leaves starting at the leaf tip. In severe cases, the affected leaves show scorching or firing along leaf margins. Plant growth and root development are reduced in K-deficient plants (Fageria and Barbosa Filho, 1994), seed and fruit are small and shriveled, and K-deficient plants may be predisposed to disease.

Effect of potassium on controlling rice diseases

Potassium alone or its combination with N, P and other nutrients can alter the disease severity of many soil-borne and foliar plant pathogens (Kiraly, 1976; Fageria *et al.*, 1997). These have been extensively reviewed before on a number of crops, diseases, and pathogens (Prabhu and Fageria, 2006; Huber, 1980; Huber and Arney, 1985, Huber, 1990; Datnoff, 1994). Even though no generalization can be made on the effect of K on disease development, this element is reported to decrease the intensity of many diseases (Table 2). As mentioned above with Cl, many investigators have failed to give adequate consideration to the companion anions, nutrient balance, and nutrient status in order to determine a definitive role of K (Prabhu and Fageria, 2006). Thus, there may be a greater response to K in deficient than fully sufficient plants or with an excess of K beyond that required for nutrient sufficiency (Huber and Arny, 1985). This suggests that K may affect host resistance more as opposed to a direct effect on the pathogen.

Table 2. Reported effects of potassium on fungal diseases[a]

Host	Disease	Pathogen	Effect[b]
Alfalfa	Leaf spot	Pseudopeziza medicaginis	⊕
Apple	Gleosporium fruit rot	*Pezicula malicorticis*	⊗
Apricot	Brown rot	*Sclerotinia fructicola*	⊕
Aspen	Canker	*Hypoxylon mammatum*	⊕
Aster	Wilt	*Phialophora asteris*	⊗
Avocado	Root rot	*Phytophthora cinnamomi*	⊕
Banana	Fusarium wilt	*Fusarium oxysporum* f.sp. *cubenses*	⊕
Barley	Net blotch	*Helminthosporium teres*	⊕
	Powdery mildew	*Erysiphe graminis*	⊕
Bean (*Phaseolus vulgaris*)	Root rot	*Rhizoctonia solani*	⊗
Bean (*Phaseolus mung*)	Leaf spot	*Mycospherella cruenta*	⊗
Beet	Damping off	*Pythium ultimum.*	⊕
Bermuda grass	Leaf blight	*Helminthosporium cynodontis*	⊕
Broadbean (*Vicia faba*)	Chocolate spot	*Botrytis fabae*	∅
Cabbage	Club root	*Plasmodiophora brassicae*	⊗
	Downy mildew	*Peronospora parasitica*	⊗
	Gray mold	*Botrytis cinerea*	⊕
	Yellows	*Fusarium oxysporum* f.sp. *conglutinans*	⊕

Carnation	Stem rot, stub dieback	*Gibberella zeae*	⊗
	Wilt	*Fusarium* spp.	⊕
Castor bean	Capsule browning and maceration	*Botrytis* spp.	⊗
Cedar, red	Blight	*Phomopsis juniperovora*	⊗
Celery	Yellows	*Fusarium oxysporum* f.sp. *apii*	⊕
Cereals	Rust	*Puccinia* spp.	⊕
	Powdery mildew	*Erysiphe graminis*	⊕
Chrysanthemum	Root rot	*Phoma chrysanthemicola*	⊕
Citrus	Brown rot gummosis	*Phytophthora parasitica*	⊗
Clover, red	Wilt and root rot	*Fusarium* spp.	⊕
Conifers	Root rot	*Armillariella mellea*	⊗
Cotton	Wilt	*Fusarium oxysporum* f.sp. *vasinfectum*	⊕
	Root rot	*Phymatotrichum omnivorum*	⊕
	Wilt	*Verticillium albo-atrum*	⊕
	Wilt	*Verticillium dahliae*	∅
	Wilt	*Fusarium oxysporum* f.sp. *vasinfectum*	∅/⊕
	Seedling blight	*Rhizoctonia solani*	⊗/⊕
	Leaf blight	*Cercospora gossypina*	⊕
	Leaf blight	*Alternaria solani*	⊕
Cowpea (*Vigna sinensis*)	Damping-off	*Rhizoctonia solani*	⊗
	Rust	*Uromyces phaseoli*	∅
Flax	Wilt	*Fusarium lini*	⊕
	Rust	*Melampsora lini*	⊕
Grape	Fruit rot	*Botrytis cinerea*	⊕
Hemp, sunn	Root rots	*Rzhizoctonia solani*	⊕
	Root rots	*Pythium butleri*	⊕
	Root rots	*Sclerotium rolfsii*	⊕
Jute	Anthracnose	*Collectotrichum corchorum*	⊕
	Root rot	*Rhizoctonia solani*	⊕
	Stem rot	*Macrophomina phaseoli*	⊕
Maize	Northern leaf blight	*Exserohilum turcicum*	⊕
	Root rot	*Gibberella saubinetti*	⊕
	Stalk rot	*Fusarium moniliforme*	⊕

	Stalk rot	*Gibberella zeae*	⊕
	Stalk rot	*Diplodia zeae*	⊕
	Stem rot	*Fusarium culmorum*	⊕
Mangolds	Leaf spot	*Pleospora herbarum*	⊕
Melon	Wilt	*Fusarium oxysporum* f.sp. *melonis*	⊕
	Gummy stem blight	*Mycophaerella melonis*	⊗
Millet	Downy Mildew	*Sclerospora graminicola*	∅
Muskmelon	Downy mildew	*Pseudoperonospora cubensis*	⊗
Narcissus	Basal rot	*Fusarium oxysporum* f.sp. *narcissi*	⊕
Onion	Purple blotch	*Alternaria porri*	⊗
Palm	Wilt	*Fusarium oxysporum* f.sp. *elaeidis*	⊕
	Boyomi	*Fusarium bulbigenum*	⊗
Pea	Root rot	*Aphanomyces euteiches*	⊕
	Wilt	*Fusarium oxysporum* f.sp. *pisi*	⊕
Peanut	Pod rot	*Rhizoctonia solani*	⊗
	Leaf spot	*Mycospherella arachadis*	⊕
Pine (*Pinus* sp.)	Wood rot	*Fomitopsis annosa*	⊕
Pine (*P. elliottii* and *P. taeda*)	Fusiforme rust	*Cronartium fusiforme*	⊗
Pine (*P. radiata*)	Root rot	*Phythopthora* spp.	⊗
Pine, white (*P. strobus*)	Rust	*Peridermium* spp.	⊕
Pineapple	Root rot	*Phytophthora cinnamomi*	⊕
Potato	Canker	*Rhizoctonia solani*	⊕
	Canker	*Rhizoctonia solani*	⊗
	Late blight	*Phytophthora infestans*	⊕
	Scab	*Streptomyces scabies*	⊗
	Scab	*Streptomyces scabies*	∅
	Stem end rot	*Fusarrium* spp.	⊕
Prune	Canker	*Cytospora leucostoma*	⊕
Pumpkin	Stem rot	*Sclerotinia sclerotiorum*	⊕
Rice	Leaf spot	*Cercospora oryzae*	⊕
	Leaf spot	*Helminthosporium* spp.	⊕
	Brown leaf spot	*Cochliobolus miyabeanus*	⊕
	Sheath blight	*Corticium sasakii*	⊕
	Stem rot	*Leptosphaeria salvinii*	⊕
	Stem rot	*Helminthosporium sigmoideum*	⊕

	Brown spot	*Ophiobolus miyabeanus*	⊕
	Leaf blast	*Pyricularia oryzae*	⊕
	Sclerotial disease	*Sclerotium oryzae*	⊕
	Sheath rot	*Sarocladium oryzae*	⊕
Rose	Mildew	*Phyllactinia guttata*	⊕
Rye	Stalk smut	*Urocystis occulta*	⊕
Snapdragon	Wilt	*Verticillium dahliae*	⊕
Soybean	Pod rot	*Diaporthe sojae*	⊕
	Root rot	*Phytophthora megasperama*	⊗
	Pod rot	*Diaporthe sojae*	∅
	Purple seed stain	*Cercospora kikuchii*	⊕
Squash	Foot rot	*Fusarium solani* f.sp. *cucurbitae*	⊕
Sugarcane	Eye spot	*Helminthosporium sacchari*	⊕
Timothy	Leaf spot	*Heterosporium phlei*	⊕
Tobacco	Leaf blights	*Alternaria, Cercospora,* and *Sclerotinia*	⊕
Tomato	Wilt	*Fusarium oxysporum* f.sp. *lycopersici*	⊗/⊕
Turf	Fuarium patch	*Fusarium ivale*	⊕
	Ophiobolus patch	*Ophiobolus graminis*	⊕
	Leaf spot	*Helminthosporium* spp.	⊕
Walnut, black	Anthracnose	*Gnomonia leptostyla*	⊗
Watermelon	Wilt	*Fusarium oxysporum* f.sp. *niveum*	⊗
Wheat	Leaf blotch	*Septoria tritici*	⊕
	Glume blotch	*Septoria nodorum*	⊕
	Root rot	*Fusarium* spp.	⊗
	Take-all	*Gaeumannomyces graminis*	⊗/⊕
	Stem rust	*Puccinia graminis*	⊕
	Leaf rust	*Puccinia recondita*	⊕
	Leaf rust	*Puccinia trticina*	⊕
	Stripe rust	*Puccinia striiformi*	⊕
	Bunt	*Tilletia* spp.	⊗/⊕
	Flag smut	*Uromyces tritici*	⊗
	Powdery mildew	*Erysiphe graminis*	⊕

[a]Data compiled from Huber and Arny (1985) with additional articles. See Prabhu and Fageria (2006) for K effects on bacteria, nematodes and viruses
[b]Potassium can decrease (⊕), increase (⊗), or has no effect (∅) on disease intensity

Rice blast (*Magnaporthe grisea* (Hebert) Barr) (anamorph *Pyricularia grisea* Sacc. = *P. oryzae* Cavara) has been classified as a high sugar disease and a well-nourished plant is prone to greater susceptibility. There was a highly significant positive ($P < 0.01$) relationship between leaf blast and K applied to lowland rice (Fig 1). All plants received 52 kg P ha^{-1} and 60 kg N ha^{-1} at sowing and an additional 60 kg N ha^{-1} at the active tillering stage. However, resistant plants frequently contained more K in plant tissues than those that are susceptible. Panicle blast severity was negatively correlated with K and Ca, but positively correlated with N, P, and Mg levels in panicle tissues (Filippi and Prabhu, 1998). The effect of K was confined to the deficiency range and no further increase in resistance was achieved beyond an optimal supply of this element.

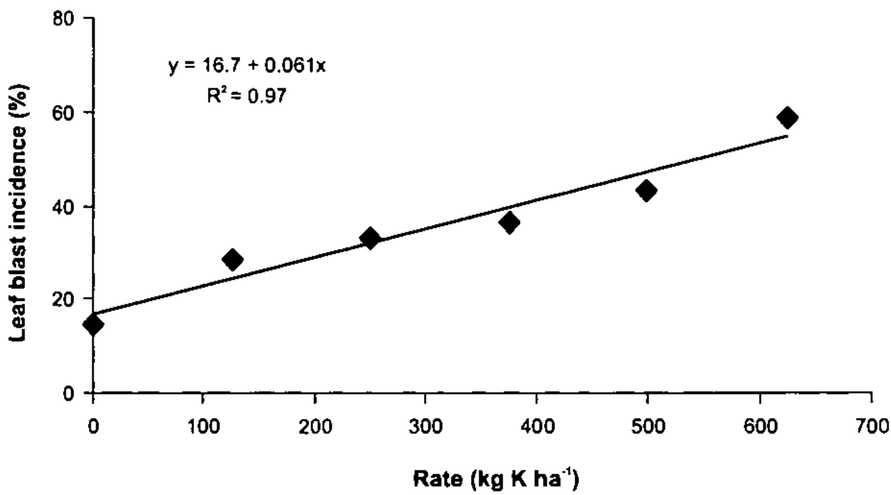

Fig 1. Effect of potassium rates on leaf blast of irrigated rice cultivar Epagri 109 grown on an Inceptisol in Brazil (Prabhu and Fageria, 2006)

Some genotypes are more efficient than others in K uptake, and this may contribute to their increased disease resistance and higher grain yield (Fageria *et al.*, 1990). Distinct differences in grain yield of upland rice cultivars susceptible and resistant to rice blast at different K levels have been reported (Table 3). The wide differences in yield were mainly due to blast incidence. In the blast resistant line, CNA 418, a significant linear yield response to applied K was attributed to enhanced blast resistance and possibly K uptake since the relationship between tissue K and disease severity was negative and linear.

Table 3. Effect of potassium rates on the yields of susceptible and resistant rice blast cultivars

K applied	Susceptible			Resistant		
	Dourado Precoce	IAC 47	IAC 164	CNA 466	CNA 4476	CNA 418
	kg ha^{-1}					
0	622	625	563	2277	2118	2050
25	708	650	647	2403	2302	2183
50	700	647	662	2285	2352	2245
75	716	657	683	2317	2368	2482
100	740	640	675	2332	2010	2447
Linear	*	ns	*	ns	ns	**
Quadratic	ns	ns	ns	ns	ns	ns

* and ** = significant at 5 and 1% probability level, respectively; ns = non significant
Source: Fageria *et al.* (1990)

Several diseases increase with an increase in N and the effect of K can be directly correlated with the level of N. The critical factor affecting rice leaf blast is the N:K ratio in leaves. Blast severity is low when there is a high tissue K:N ratio while a high N:K ratio increases blast (Ou, 1985). When the concentration of N is low, the addition of K suppresses rice blast. On the other hand, when the level of N is high, the addition of K increases blast. The K and N ratio greatly influences plant growth as well as disease development, and the ratio may change with growth of the plant.

The relationship between K_2O and panicle blast in rice at three different N rates was studied in a field experiment conducted on Dark Red Latosol (Oxisol) using a susceptible upland rice cultivar (Prabhu *et al.*, 1999). Potassium fertilization in the absence of additional N greatly decreased panicle blast. The response was significantly linear and negative with increasing levels of K (Fig 2). On the other hand, the response of panicle blast to different levels of K was quadratic at 30 kg ha^{-1} of N. Disease severity increased as the N rate increased from 0 to 60 kg ha^{-1} and decreased at rates above 60 kg N ha^{-1}. In contrast to lower N rates, K fertilization did not affect panicle blast when 60 kg N ha^{-1} was applied. These results are consistent with earlier reports that excess K results in more severe blast under high N conditions (Kozaka, 1965). Thus, K fertilization may increase, decrease or have very little effect on rice blast depending on the N rate. Soave *et al.* (1977) reported that both N and K increased the percentage of leaves with blast lesions. Because the critical factor affecting blast development is the K:N ratio, the results of K fertilization on blast incidence and development have been contradictory when the ratio is not considered (Ou, 1985).

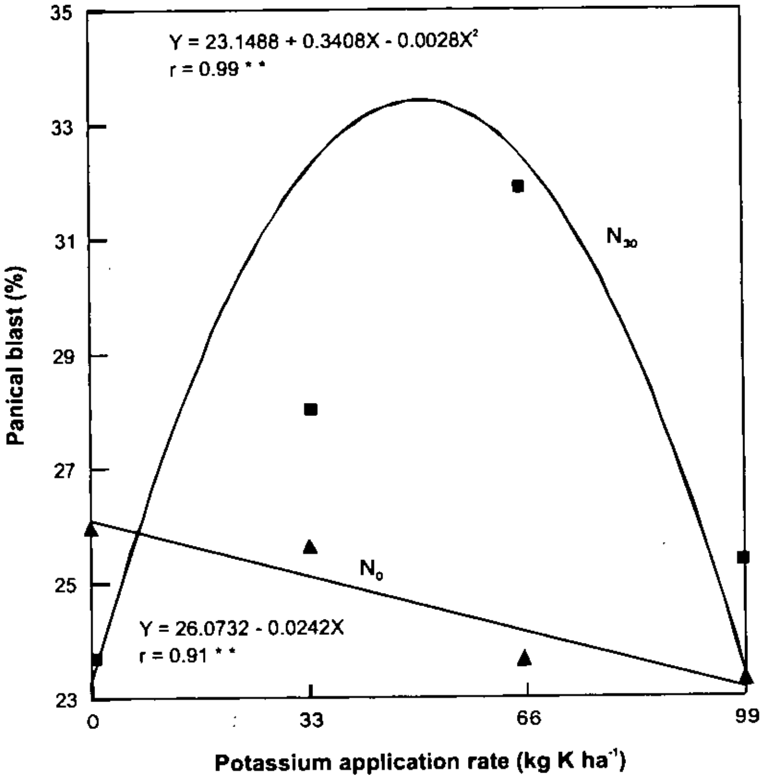

Fig 2. Effect of potassium fertilization on panicle blast at two nitrogen (N) levels in upland rice (N_0 =▲; N_{30} =■). The regression equations were calculated using fertilizer application rates expressed as K_2O

Certain plant growth stages are more susceptible to disease and the yield loss greatly depends on the stage at which plants are attacked. Rice is more susceptible to leaf blast during the vegetative phase of growth that occurs 30 to 45 days after seeding, and to panicle blast at the milky dough stage (Prabhu and Morais, 1986). Both leaf and panicle blast increase in upland rice with increasing rates of N applied all at planting (Faria *et al.*, 1982).

Brown spot of rice (*Cochliobolus miyabeanus* (Ito and Kuribayashi) Drechs. ex Dastur (anamorph: *Bipolaris oryzae* (Breda de Haan) Shoemaker) is usually associated with a K:N imbalance, and K amendments decrease the intensity of brown spot (Baba *et al.*, 1951). Although a low N:K ratio (0:30) resulted in high brown spot incidence, brown spot severity decreased when the N:K ratio was 45:30 (Faria and Prabhu, 1983).

Fertilizer sources of K include various salts from which the anion may also manifest an effect on disease in combination with or independent of the K ion. The more common sources of K fertilizers include the chloride (muriate) or sulphate salts; however, carbonate, nitrate, phosphate (mono and dibasic), silicon, and various organic salts are also used. It is difficult to distinguish between the effect of the K or the anion in the fertilizer salt used on disease unless many combinations are studied. It is well known that the Cl anion can affect various diseases independent of K (Elmer, 2003; Huber and Arny, 1985; Huber, 1991) and that K influences plant uptake of nitrate, Ca, and other mineral elements. Similar interactions are observed with phosphate salts of K (Lopez and Lucas, 2002).

The level of K in plants depends on the availability of Mg and Ca. Calcium alters the Ca:K ratio and interacts with other elements. The function of K in cellular organization and permeability is complimented by large Ca reserves in mature plant tissue. Calcium enhances K availability in neutral soils, but not in acid soils. An interaction between K and Mg was demonstrated on rice leaf blast (Sako and Takamore, 1958; Kozaka, 1965). Disease increased when K was applied alone but could be reduced by adding Mg. In addition, a negative correlation between tissue K and Mg was observed.

A combination of Si and K reduced rice blast (Winslow, 1992; Prabhu *et al.*, 2001). Potassium deficiency reduces the accumulation of Si in epidermal cells and increases susceptibility of rice to blast (Nogushi and Suagawara, 1966). Predisposition of upland rice to blast under low moisture conditions could be attributed to reduced K and Si uptake by the rice plant (Baba *et al.*, 1951). Integration of Si and K application is important for disease management and sustainable upland rice yields (Savant *et al.*, 1997).

How potassium suppresses plant diseases?

Although the physiological function of K in disease resistance mechanisms is not well understood, nutritional factors favoring host plant resistance have been attributed to alterations in protein or amino acid availability, decreased cell permeability, or decreased susceptibility of tissue to maceration and penetration. Potassium and Mg in potato extracts inhibited the macerating action of some enzymes (Huber, 1980). Arginine increases as the level of K increases and resistance of potato plants to late blight increases as the levels of K increases due to the accumulation of fungistatic levels of arginine in leaves. Exudates of arginine inhibit germination of sporangia of *P. infestans* and exudation is lowest in the absence of K when N and P are high (Alten and Orth, 1941). The ability of various soil or foliar applied K salts such as potassium phosphonate, K_2HPO_4, KH_2PO_4, and KNO_3 to stimulate systemic acquired resistance (SAR) in susceptible plants against powdery mildews, anthracnose, rust and several other pathogens suggests fundamental changes in physiological pathways are probably important in disease resistance (Reuveni *et al.*, 1995; Reuveni and Reuveni, 1998; Reuveni *et al.*, 2000; Becot *et al.*, 2000; Orober *et al.*, 2002). Interestingly, a partially purified extract from barley seedlings referred to as the papilla-regulating extract (PRE) that induced resistance to penetration by the powdery mildew fungus was shown to be a potassium phosphate (Inoue *et al.*, 1994).

Anatomical changes affected by K nutrition may also play an important role in disease resistance. Enhanced silicification of cell walls by K is one explanation for increased disease resistance. A deficiency of K decreases Si accumulation in epidermal cells and increases the susceptibility of rice to leaf blast (Nogushi and Sugawara, 1966). Potassium, in combination with P, induces the development of thicker cuticles and cell walls that function as mechanical barriers to infection by several pathogens or limit the growth of some pathogens as a result of a higher proportion of sclerenchyma tissue (Huber, 1980).

Silicon

Silicon (Si) is the second most abundant mineral element in soil and comprises approximately 28% of the earth's crust (Elawad and Green, 1979; Singer and Munns, 1987; Epstein, 1991). Many plants are able to uptake Si and, most recently, a Si transporter gene, Lsi1, was identified and characterized in rice (Ma *et al.*, 2006). Depending upon the species, the content of Si accumulated in the biomass can range from 1 to greater than 10% (Elawad and Green, 1979; Epstein, 1991). Plant species are considered Si accumulators when the concentration of Si (on dry weight basis) is greater than 1% (Epstein, 1999). Relative to monocots, dicots such as tomato and soybean are considered poor accumulators of Si with values less that 0.1% of Si in their biomass. Dryland grasses such as wheat, oat, rye, barley, sorghum, corn, and sugarcane contain about 1% of Si in their biomass, while aquatic grasses have Si content up to 5% (Jones and Handreck, 1967; Epstein, 1991; 1999; Rodrigues *et al.*, 2001). Silicon is taken up at levels equal to or greater than essential nutrients such as nitrogen and potassium in plant species belonging to the families Graminaeae, Equisetaceae, and Cyperaceae (Savant *et al.*, 1997). The Si:Ca ratio is another criterion used to determine if a plant species is a Si accumulator (Ma and Takahashi, 2002). Although Si has not been considered an essential element for crop plants for lack of supportive data, species such as *Equisetum* and some diatomaceaes cannot survive without an adequate level of Si in their environment (Epstein, 1991; 1999).

The beneficial effects of Si, direct or indirect, to plants under biotic and/or abiotic stresses occur in a wide variety of crops such as rice, oat, barley, wheat, cucumber, and sugarcane (Datnoff *et al.*, 2001; Ma and Takahashi, 2002). Leaves, stems, and culms of plants grown in the presence of Si show an erect growth, especially for rice. This suggests that the distribution of light within the canopy is greatly improved (Elawad and Green, 1979; Ma and Takahashi, 2002; Epstein, 1991; Savant *et al.*, 1997). Silicon increases rice resistance to lodging and drought and dry matter accumulation in cucumber and rice (Lee *et al.*, 1985; Adatia and Besford, 1986; Epstein, 1991). Silicon can positively affect the activity of some enzymes involved in the photosynthesis in rice and turfgrass (Savant *et al.*, 1997; Schmidt *et al.*, 1999) as well as reduce rice leaf senescence (Kang, 1980). Silicon can lower the electrolyte leakage of rice leaves promoting greater photosynthetic activity in plants grown under water deficit or heat stress (Agarie *et al.*, 1998). Silicon increases the oxidation power of rice roots, decreases injury caused by climate stress, such as typhoons and cool summer damage in rice, alleviates frost damage in sugarcane and other plants, and favors super cooling of palm leaves (Savant *et al.*, 1997; Hodson and Sangster, 2002). Silicon reduces the availability of toxic elements such as Mn, Fe and Al to roots of plants such as rice and sugarcane and increases rice and barley resistance to salt stress (Horiguchi, 1988; Liang *et al.*, 1996; Savant *et al.*, 1997). Moreover, the most significant effect of Si to plants, besides improving their fitness in nature and increasing plant productivity, is the suppression of plant disease development (Bélanger *et al.*, 1995; Datnoff *et al.*, 1997; Savant *et al.*, 1997).

Effect of silicon on controlling rice diseases

The majority of research using Si to control plant disease(s) has been conducted with rice; however, this element has reduced the intensity of several diseases in a number of important crops (Table 4). Suzuki (1935) reported that Si application to paddy soils enhanced rice resistance to blast (*M. grisea*). Volk *et al.* (1958) observed that the number of blast lesions on leaves of Caloro rice cultivar decreased linearly as the Si content in leaf blades increased. Rabindra *et al.* (1981) found that the content of Si in leaf and neck tissues varied among four rice cultivars grown under similar climatic conditions; and that those cultivars accumulating more Si in shoots showed less incidence of leaf and neck blast. Interestingly, the susceptibility to blast was negatively correlated with the content of Si accumulated in shoots for specific rice cultivars grown at different Si rates (Kozaka, 1965; Ou, 1985). However, other reports have revealed that rice cultivars accumulating higher levels of Si in shoots are not always more resistant to blast than cultivars accumulating lower levels of Si when grown under the same cultural and environmental conditions (Kozaka, 1965; Ou, 1985; Winslow, 1992).

Table 4. Host, disease and plant pathogen response to silicon applications

Host	Disease	Pathogen	Effect[a]
Rice	Leaf and neck blast	*Magnaporthe grisea*	⊕
	Brown spot	*Cochliobolus miyabeanus*	⊕
	Sheath blight	*Thanathephorus cucumeris*	⊕
	Leaf scald	*Monographela albescens*	⊕
	Stem rot	*Magnaporthe salvinii*	⊕
	Grain discoloration	Many fungi species	⊕
	Bacterial leaf blight	*Xanthomonas oryzae pv. oryzae*	⊕
	Root knot nematodes	*Meloidogyne* spp.	⊕
Wheat	Powdery mildew	*Blumeria graminis*	⊕
	Septoria leaf blotch	*Septoria nodorum*	⊕
	Foot rot	*Fusarium* spp.	⊕
	Leaf spot	*Phaeosphaeria nodorum*	⊕
	Eye spot	*Oculimacula yallundae*	⊕
	Brown foot rot	*Fusarium culmorum*	∅
	Brown rust	*Puccinia recondita*	∅
Sorghum	Anthracnose	*Colletotrichum graminicola*	⊕
Barley	Black point	*Alternaria* spp.	⊕
	Powdery mildew	*Erysiphe graminis* f.sp. *hordei*	⊕
Rye	Powdery mildew	*Erysiphe graminis*	⊕
Sugarcane	Rust	*Puccinia melanocephala*	∅
	Ring spot	*Leptosphaeria sacchari*	⊕
Zoysiagrass	Leaf blight	*Rhizoctonia solani*	⊕
Creeping bentgrass	Root rot	*Pythium aphanidermatum*	⊕
	Brown patch	*Rhizoctonia solani*	⊕
	Dollar spot	*Sclerotinia homoeocarpa*	⊕
Kentucky bluegrass	Powdery mildew	*Sphaerotheca fuliginea*	⊕
Bermudagrass	Leaf spot	*Bipolaris cynodontis*	⊕
St. Augustine-grass	Gray leaf spot	*Magnaporthe grisea*	⊕

Corn	Stalk rot	*Pythium aphanidermatum* and *Fusarium moniliforme*	⊕
	Corn smut	*Ustilago maydis*	⊕
Dicots			
Tomato	Fusarium wilt	*Fusarium oxysporum* f.sp. *lycopersici* (races 1 and 2)	∅
	Fusarium crown and root rot	*Fusarium oxysporum* f.sp. *radicis-lycopersici*	∅
	Powdery mildew	*Oidiopsis sicula*	⊕/∅[b]
	Bacterial wilt	*Ralstonia solanacearum*	⊕
Cucumber	Powdery mildew	*Sphaerotheca xanthii*	⊕
	Anthracnose	*Colletotrichum orbiculare*	⊕
		Colletotrichum lagenarium	∅
	Leaf spot	*Corynespora citrullina*	⊕
	Crown and root rot	*Pythium ultimum* and *Pythium aphanidermatum*	⊕
	Gray mold rot	*Botrytis cinerea*	⊕
	Black rot	*Didymella bryoniae*	⊕
	Fusarium wilt	*Fusarium oxysporum* f.sp. *cucumerinum*	⊕
Muskmelon	Powdery mildew	*Sphaerotheca xanthii*	⊕
Zucchini squash	Powdery mildew	*Erysiphe cichoracearum*	⊕
Pumpkin	Powdery mildew	*Sphaerotheca xanthii*	⊕
Rose	Powdery mildew	*Sphaerotheca pannosa*	⊕
	Black spot	*Diplocarpon rosae*	⊕
Morning gloria	Anthracnose	*Colletotrichum gloeosporioides*	⊕
Pea	Leaf spot	*Mycosphaerella pinodes*	⊕
Paper daisies	Anthracnose	*Colletotrichum gloeosporioides*	⊕
Grape	Powdery mildew	*Uncinula necator*	⊕/∅[b]
Soybean	Stem canker	*Diaporthe phaseolorum* f.sp. *meridionalis*	⊕
Tobacco	BdMV	*Belladonna mottle virus*	⊗
Strawberry	Powdery mildew	*Sphaerotheca macularis* f.sp. *macularis*	⊕
Lettuce	Pythium root rot	*Pythium* spp.	

[a]Silicon can decrease (⊕), increase (⊗), or has no effect (∅) on disease intensity.
[b]Silicon decreases disease intensity if sprayed onto the leaves, but has no effect on disease if added to the nutrient solution (Datnoff *et al.*, 2006)

The source and rate of Si used can strongly affect the magnitude of disease(s) control in rice. According to Aleshin *et al.* (1987), the incidence of rice blast was reduced by nearly 50% in rice plants amended with various inorganic and organic silicon sources relative to plants not receiving Si. In Nigeria, the application of sodium silicate to a Si-depleted soil cultivated with upland rice decreased the severity of neck blast on three cultivars around 40% (Yamauchi and Winslow, 1989). Winslow (1992) reported that the addition of sodium metasilicate to Si-deficient soils in Nigeria reduced by over 50% the severity of neck blast on eight different genotypes of rice. Datnoff *et al.* (1991) noted a significant reduction of neck blast in rice plants growing in a Si-deficient Histosol in southern Florida amended with 5, 10, and 15 tonne ha^{-1} of calcium silicate slag. The authors found significant linear and quadratic relationships among the rates of slag and the severity of neck blast and yield, respectively. Additional studies conducted with calcium silicate slag revealed that finely ground grades were more effective than more coarsely ground grades at reducing the intensity of neck blast (Datnoff *et al.*, 1992). The use of finely ground grades of slag was also correlated with higher silicon content in rice shoots and increased yield. Datnoff and Snyder (1994) demonstrated that reductions in the severity of neck blast brought about by the application of 0.4 tonne Si ha^{-1} did not differ significantly from those achieved by applying a labeled rate of the fungicide benomyl. In their studies, disease severity was negatively correlated with the content of Si that accumulated in plant tissue. Studies conducted by Seebold *et al.* (2004) revealed that Si alone at 0.1 tonne ha^{-1} was as effective as labeled rates of fungicides, edifenphos and tricyclazole, for the control of leaf and neck blast at low intensity levels. Furthermore, application of Si plus a 10-25% rate of fungicide provided control equal to the full rate of fungicide under conducive environmental conditions for leaf and neck blast development. Indeed, a single soil application of Si had a significant effect in controlling leaf and neck blast in the next rice season. The effect of Ca on disease development was avoided by adding lime to the plots to achieve equivalent levels of Ca throughout the treatments. It has been reported that Si was the only element that significantly increased in tissues of rice grown over a 3-year period in organic soil amended with calcium silicate slag (Snyder *et al.*, 1986). Silicon uptake may depress the absorption of Ca and its accumulation in shoots (Ma *et al.*, 1989; Inanaga *et al.*, 1995). It appears that Si can be used to augment inherent levels of resistance of some rice cultivars to blast. At one experimental area in eastern Colombia, Seebold *et al.* (2000) found that application of Si reduced the severity of rice blast in a partially resistant cultivar to levels of severity observed in a resistant cultivar not amended with Si.

Silicon also reduced the intensity of sheath blight (*Thanatephorus cucumeris* (A.B. Frank) Donk (anamorph *Rhizoctonia solani* Kühn)) even though there was no significant difference between the high and low rates of

Si applied (Mathai *et al.*, 1977). Winslow (1992) reported that Si reduced the severity of sheath blight in irrigated *indica* rice genotypes, but not on *japonica* upland rice and intermediate genotypes. However, Rodrigues *et al.* (2001) showed that Si can decrease the severity of sheath blight in both tropical *japonicas* and an *indica* type rice cultivar, which indicates that enhanced disease resistance by Si is not limited to *indica* types. Indeed, the authors noted that Si reduced the intensity of sheath blight of two susceptible (Lemont and Labelle) and two moderately susceptible (Drew and Kaybonnet) rice cultivars to levels of intensity observed in two cultivars (Jasmine and LSBR-5) with high partial resistance to sheath blight but not amended with Si. In Brazil, application of Si to a Si-deficient typic acrustox Red Yellow Latosol (Oxisol) reduced significantly the total number of sheath blight lesions on sheaths, the total area under the relative lesion extension progress curve, the severity of sheath blight, and the highest relative lesion height on the main tiller by 37%, 40%, 52%, and 24%, respectively, in six rice cultivars as the rate of Si increased from 0 to 8 tonne ha^{-1} (Rodrigues *et al.*, 2003c). Rodrigues *et al.* (2003b) also studied the effect of Si and rice growth stages on tissue susceptibility to sheath blight and observed that as the rates of Si increased in the soil, the intensity of sheath blight was significantly reduced at all rice growth stages.

Brown spot (*C. miyabeanus*), stem rot (*Magnaporthe salvinii* (Cattaneo) R. Krause & Webster), leaf scald (*Monographella albescens* (Thuem.) and grain discoloration (caused by a complex of insects and fungal species) are other diseases controlled by Si (Gangopadhyay and Chatopadhyay, 1974; Datnoff *et al.*, 1990; 1991; 1992; Correa-Victoria *et al.*, 1994; Deren *et al.*, 1994; Savant *et al.*, 1997; Komdörfer *et al.*, 1999; Seebold *et al.*, 2000). Regarding bacterial diseases, Chang *et al.* (2002), reported a significant reduction in lesion length of bacterial leaf blight (*Xanthomonas oryzae* pv. *oryzae* (Ishiyama). The reduction in lesion length was positively correlated with a decrease in the content of soluble sugar in leaves of plants amended with Si. Rice cultivars accumulating high content of Si in roots also showed increased resistance to the root-knot nematode *Meloidogyne* spp. (Swain and Prasad, 1991).

How silicon suppresses plant diseases?

The effect of Si on plant resistance to disease is considered to be due to either an accumulation of absorbed Si in the epidermal tissue or an expression of pathogenesis-induced host defense responses (Datnoff and Rodrigues, 2005). Accumulated monosilicic acid polymerizes into polysilicic acid and then transforms to amorphous silica, which forms a thickened Si-cellulose membrane. By this means, a double cuticular layer protects and mechanically strengthens plants. Silicon also might form complexes with organic compounds in the cell walls of epidermal cells, therefore increasing their resistance to degradation by enzymes released by fungi. Research also points to the role of Si *in planta* as being active and this suggests the element might be a signal for inducing defense reactions to plant diseases (Belanger *et al.*, 2003; Rodrigues *et al.*, 2003a). Silicon has been demonstrated to stimulate chitinase activity and rapid activation of peroxidases and polyphenoxidases after fungal infection. Glycosidically bound phenolics extracted from Si amended plants when subjected to acid or B-glucosidase hydrolysis displayed strong fungistatic activity (Cherif *et al.*, 1994). More recently, flavonoids and momilactone phytoalexins, low molecular weight compounds that have antifungal properties, were found to be produced in both dicots and monocots, respectively, fertilized with Si and challenged inoculated by the pathogen in comparison to non-fertilized plants also challenged inoculated by the pathogen (Fawe *et al.*, 1998; Rodrigues *et al.*, 2004). These antifungal compounds appear to be playing an active role in plant disease suppression. In addition, an increase in superoxide (O_2^-) generation was observed in rice leaves of plants treated with Si 15 minutes after inoculation with *M. grisea* (Maekawa *et al.*, 2002). More recently, Prabhu *et al.* (2005) demonstrated that silicon will suppress the sugar content of rice plants (Fig 3) while Rodrigues *et al.* (2005) showed that B 1-3 glucanase, peroxidase and PR-1 proteins are associated with rice blast suppression. Both these studies further suggest other additional mechanisms may be involved in Si mediated resistance to plant diseases.

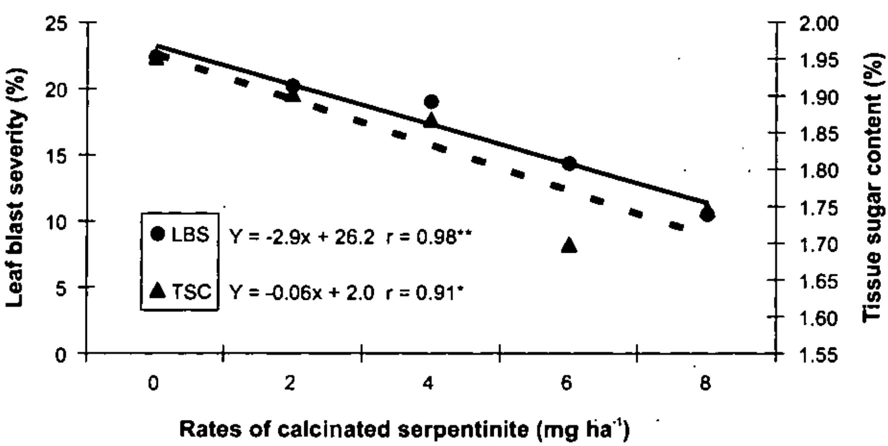

Fig 3. Relationships of leaf blast severity and tissue soluble sugar content to rates of calcinated serpentinite applied as a silicon source to irrigated rice (Prabhu *et al.*, 2005)

Conclusion

The Cl, K, and Si nutrient-host relationships outlined above demonstrate well how important each one of these elements can be for plant health, especially when the plant is low or deficient and/or under some adverse environmental stress. Although K may fluctuate in its ability to suppress plant disease, Cl and Si clearly play important roles in plant disease defense. Large gaps still exist in growers' awareness for these two elements in improving plant health. Large gaps also still exist for all three elements in understanding their ratio to other key elements in plant tissue, and subsequent effects on plant diseases and their mechanism (s) in disease suppression. More research is warranted in understanding adequate rates and application times for these three elements to improve plant utilization and subsequently plant production and health.

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Review of Waterlogging Tolerance of Wheat in India: Involvement of Element/Microelement Toxicities, Relevance to a Yield Plateau and Opportunities for Crop Management

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Abstract

Over five years of field research on waterlogging tolerance of wheat in the Indo-Gangetic Plains of Northern India has contributed to an understanding of some of the major constraints limiting wheat production in neutral and sodic soils under both waterlogged and drained conditions. Waterlogging (anaerobiosis of soils due to saturation) is confirmed in wheat crops by measurements of soil redox potentials during rainfall events or after irrigation. Waterlogging exacerbates the adverse effects of element/microelement toxicities (Al, B, Na, Mn and Fe) on wheat growth and grain yield, hence any microelements that soils are predisposed to become amplified during waterlogging.

The impact of this research is that element/microelement toxicities are now indicated across India for many areas of the: (i) 11 m hectares of rice-wheat farming systems where soils are specifically puddled (and therefore waterlogged) to enhance rice production, (ii) the 2.4 to 6.9 m hectares of sodic soils where soils have a low hydraulic conductivity and waterlogging may occur every time that the crops are irrigated or following heavy rains, and (iii) the 16 M ha of acid soils where microelement toxicities are well known from other published work. Data focus on results in India, however these findings are supported by concurrent research in acidic and neutral soils in Western Australia.

Methods to confirm microelement constraints are recommended, and these will be important factors affecting the efficient use of applied fertilizers. Element/ microelement toxicities may explain some or many of the observations for a yield plateau or decline in grain yields observed for many locations even in drained soils in India. This could be easily confirmed. These findings also relate to opportunities for improving crop management. This area of abiotic stress tolerance should be a top priority for research and germplasm improvement for wheat, rice and other major crops, particularly where stresses like waterlogging may affect yield potential and be a natural part of the cropping system such as in areas of rice-wheat farming systems and sodic soils throughout India.

Keywords: Waterlogging, wheat, microelement toxicities, aluminium, manganese, iron

Research on waterlogging tolerance of wheat has been conducted in India at the Central Soil Salinity Research Institute (CSSRI), the Directorate of Wheat Research (DWR) and the Narendra Deva University of Agriculture and Technology (NDUAT) for over five years, supported by the Australian Centre for International Agricultural Research (ACIAR). Australian partners included the Department of Agriculture and Food, Western Australia (DAFWA) and The University of Western Australia (UWA). This research includes major components of environmental characterisation, screening, evaluation of physiological mechanisms of tolerance, and germplasm development. Soil scientists, physiologists and breeders have formed multi-disciplinary teams to achieve the project aims of (i) determining what constraints limit crop growth during waterlogging, (ii) determining what adaptive physiological traits diverse wheat varieties have for tolerance to this stress, and (iii) developing over 1500 new genetically fixed breeding lines with improved microelement and waterlogging tolerance (Setter, 2006). This paper focuses on the first aim and relevance of this research to crop management.

Past publications have criticised research on waterlogging tolerance in India suggesting that the original areas said to be affected from canal seepage of 10 m ha were exaggerated and misquoted for commercial and professional interests (Chambers, 1997). The clear priority of drought and heat tolerance (Nagarajan 1998) above waterlogging tolerance of wheat in India makes it important to quantify the importance of the waterlogging stress in these target environments. Field survey work initiated by CSSRI (CSSRI, 1997) provided the first major quantification that waterlogging in India occurs in three types of areas: canal command areas (2.2 m ha), and undefined areas including unlevelled fields and sodic soils (2.3 m ha; but up to 6.9 m ha for sodic soils as cited by Bhargava and Kumar, 2004); these areas account for a total area affected by waterlogging of at least 4.5 m ha. More recent research highlights that waterlogging is also associated with the large areas of rice-wheat farming systems in India (Setter, 2006), confirming earlier observations from Nepal (Hobbs *et al.*, 1996).

The occurrence of waterlogging is demonstrated in research based on measurements of soil redox potentials (Setter and Waters, 2003). In an aerated soil, redox potentials are usually ≥400 mV, and once waterlogging occurs, the oxidation-reduction status of the soil decreases until there is no free oxygen available, i.e. soils are anaerobic (redox potentials ≤350 mV at pH 7, Marschner, 1986). Analyses of field data in India demonstrate that every time a sodic soil is irrigated, or following heavy rains, these soils become waterlogged and anaerobic with soil redox potentials as low as 0 mV; less severe results can occur in neutral and reclaimed soils.

Waterlogging results in element/microelement toxicities in crops by: (1) anaerobic conditions reduce root energy supply and therefore the ability of plant roots to exclude elements/microelements (relevant to Na, Al and B toxicities); and (2) reduced soil redox potential will result in increasing concentrations of specific microelements in soil solutions (relevant to Mn and Fe toxicities).

The implications of element/microelement toxicities affecting plants either in waterlogged or non waterlogged conditions are important for a wide range of crops and native plants grown in diverse soils. This paper considers some of the crop management aspects of these findings particularly related to yield decline and the efficient utilisation of fertilizers.

Materials and Methods

All field and pot trials were conducted at CSSRI, DWR or NDUAT. Plants were usually grown under drained conditions until 21days after sowing and then waterlogged for 5 - 20 days. Waterlogging was measured using soil redox potential measurements, where redox values ≤350 mV were used to indicate anaerobic conditions (Marschner, 1986). Soil samples were analysed at CSSRI using AAS. Plant samples collected for ICP analyses were either analysed at the University of Adelaide, South Australia, or at CRIDA, Hyderabad.

Results and Analyses

Importance of microelement toxicities for waterlogging tolerance

There are 11 approaches that have been used to indicate the importance of element/microelement toxicities in regions of wheat production in India. These findings are also relevant to other crops grown in these areas:

1) Redox potential measurements (consistent with potential high concentrations of Mn and Fe; Marschner, 1986)
2) Soil analyses using DTPA extracts to confirm high Al, Mn and Fe concentrations
3) Plant analyses (ICP) where tissues are above toxic concentrations
4) Published information from toxicities for other crops grown in the region

5) Field trial results of completely different rankings of varieties/breeding lines for waterlogging tolerance in different soils, even though waterlogging is at the same time and duration, and redox potential is similarly reduced in all soils

6) Recent theoretical findings of high [Al] in alkaline soils at these pHs (Ma *et al.*, 2003)

7) High microelement (Al) tolerance occurring in wheat from India and Australia that have been selected for waterlogging prone areas but have never been selected for Al tolerance

8) Elimination of much or all of the adverse effects of waterlogging by elimination of soil microelements using potting mix

9) Near-isogenic lines for B and Al tolerance and microelement (Al, Mn, HCO_3) indicator varieties (Table 1) that show different growth in waterlogged or in drained soils at a range of pHs

10) Waterlogging effects can often be minimised by changing pH to neutrality

11) The occasional observations that some wheat varieties even grow better in waterlogged alkaline soil (India) or acidic soil (Australia) than in drained soil which is consistent with waterlogging changing soil pH towards neutrality and thus minimising element/microelement availability or uptake

Table 1. Wheat varieties used as indicators for microelement toxicities. These varieties are available at Directorate of Wheat Research (DWR), Karnal, India

Variety	Source	Application/tolerance	Reference
ES8	CSIRO, Australia	Near-isogenic line Intolerant to Al	Ryan *et al.* (1995)a
ET8	CSIRO, Australia	Near-isogenic line Tolerant to Al	Ryan *et al.* (1995)a
Cotipora	Brazil	Variety Tolerant to Al	Ryan *et al.* (1995)b
Schomburgk	UA, Australia	Near-isogenic line Intolerant to B	Campbell *et al.* (1994)
BT-Schomburgk	UA, Australia	Near-isogenic line Tolerant to B	Campbell *et al.* (1994)
Norquay	Canada	Variety Tolerant to Mn	Moroni *et al.* (1991)
Columbus		Variety Intolerant to Mn	-
Krichauff	UA, Australia	Variety Tolerant to bicarbonate	-
Excalibur		Variety Intolerant to bicarbonate	-

Discussion and Conclusions

Relevance of research to yield plateau or decline in yield potential of wheat

There are indications that the yield potential of wheat has reached a plateau or is even declining in several areas of India (Nagarajan, 1998). Hence, even where high amounts of major nutrients are supplied, there are no increases in yield potential, even though yields in these areas are considerably below the yield potential of these crops in neighbouring areas. Root zone soil constraints such as salinity and sodicity affect water use efficiency of crops and hence, affect efficient utilisation of applied nutrients. Multiple problems also occur simultaneously in many Indian soils. Salinity, sodicity and alkaline pH - all occurring in the same soil profile may induce microelement toxicities due to Al, Mn and Fe (Rengasamy, 2000; and own measurements). Nagarajan (1998) has reviewed the possible explanations for yield plateaus in India concluding that effects were probably due to delayed sowing and weeds (*Phalaris*), although microelements were listed as a possible secondary factor.

Waterlogging can clearly be quantified by measurements of soil redox potential after rainfall or following irrigation. Waterlogging amplifies any endogenous element/microelement toxicities (Setter, 2006), which may explain why waterlogging tolerant varieties from one location, may not be suitable in another location where the microelement toxicities may be completely different. For example, the waterlogging tolerant variety Ducula-4 from CIMMYT, Mexico, does not perform well in waterlogged sodic soils at Karnal, India, where it responds more like an intolerant check variety. In this research, waterlogging has been used to identify a field constraint to crop production (element/microelement toxicities) that apparently occurs widely in both waterlogged and in many drained soils.

The extent of element/microelement toxicities now needs confirmation across more diverse soils and environments. Growth of indicator varieties or near-isogenic lines of wheat differing in tolerance to specific microelements offers a potential simple method to rapidly evaluate the possible involvement of element/microelement toxicities. Information from these genotypes could be used to further characterise environments for All India Coordinated Project trails and even as a rapid, cost effective, approach for Agricultural Extension Officers to identify microelement constraints in farmers' fields across diverse target environments. However, it is best to first confirm tolerance/intolerance of these varieties to specific element/microelement toxicities under conditions found in India. Once identified, locations with element/microelement toxicities could then be confirmed using more costly ICP analyses of soil, water and plant samples to complete these diagnoses.

Opportunities for crop management

Knowing what the constraints are that limit crop production is the first step in identifying remedial management opportunities for such conditions. Climate, soil and plant factors including fertility, pH and redox measurements, are some of the key criteria to evaluate potential limitations to crop production involving element/ microelement toxicities. Use of indicator varieties and near-isogenic lines (Table 1 for wheat) is also a simple means to rapidly evaluate potential constraints in a large number of locations. Once identified there are two major approaches for crop management for element/microelement toxicities: (1) reduce microelement concentrations in soil either directly or indirectly, e.g. through soil pH changes; or (2) grow or develop plants tolerant to these conditions. It is the first approach that is considered here, while the second approach will be the subject of other publications.

Some elements that occur at high concentrations in Indian soils include Na and B, and management approaches of growing crops on raised beds allows seasonal rain to leach these elements out of the root zone. Raised beds will also result in greater soil aeration in the bed, thus counteracting the increases in microelements like Mn and Fe associated with low redox potentials which may occur during irrigation or heavy rainfall. There are many types of raised beds or Furrow Irrigated Bed Systems (FIRBS), and whether raised beds and associated soil management options are a suitable solution for a specific area will need to be evaluated based on the economic evaluations. Changing soil pH can also be used to affect the availability of many soil elements (Atwell *et al.,* 1999), however the use of this approach as a management option depends on the specific element concerned.

The source of element/microelement toxicities can also highlight an opportunity for management. For example, in large areas of Rajasthan, Punjab, Haryana and Uttar Pradesh, groundwater is known to contain high concentrations of B (Sakal and Singh, 1995) and Na. Monitoring these elements in groundwater during the season may assist in optimising irrigation schedules so as to minimise adverse effects on crops. Once identified, colourimetric field tests can be developed to assist farmers in decision making for use of groundwater. Surrogate measurement of sodicity by clay dispersion tests and evaluation of soil pH and EC have been successfully used by farmers in Australia to diagnose similar soil constraints (Kelly and Rengasamy, 2006).

In summary, by identification of abiotic stress constraints, we can develop an improved management approach involving both soil management and appropriate selection of crop varieties that will enable effective utilisation of fertilizers and optimised intensification of our agricultural systems.

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Characteristics of Potassium Fertilization and Demand

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Abstract

World agricultural production and nutrient consumption in developing and developed countries during 1990-2005 are described and discussed in this paper. Clearly, the majority of agricultural development, as well as higher growth rates in nutrient consumption, have occurred in developed countries. Furthermore, because of growing populations, variation in calorie intake, changing diet, and urbanization, it is expected that developing countries will continue to play larger role in future agriculture.

Links between agricultural production and nutrient demand are well established, and it assumed that future nutrient consumption will follow the projected increases in agricultural production. The rapid increases in agricultural production in developing countries has also led to higher consumption of potash fertilizers than previously, which has led to improvement of the N:K ratio.

Detailed projections to production, and forecast potash requirements are presented for three major crop segments: irrigated rice in Asia, oil palm in South-eAst Asia, and soybeans in Brazil and Argentina. Future potash requirements for these three segments, together with estimated potash requirements for vegetable production in China and India, may account for approximately half a million tons of potash fertilizers per annum, or approximately 65% of the growth in the global potash market. The forecast demand for potash for irrigated rice in Asia is based on a significant change in nutrient management, which could lead to a much higher increase than the predicted on the basis of increased rice production.

More information on the demand for potash for maize, sugarcane and biofuels production will enable refinement of these estimations.

The wide array of crops grown in the various and varied agro-climatic zones of the developing world will fuel further demand for potash fertilizers.

Keywords: Potash, nutrient consumption, nutrient demand, N:K ratio, soybean, oil palm, rice, land use

Development and Changes in Agricultural Production

Developed and developing countries

World agricultural production has increased steadily during the last 25 years. However, whereas production growth rates of the main crop groups varied between 0.2 and 3.4% per annum in developed countries, the growth rates maintained in developing countries were higher, and ranged from 1.9 to 6% per annum (Table 1), demonstrating that the location of market expansion is shifting increasingly towards developing countries (OECD-FAO, 2006).

At the same time, nutrient consumption in developing countries showed very similar growth trend to that of the agricultural production: average annual growth rate of potassium (K_2O) was highest (5.8%) with nitrogen (N) and phosphate (P_2O_5) showing slightly lower rates (3.8 and 4.1%, respectively) during the period 1980-2004. In contrast, developed countries recorded negative growth rates for all the three major nutrients, i.e., N, P_2O_5 and K_2O, of 0.8, 3 and 2.8%, respectively, per annum (Table 1). These latter figures reflect achievements in fertilizer use efficiency as well as increasing awareness of environmental concerns.

Clearly, the past 25 years saw agricultural production and nutrient demand rising mostly in the regions aggregated as the 'Developing Countries'. China, Brazil, India and other countries in Asia are the major contributors both to the increases in agricultural output and to the consequently increased nutrient consumption.

Table 1. Annual production (mt) and growth rates (%) of major crop groups, and averaged nutrient consumption in developed and developing countries (1980-2004)

Crop/factor	Developed countries			Developing countries		
	Production		Av. annual	Production		Av. annual
	1980	2004	growth rate	1980	2004	growth rate
	mt		%	mt		%
Cereals	783.7	990.7	1.4	766.2	1,273.3	2.2
Fruit & Vegetables	271.8	301.2	0.5	355.6	1,067.9	4.7
Roots and tubers	184.4	182.7	0.2	337.8	532.7	1.9
Soybean	51.1	91.6	3.4	29.9	112.7	6.0
Meat	89.7	81.6	0.8	47.0	150.6	5.0
Nutrient consumption						
N			-0.8			3.8
P_2O_5			-3.0			4.1
K_2O			-2.8			5.8

Source: FAOSTAT, 2005

Increased production

The annual additional agricultural outputs between 1990 and 2005 are presented, according to crop, in Table 2 (calculated from FAOSTAT). For example, the global production of vegetables and melons in 2005 was 420 Mt higher than that in 1990, i.e., a 90% increase (over 1990). The production of oil palm fruit recorded the highest growth rate, as production in 2005 was 250% higher than that in 1990. Table 2 clearly shows the magnitudes and locations of the added agricultural production: the major large increases occurred in the developing countries of Brazil, China, India, Vietnam, Argentina, Malaysia and Indonesia.

Table 2. Additional production of major crops during the period 1990-2005

Crop	Additional production[(1)]	Percentage increase[(1)]	Major increases in...
	mt	%	
Vegetables & melons	420	90	All developing countries
Sugar cane	240	25	Brazil, China, India, Vietnam
Maize	218	45	USA, China
Fruit	140	40	All developing countries
Oil Palm fruit	110	250	Indonesia, Malaysia
Rice	100	20	Developing countries (Asia)
Soybean	100	100	Argentina, Brazil, USA, India, China

[(1)] Calculated as the difference between 2005 and 1990 yearly production levels. Base year is 1990
Source: FAOSTAT, 2006

To better understand the drivers for increased agricultural production, it is vital to reflect on the food requirements, which are constantly changing in response to processes in society. The following drivers account for the changes we observe:

- The world population increased at 1.26% per annum since 1960 and is projected to maintain its growth at 1.1% per annum through 2015. Africa sustained the highest regional rate, with 2.08% (OECD-FAO, 2006).
- There are wide gaps among the various regions in their calorie intakes: per capita food consumption in 1997/99 in industrialized countries was 26% higher than that in developing countries (FAO, 2003).
- Diet composition for many is suboptimal: for 76% of the world population the per capita consumption of protein from animal or marine sources was under 40

g day^{-1}, which is considered below the optimal level for humans, especially for children (Gilland, 2002). Since meat production involves protein conversion from grain, it means that much greater quantities of grain are needed to supply protein unit from livestock (Smil, 2002).

- Urbanization is rapidly increasing: within the next 5 years, half of the world's population will live in cities; and the link between urbanization and consumption of meat, diary products and other oils and fats is well established. As urban population (and incomes) grow, demand for these products rises (OECD-FAO, 2006).

All these factors influence and create strong demands for livestock and poultry products, and for oils, vegetables, and fruits, and various cereals. This demand is mostly found in the developing countries with growing populations, where higher calorie intakes with more protein are predicted. Production of these commodities in developing countries may lag behind the strong and increasing demand, and may increase the need of imports.

Changes in land use

Global agriculture has responded to the challenge of strongly increased demand for agricultural products in several ways. Productivity has steadily increased, thanks to irrigation, fertilization, better seeds, and better management, even though not at the same pace as was seen during the 1960s and 1970s. At the same time, there were marked changes in the amounts of land under certain crops. During the last 15 years, the area under oil palm almost doubled, and that used for vegetables, soybean and fruit increased by ~50% (Fig 1). The areas under maize and rice also increased modestly, but that under wheat decreased by almost 7%, equivalent to 14 m ha.

Whereas the increases in land used for oil palm and soybean has been largely at the expense of rainforest and savannah (Grau *et al.*, 2005; Koeppe *et al.*, 2005), the shift in land use in China and India during the last 25 years has been at the expense of cereals: mainly wheat and rice (in China), and sorghum (in India) (FAOSTAT, last accessed 8-2006 (Table 3). During the last 25 years, land used for cultivating vegetables and melons in China has dramatically increased from 6 to 32 m ha, whereas that used for wheat and rice decreased by 11 m ha. In contrast to the declining trends of rice and wheat land use, land under maize has expanded by 6 m ha, in response to increasing demand for animal feed. A similar shift in land use is observed in India, but mainly at the expense of sorghum (jowar).

Development of Nutrient Consumption

Global changes in nutrients demand

These changes in the global agriculture scene have had an impact also on nutrient demand in two major ways: 1) more agricultural production means more removal of nutrients that have to be replaced with added nutrients; and 2) the shift from low-nutrient-demanding crops (e.g., cereals) to high-nutrient-demanding crops (e.g., oil palm and vegetables).

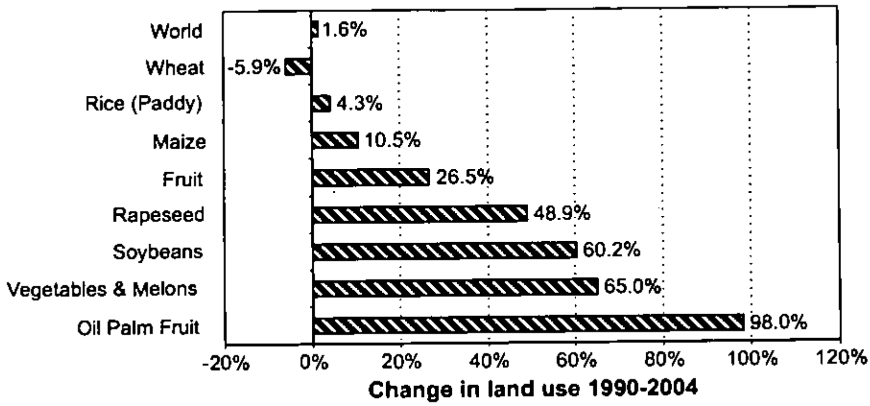

Fig 1. Change (%) in world harvested area (1990-2004) of selected crops (Calculated from FAOSTAT, 2005)

Table 3. Change in land use in China and India, 1980 - 2005

Crop	China		India	
	1980	2005	1980	2005
	Land use (m ha)			
Wheat	29	23	22	26
Rice (paddy)	34	29	40	43
Maize	20	26	6	7
Sorghum (jowar)	3	0.6	16	9
Vegetables and melons	4	22	4	7
Fruit	2	10	2	4

Source: FAOSTAT, 2006

World nutrient consumption has increased significantly since the early 1960s, much as fertilizer inputs played an important role in the Green Revolution in Asia (Borlaug, 1997; Tilman *et al.*, 2002). During the last 45 years, the average annual increase in nutrient consumption was highest for N (4.4%) followed by P_2O_5 and K_2O, at 2.9 and 2.6%, respectively. During the late 1980s and early 1990s, as the former Soviet Union collapsed, nutrient consumption fell significantly. In the present paper, we focus on the relatively stable period of the last 11 years from 1993 through 2004 (Fig 2).

During this period (1993-2004), growth rates in world consumption of all three major nutrients were lower than during the previous 45 years, but K_2O exhibited the highest average annual increase of 2.8%, with N and P_2O_5 following at 1.4 and 1.2%, respectively. The stable growth in nutrient consumption is also apparent in the high linear regression trend with R^2>0.75 for all three macronutrients (Fig 2).

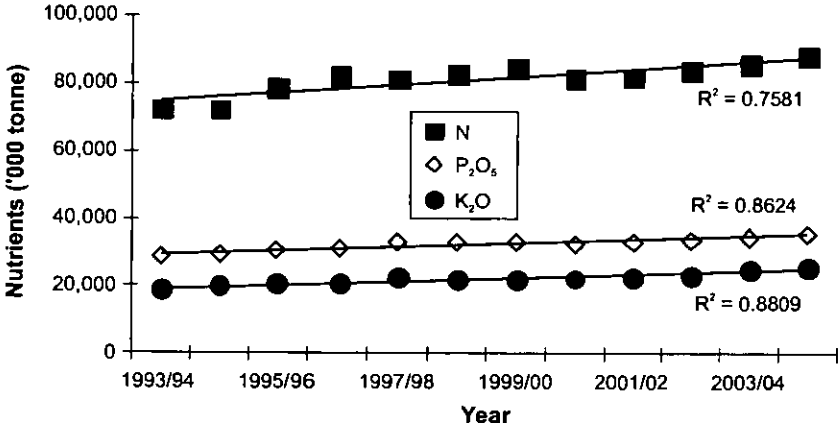

Fig 2. Global nutrient consumption 1993-2004 (Calculated from FAOSTAT, 2006). Annual growth rates are 1.4% for N, 1.2% for P_2O_5 and 2.8% for K_2O

Balanced fertilization; the N:K ratio

Fertilizers contain the nutrients that are essential to plant growth and development, and which enable plants to produce the food that animals and humans consume. Plants require 16 nutrient elements, which are essential for completion of the life cycle. Carbon (C), hydrogen (H) and oxygen (O) are derived from air (carbon dioxide, CO_2) and water, and nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), zinc (Zn), and selenium (Se) are mineral nutrients that are derived from the soil in the form of inorganic salts (Marschner, 1995). Absence or low availability of these nutrients results in poor growth and crop production, and is generally accompanied by visible deficiency symptoms.

The German agronomist and chemist Carl Sprengel (1787-1859) conducted basic and high-impact research on soil fertility and plant nutrition during the first half of the 19th century (read more about Sprengel in the 'History of Soil Science' by van der Ploeg *et al.*, 1999). In 1828 Sprengel published a journal article on soil chemistry and mineral nutrition of plants that contained, in essence, the first appearance of the theory of the 'Law of the Minimum'. He wrote that a soil may be favorable in almost all respects, "...yet may often be unproductive because it is deficient in *one single element* that is necessary as a food for plants" (Epstein and Bloom, 2005). In 1840 Justus von Liebig (1803-1873) published a report on "Organic chemistry in its applications to agriculture and physiology" in which he further elaborated the 'Law of Minimum' and the theory of mineral nutrition (van der Ploeg *et al.*, 1999). Since then, for more than 160 years, agronomists, farmers and scientists have been applying nutrients, while bearing in mind that deficiency of any single nutrient might impair the growth of a given crop. That would be the source of the term 'balanced fertilization'.

Although the nutrient requirements of crops may differ, the amounts of N and K removed by many of them tend to be large and similar, except for many fruits and vegetables, for which the amount of K removed exceeds that of N. In this respect, the ratio between N and K applied through mineral fertilizers is crucial for adequately balanced fertilization.

It is apparent that the trends of agricultural production and nutrient consumption during the last 15 years have led to an improvement in the N: P_2O_5: K_2O ratio in developing countries, from 1:0.42.0:0.16 in 1980 to 1:0.58:0.23 in 2002, reflecting much larger relative application rates of K. However, the N:K ratio in developed countries still reflects much higher K use. The fact that N consumption in developed countries is only 2.8 times that of K_2O, whereas in developing countries it is as high as 4.3 times implies excessive N and insufficient K use in developing countries. Indeed, in the late 1980s, N and P_2O_5 consumption in developing countries surpassed that in developed countries, whereas that of K_2O achieved this level only after another 10 years (Fig 3).

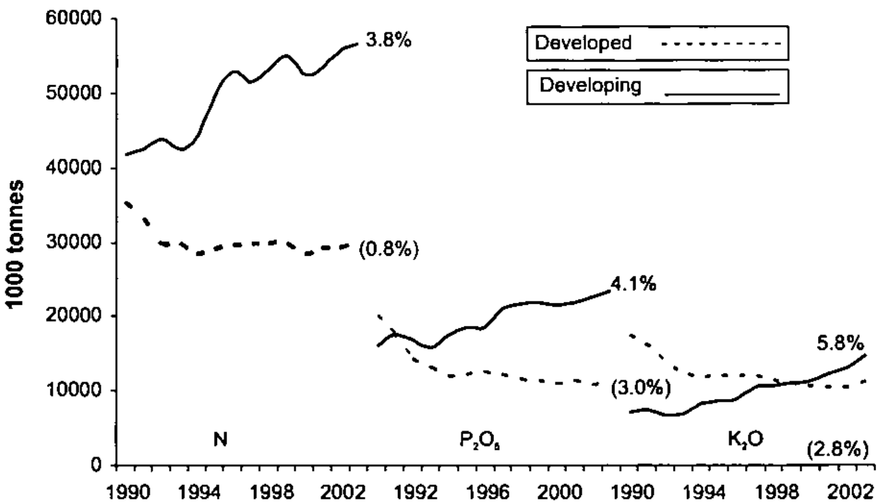

Fig 3. Consumption and annual growth rates of N, P_2O_5 and K_2O in developed and developing countries, 1990-2004 (calculated from FAOSTAT, 2005)

From the agronomical point of view, an interesting example of development in the N:K_2O ratio is shown in the work of Lu Jianwei (2005), who monitored the N, P_2O_5 and K_2O application rates, and calculated the ratio in 1301 rapeseed farms in 1997, and did the same for the nitrogen, phosphate and potassium application rates in 713 farms in 2004. The results show that during this 7-year period, the N application rate, per unit area, dropped by 37%, from 161 to 103 kg ha^{-1}, whereas K_2O application rates almost doubled, from 19 to 35 kg ha^{-1} (Fig 4), leading to a massive change in the N:K_2O ratio, from 1:0.12 to 1:0.34.

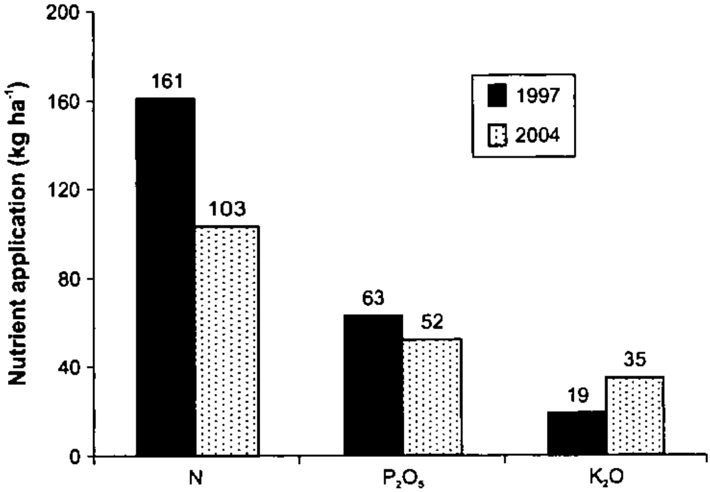

Fig 4. Changes in nutrient application rates in rapeseed farms, China, 1997-2004 (Adapted from Lu Jianwei, 2005)

Between 1990 and 2002, the N:K_2O ratio in China and Brazil improved significantly (Fig 5), because the increase in K consumption was greater than that of N. During the same period the N:K ratio in the US did not change from its relatively high level (>0.4), whereas in France it decreased. The N:K_2O ratio in India did not improve during this 12-year period, and it still remains very low (<0.18), which leads to constant removal of soil K from Indian soils (Krauss, 2000).

Future trends of nutrient consumption for irrigated rice were described by Dobermann and Dawe (2000), who asked "How much fertilizer is needed for irrigated rice in Asia". They concluded that the possible large improvement in nutrient management for rice in Asia would require a large increase in potassium fertilization. This change is projected to drastically change the N:K ratio from 1:0.2 in year 2000 to 1:0.48 in 2020 (Fig 5, see the bar marked as "IR Asia"). More data from this work presented in the last section of this paper.

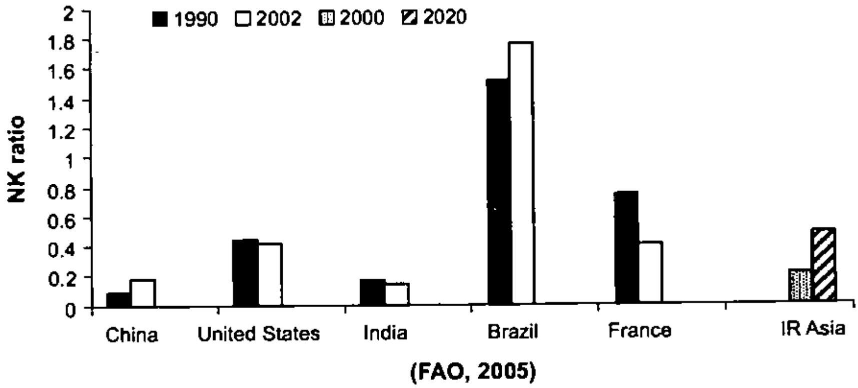

Fig 5. N:K ratio during in 1990 and 2002 in selected countries; projected N:K ratios in irrigated rice (IR) in Asia during 2000 and 2020. (Adapted from IFA (2005) for 1990-2002 data, and from Dobermann and Dawe (2000) for 2000 and 2020 data)

To conclude, because of the currently ongoing increases and changes in agricultural production in developing countries, the $N:K_2O$ ratio is slowly improving towards higher relative use of potash. Intensification of field crop growing as well as strong increases in vegetable and fruit production can be expected to fuel further higher relative use of potash fertilizers.

Future Development of Agricultural Production

By 2050, global population is projected to be 50% larger than at present and to reach approximately 9 billion people, with some variation according to the analysis used (UN population division, http://esa.un.org/unpp/). Of these 3 billion people to be added to today's population, 2.5 billion will be in the less-developed countries; 1.2 billion of them in Asia, and 1 billion in Africa.

According to various sources, annual global cereal demand is projected to reach 2.5 Bt in 2020 (Rosgrant *et al.*, 2001), 2.8 Bt in 2030 (FAO, 2003) and 3.4 Bt in 2050 (Gilland, 2002), compared with the current annual consumption of approximately 2 Bt. This increased demand will result from the increased global population, the projected 2.4-fold increase in per capita real income, and from shifts towards diets containing a higher proportion of meat (Tilman *et al.*, 2002). This additional demand will be met by a projected almost doubling of the irrigated land area, to 529 m ha in 2050 (Tilman *et al.*, 2001), increased nutrient use (see next section), enhanced efficiency of nutrient and water use, improved disease and pest control, and improved seeds, extension services and management - all which are outside the scope of this paper.

GDP growth is a major factor driving the increased consumption of fertilizers. The annual growth in real GDP in various countries and regions, expressed as percentage changes from the previous year, was addressed by the OECD-FAO (2006). According to this forecast, which was prepared by the World Bank, the high growth rates, of approximately 4-8% per annum, of the economies of China, India and Brazil - which are also rapidly growing fertilizer markets - and that of Russia, of about 3% per annum, will have a strong impact on global agricultural production and trade. In comparison, the expected growth of other developed economies is slower, at ~2% pa, as shown for the EU15 (OECD-FAO, 2006).

Will past developments continue in the future? The world's projected annual growth rates for several agricultural products over the 10 years, 2006-2015 (OECD-FAO, 2006) are compared with actual historical growth rates over the 15 years, 1990-2005 (FAOSTAT, 2006) are compared in Fig 6. Among the various agricultural products compared, some, such as oilseed meal, show slight reductions in growth rates in the future, whereas some, such as sugar, coarse grain and rice, show slight increases in growth rates. It can be concluded, according to these data, that the rate of increase in production of agricultural products over the next 9 years will continue similarly to what we have seen during the last 14 years.

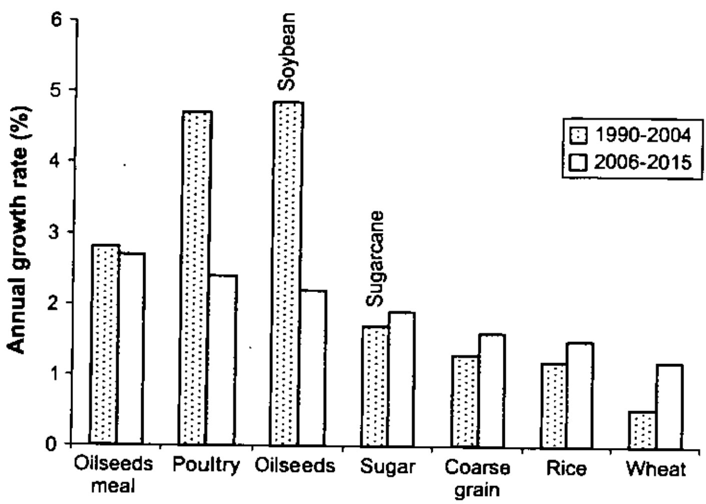

Fig 6. Growth rates in world production of agricultural products; projected (2005-2015, adapted from OECD-FAO, 2006) and historical (1990-2004, calculated from FAOSTAT, 2006)

These trends foreshadow a very demanding future for global agriculture. On the one hand, it is well recognized that increased production poses challenges for the sustainability both of food production systems and of terrestrial and aquatic ecosystems (Tilman *et al.*, 2002). On the other hand, the benefits of nutrient inputs in achieving targeted growth of various crops are often underestimated, and even ignored: it is estimated that at least 30 to 50% of crop yield is attributable to inputs of commercial fertilizer nutrients (Stewart *et al.*, 2005). It is likely, then, that nutrient inputs will continue to play a major role in future agricultural production. Nevertheless, it will require increased nutrient use efficiency especially of nitrogen and phosphorus, as well as improved management practices, judicious use of pesticides and antibiotics, and major changes in some livestock production practices (Tilman *et al.*, 2002).

Agricultural Perspectives

In this paper, we will describe three cases of agricultural development and the potassium requirements of specific crops: 1) irrigated rice in Asia; 2) oil palm in Malaysia and Indonesia; and 3) soybean in Brazil and Argentina. This approach can be used for other crops and regions to identify potential growth and trends in demand for nutrients.

Irrigated rice in Asia

Rice is grown on some 153 million ha and it provides food for millions of consumers as well as income and livelihood to a myriad of farmers, most of them living in Asia. It is a story of success: from 1.9 t ha^{-1} in 1961, the yield reached 2.7 t ha^{-1} in 1980, and these days can be as much as 4 t ha^{-1}, demonstrating an increase in yield of almost 1 t ha^{-1} every 20 years. Without these yield increases the paddy area would have to be twice its present size to provide the current annual output of nearly 600 million tonnes. In other words, increasing yields contributed substantially to the preservation of both the natural resources, land and water.

In Asia irrigated rice is grown on some 79 million ha, which is slightly more than half of the global rice acreage, but which accounts for about 75% of the world's annual rice production (Huke and Huke, 1997). The International Food Policy Research Institute (IFPRI), using the IMPACT model, calculated that rice production in Asia will increase by 25% from, 406 mt in 1999 to 527 mt in 2020, i.e., an annual increase of 1.25%. In light of the expected growth of 0.15% per year in land under rice cultivation, productivity needs to be increased from 5.3 t ha^{-1} in 1999 to to 6.7 t ha^{-1} in 2020 (Witt *et al.*, 2002).

On the basis of a large set of data from on-farm experiments conducted in South-East Asia, Witt *et al.* (2002) used the QUEFTS model (Janssen *et al.*, 1990) to develop two scenarios to assess future demand for nutrients for irrigated rice in Asia (Fig 7). The first scenario assumes no change in nutrient management, and nutrient consumption follows increases in productivity. According to this scenario, use of N, P and K each increases by 25%, in parallel to the 25% increase in productivity projected by IFPRI. In the second scenario, the authors assumed a different nutrient management, based on balanced fertilization through site-specific nutrient management (SSNM). In this scenario, nitrogen, phosphate and potassium use will increase by 12, 0 and 130%, respectively, i.e., the increase in K use will be five times that predicted in scenario 1. The increased use of potash, as K_2O from 20 to 56 t ha^{-1} or, in terms of total quantity from 1.8 mt in 2000 to 5.3 mt in 2020, will also lead to a massive change in the N:K ratio (Fig 5).

Nutrient management is not the only factor, but will be the most dominant, in achieving the future increase of irrigated rice production in Asia. Dobermann and Dawe (2000) identified the factors leading to increased irrigated rice production in Asia as follows: 1) increased genetic yield potential (10-15%); 2) increased use of N and P (20-25%); 3) improved N use efficiency (40-50%); and 4) a 200-300% increase in K use.

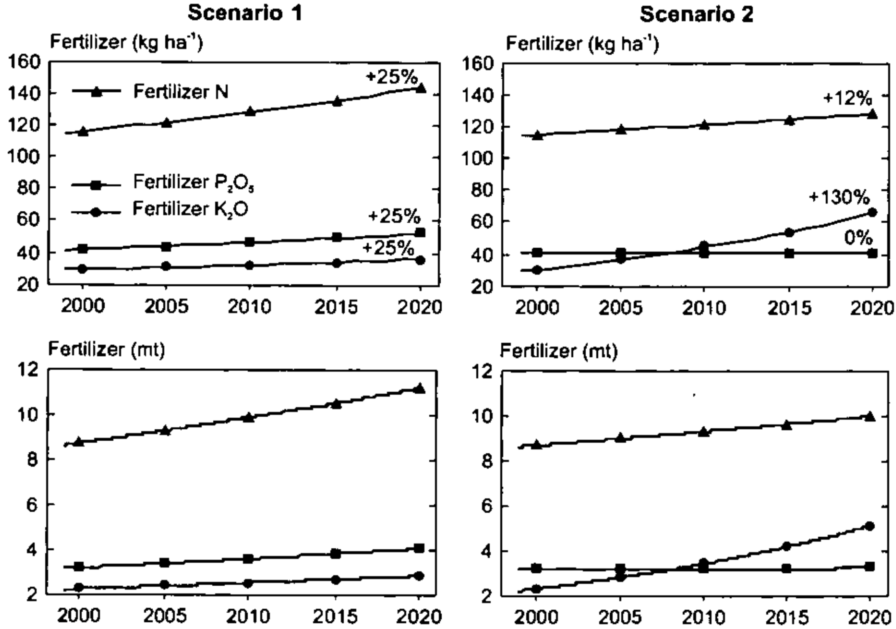

Fig 7. Fertilizer requirements based on baseline growth in fertilizer use (scenario 1) and nutrient efficiency growth (scenario 2) based on the model QUEFTS (Witt *et al.*, 2002)

Oil palm in Malaysia and Indonesia

During the last 15 years (1990-2005), the global oil palm growing area more than doubled, to 12 m ha. During this period, Malaysia and Indonesia increased the land under oil palm production from 1.75 and 0.67 m ha, respectively, in 1990 to 3.6

m ha each in 2005, and together they account for 57% of the global area (FAOSTAT, 2006). In terms of production, during this period, total world production almost tripled to 173 mt in 2005, of which the big two producers, Malaysia and Indonesia, produced 76 and 64 mt, respectively, i.e., they shared 80% of the global total (FAOSTAT, 2006) (Fig 8). Thus, understanding the patterns of nutrient consumption in both countries' oil palm sectors leads to further understanding of future nutrient requirements in this sector.

According to the FAO (2002), the oil palm sector in Malaysia consumed 570,000 t of K_2O, which amounted to 90% of all the K market of this country. Fairhurst and Witt (2005) calculated and estimated the area occupied by and the nutrient use in oil palm plantations in Indonesia, and showed that on average, the oil palm growers applied K_2O at 105 kg ha^{-1}, and used a total of approximately 345,000 t of this nutrient, which is well over 60% of the K market of that country. Thus, we can assume that the oil palm sectors in Indonesia and Malaysia consume approximately 1 mt of K_2O annually, which is about 4% of the global potash market.

Since 1990, the average annual growth rates of oil palm production in Malaysia and Indonesia were 12.5 and 7.4%, respectively (Fig 8). Strong future demand for palm oil is anticipated, for use in food, in the development of palm-oil-based biodiesel production, and to satisfy an increasing share of in the needs of oil-based industries (Wahid and Kook Weng, 2005). Nevertheless, during this period the productivity of palm oil in both Malaysia and Indonesia grew relatively modestly at 1.4 and 0.7% per annum, respectively (FAOSTAT, 2006), meaning that much of the increased nutrient demand was used in newly planted plantations.

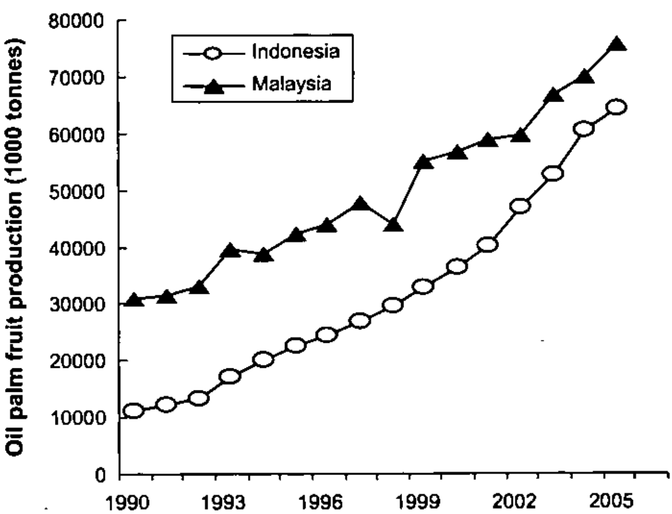

Fig 8. Oil palm fruit production (mt) in Malaysia and Indonesia 1990-2005 (Calculated from FAOSTAT, 2006)

Preliminary results from the IPI-PPI/PPIC SEAP project on 'Best Management Practices (BMP) for Maximum Economic Yield in Oil Palm' suggest that there is a large potential for increased productivity, through the adoption of various technologies, including improved nutrient management (Fairhurst and Witt, 2005; Witt, internal report). Adoption of BMP could exploit a large potential to increase crude oil productivity, which is currently stagnant at ~3.5 t ha^{-1} in both Malaysia and Indonesia. Indeed, preliminary results of BMP adoption show that after a few years, bunch yield can be increased by 50%. We assume that K consumption in this sector will exhibit at least the same growth rates as that of oil palm production, or 10% per annum. This is equivalent to an annual K_2O requirement of approximately 95,000 t, or 10% of the worldwide additional annual requirements.

Soybean in Brazil and Argentina

World soybean production increased by an average of 4.85% per annum since 1990, equivalent to approximately 10 mt of additional bean production per annum. In 2005 Brazil and Argentina together produced approximately 80 mt of beans, a similar output to that of the US. These three big producers account for 75% of global production. However, whereas the US production increased modestly, by 4% per annum, both South American countries, and several others are expanding their production rapidly: in Brazil and Argentina, annual soybean production has increased by 7.6 and 10.3%, respectively, since 1990.

Most of this increased production reflects the increased area under soybean cultivation. During 1990-2004 soybean land use increased by 60% worldwide (Fig 1), and most of this growth took place in Argentina and Brazil. The area under soybean production in Argentina and Brazil rose from 5 to 14 and from 11.5 to 23 Mha, respectively (1990-2004, FAOSTAT 2006), increasing the share of these two countries in the worldwide soybean growing land area from 29 to 40%.

The IFPRI calculated future production of soybean in 2020 at 26.8, 48.1 and 94.9 mt in Argentina, Brazil and the USA, respectively (Rosgrant *et al.*, 2001). However, whereas this 2001 publication compared 1997 figures with predicted 2020 data, the actual production figures of 2001 and 2004 in Argentina and Brazil, respectively, (FAOSTAT, 2006) had already matched the IFPRI forecast for 2020, indicating much faster growth in these two countries (Fig 9).

The soybean crop uses approximately 1.3 mt of K_2O per annum, or 40% of the K used in Brazil, i.e., far more than maize, which accounts for 15% of K consumption (Yamada, 2006). Although the demand for soybean is expected to remain strong, the Brazilian soybean production is facing great economic difficulties, mainly because of the unfavorable exchange rate between the Brazilian real and the US dollar, rust disease, and erratic rainfall in some regions (Yamada, 2006). Some of these factors affect the productivity in Brazil, which ranged from 2.31 to 2.82 t ha^{-1} during 2000-2005 (Table 5).

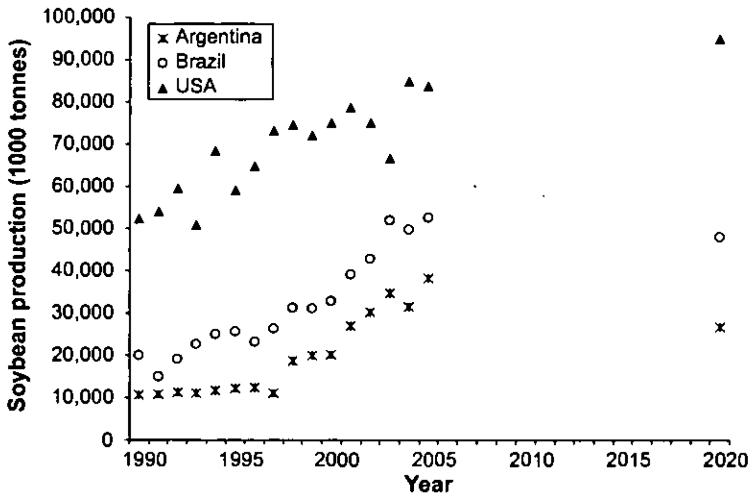

Fig 9. Soybean production in Argentina, Brazil and the USA 1990-2005 (Source FAOSTAT, 2006) and forecast for 2020 (Source: Rosgrant *et al.*, 2001)

Table 5. Soybean productivity in Argentina, Brazil, the USA and the world: 2000-2005

	2000	2001	2002	2003	2004	2005
	t ha^{-1}					
Argentina	2.34	2.58	2.64	2.80	2.20	2.73
Brazil	2.40	2.80	2.61	2.82	2.31	2.30
USA	2.56	2.66	2.56	2.28	2.84	2.91
World	2.17	2.32	2.30	2.28	2.26	2.34

Source: FAOSTAT (2006)

With US soybean production increasing at a much slower rate than those of Argentina and Brazil, and since Argentina's production relies on the rich K reserves in the Pampa region, most of the future development in K consumption in soybean production may come mainly from Brazil and the neighboring countries of Paraguay and Bolivia. Cerrado soils are acidic, with low fertility, therefore there is strong dependence on fertilization for achieving high yields.

Despite fluctuations in soybean productivity in Brazil, we assume that the K market for soybean in Brazil will continue to grow at 5% per annum, in parallel with production growth. On the basis of the share of Brazil's K consumption used in soybean production, we estimate that approximately an additional 85,000 t of K_2O per annum may be required.

Assumptions and Calculations of Future Potash Demand

Future agricultural production will continue to be mainly in developing countries (or non-OECD countries) and most of the commodities are projected to continue their growth rates at similar rates to those of the last 15 years (OECD-FAO, 2006). We assume that nutrient consumption in these countries will follow the same pattern.

Average production growth rates of rice, soybean, vegetables, oil palm, and sugarcane were calculated for developing countries because developed countries, in general, have not increased production. In fact, it would be preferable to analyze the portion of production that is undergoing change, i.e., that in developing countries, and to neglect the stable portion, i.e., that in developed countries. In our detailed calculation (Table 7) we refer only to the growing segment: developing countries.

Table 6 compares historical and projected growth rates of agricultural production in the main crop groups, in developed and developing countries. According to the data presented in Table 6, projected growth rates in OECD countries are very low and similar to the historical data from 1990-2005. In contrast, in non-OECD (developing) countries: sugar and rice production are projected to grow at higher rates than those achieved during 1990-2005, and the outputs of coarse grain, oilseeds, beef and poultry meat are expected to rise more slowly than the historical rates, but still to increase at healthy rates. The clearly projected production growth rates in OECD, i.e., developed countries are very low, and in some cases even negative: e.g., sugar, -1.1%. These low and even negative growth rates will put pressure on nutrient consumption in these countries. On the assumption that nutrient, including potash, consumption follows production trends, we consider that most of the additional potash consumption will be in the developing countries.

Consumption of potash, per unit area, for producing vegetables and fruits is relatively higher than for cereals and when large-scale production is involved, may account for a significant proportion of nutrient consumption. China and India used approximately 40-50% of their potash consumption in vegetable and fruit production, whereas in the US this segment accounted for only 13% of the potash used (FAO, 2002). The rapid increase in vegetable production in China and India is thus another significant growth engine for the potash market.

As mentioned above, the land area under soybean cultivation has increased globally by 60% since 1990, to reach 91 m ha in 2005, and 65% of this expansion occurred in Latin America. It is assumed that further expansion of land for this purpose will be constrained, as public opinion strongly opposes it. Nevertheless, Brazil is projected to surpass the US as the leading exporter of oilseeds, and its exports will increase strongly through 2015 (OECD-FAO, 2006). With world productivity increasing by only 1.55% per annum (average for 1990-2005) and production by 4.85% per annum, it is imperative to increase productivity of soybean further, to reduce the pressure for expanded land use. This in part, should result from better nutrient management.

Table 6. Historical and projected production growth rates for main crops

	Historical production growth rates (1)		Projected production growth rates (2)	
	Developed countries	Developing countries	OECD countries	Non-OECD countries
Sugar			-1.1	2.9
Sugarcane	1.6	1.5		
Coarse grain			1.3	2.0
Maize	3.5	2.8		
Rice	0.6	1.3	0.0	1.6
Vegetables & melons	0.7	5.8		
Wheat	0.0	1.4	1.0	1.3
Oilseeds			0.6	3.3
Soybean	3.8	6.5		
Oil palm	0.0	7.3		
Beef	-1.1	3.4	0.7	2.7
Poultry meat	2.4	7.5	1.6	3.0

(1) 1990-2005, by FAOSTAT (2006)

(2) OECD-FAO (2006)

Table 7 summarizes and locates the main effects and assumptions that we anticipated will influence the potash market. These include soybean production in Brazil, vegetable production in China and, to a lesser extent, India, oil palm production in Malaysia and Indonesia, and, finally, irrigated rice in Asia.

The calculations whose results are presented in Table 7 help to clarify the nature of projected growth of the potash market. These calculations take into account the projected expansions in the production of soybean, fruits and vegetables, oil palm and rice. The Table does not include data for maize and sugarcane, two crops with large potential to increase potassium demand further.

Vegetable (and melon) production in China appears to be the major segment in which increased consumption is to be expected. Indeed, per capita consumption of vegetables in China has been increasing rapidly, and it is assumed that it will continue to rise. Soybean in Brazil, oil palm in South-East Asia, and rice production

Table 7. Location of additional projected potash consumption by crop and region

Market	Crop	Potash market size	Projected growth rate of main crops	Additional K consumption [9]
		Thousand tonnes of K_2O	% per annum	Thousands of tonnes of K_2O
Asia	Rice (paddy)	1,800[1]	4.0[2]	72
Malaysia & Indonesia	Oil palm	1,070[3]	8.5[4]	90
Brazil	Soybean	1,716[5]	5.0[6]	86
China	Vegetables	2,330[7]	8.6[8]	200
India	Fruit & vegetables	640[7]	6.2[9]	39
World total		7,556		487
(as %)		29%		49%

(1) Dobermann and Dawe, 2000; Witt *et al.*, 2002
(2) Witt *et al.*, 2002
(3) Fairhurst and Witt; 2005; FAO, 2002
(4) Production growth rate 1990-2005 was 8.5% pa. This is assumed to continue.
(5) Yamada, internal report, 2006
(6) Production growth rate 1990-2005 was 7.6% pa. 5% is a modest assumption.
(7) FAO, 2002
(8) Production growth rate 1990-2005 was 8.6% pa. This is assumed to continue.
(9) Mullen *et al.*, 2005

in Asia will also play key roles in future potash consumption. The aggregated additional K consumption per annum (510,000 tonne of K_2O; see Table 7) accounts for about 63% of the annual growth that the potash market achieved during the last 10 years. This is also consistent with the IFA's projections for the mid-term outlook for world agriculture and fertilizer demand: potash consumption is projected to grow at 3% per annum (IFA, 2006). This calculation does not take into account projected declines in nutrient consumption in some regions, notably Western Europe, although, in fact, the global annual growth of potash consumption encompasses this decline, which is much smaller than the increases elsewhere.

In conclusion, potash consumption is considered to be driven by increasing demands for quality foods, meat, staple foods, oil, and also biofuels. Advanced nutrient management in developing countries will probably boost potash consumption further, as these countries are generally under-fertilized with respect to potash. This wide array of crops that are grown in different regions and that satisfy differing needs for human well-being is another characteristic of the potash market.

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Role of Fertilizer Industry in Balanced Fertilizer Use

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Promotion of balanced fertilization has been one of the main planks of the marketing philosophy of the fertilizer companies in India since the time the concept of balanced fertilization emerged. The role of Indian fertilizer industry in promotion of balanced fertilizer use has been immensely recognized. Fertilizer companies have been carrying out a variety of promotional and educational programmes to educate the farmers on balanced and efficient use of fertilizers. The programmes conducted by the industry include the farmers meetings, field days, dealers/cooperative salesman trainings, crop seminars, field demonstrations, intensive campaigns, farmers fair and exhibitions, audio-visual shows, printed literature, soil test campaign and village adoption to name a few. The range of programmes is so large and wide that even to list them all will be a stupendous task. A brief account of such activities carried out by some of the companies in the fertilizer industry has been published in the Indian Journal of Fertilizers Vol. 2, No.1 (April, 2006). It is worth mentioning here that only a part of the amount being spent by the fertilizer companies on these activities is being recognized by the GOI. The companies are carrying out these activities virtually on their own, mainly with a view to providing educational and advisory services to the farming community. While these programmes have benefited the farmers at large, the industry has also gained in the process. The balanced and efficient use of fertilizers has led to enhancement in productivity and production leading to higher income to the farmers resulting in larger volumes of sale of fertilizers.

Fertilizer consumption (N+P+K) remained almost stagnant around 16-17 million MT during 1998-2004 period. During the same period food grain production has also not shown any growth. In fact, in the subsequent two years 2004-05 and 2005-06, while the fertilizer consumption has increased substantially (20.34 million MT in 2005-06), food grain production continues to hover around the levels achieved during 1998-2004. Virtual stagnation in agricultural productivity and production has agitated the minds of all concerned with agriculture. One of the possible reasons being cited for this typical phenomenon is the imbalanced and inefficient use of fertilizers. Intensive cultivation since adoption of HYVs in the mid sixties has resulted in removal of all the plant nutrients in significantly large quantities. During this period of 40 years, primary nutrients N, P and K were replenished, though only partly, but the secondary and micronutrients were either not replenished at all or were replenished in negligible quantities only. This has resulted in acute deficit of secondary and micro plant nutrients in the soil, resulting in imbalanced availability of the plant nutrients to the crops leading to deterioration in soil health and crop productivity. In view of this fact, the concept of balanced fertilization is no longer confined to N, P and K. It has to be extended to secondary and micronutrients as well. While the Government machinery will be doing something on its part to promote the cause of balanced fertilization, the industry will have to play a dynamic role not only in educating the farmers on the concept of balanced fertilization as extended to the secondary and micro nutrients but also in facilitating adoption of balance fertilization by the farmers by way of providing required feritliser material etc.

The industry will have to restructure its basket of activities/ programmes. Merely continuing to carry out the activities which it has been traditionally doing in the past will not suffice. The industry will have to adopt a multi pronged approach to play its role in an effective manner. Broadly speaking, role to be played by the fertilizer industry can be classified into four major categories:

i) Paradigm shift in Extension Programmes
ii) Dealer/Retailer/Cooperative Salesman Training
iii) Development of facilities for soil testing including that of secondary and micronutrients
iv) Make available appropriate fertilizer products

Paradigm Shift in Extension Programmes

As mentioned earlier, fertilizer promotion has remained an integral part of fertilizer marketing activities. Fertilizer industry, since inception has deployed available extension education tools to increase fertilizer consumption. The extension promotion programmes created general awareness about fertilizer application. As a result, technology generated by the research organizations reached the farmers and fertilizer consumption increased many fold. In this endeavor, Extension wing of State Agriculture Departments and State Agriculture Universities also contributed largely.

In the changed scenario, a paradigm shift in extension promotion activities of the industry has become imperative. India with a diverse population, literacy level, cropping pattern, socio-economic status and large number of well spread farm households needs to continue with the well established extension methods with a changed message and approach that will address the emerging problems in fertilizer use. At the same time, it has to use new generation's advanced tools of information and communication technology. The approach will shift from individual farmer to farming community; from individual crops to cropping systems and farming systems; from generalized fertilizer recommendations and nutrient management to site-specific nutrient management for all primary, secondary and micro nutrients;

from individual farm to area or watershed; from publicity to services; from input supply to supply chain management, from fertilizers in isolation to total package of crop production, from conventional farming to high tech agriculture including fertigation, precision farming, protected farming in poly-houses, diversified agriculture and contract farming and so on. The content of farmers education programme has to be made dynamic to suite the changing need of time. Balanced use of fertilizers and input use efficiency will be key to all educational programmes. While the industry has to continue with programmes of interpersonal communication of demonstrations and farmers meeting etc., it will be appropriate to formulate area or watershed development programmes using geographical information system.

Dealer/Retailer/Cooperative Salesman Training

The dealers/retailers and the managers of the cooperative societies are the ultimate unit in the input supply chain. They are the main link between the manufacturers/marketers and the farmers. Farmers look upon them as their friend, philosopher and guide. Almost any and every buyer seeks guidance from the salesman while making any purchase. Even the highly educated and very well informed customers, knowing it fully well that the salesman will first serve his own interest, ask for the opinion of the salesman with regard to the quality of the product, its price and all other desirable attributes in respect of the product he wishes to buy. In many cases, he lands up buying the product suggested by the salesman. Indian farmer is not an exception to this well established buyer behavior. It is, therefore, of vital importance that the dealers/retailers/cooperative salesmen are properly educated about the concept and importance of balanced and efficient use of fertilizers. They also need to be told that ultimately it is in their business interest that they transmit this information further down to the farmers. Manufacturers/marketers role does not come to end with transmitting this information to the dealers, but they will also have to ensure that the dealers/retailers/cooperative salesmen are supplied all the products needed by the farmers for practicing balanced fertilization. The industry will have to ensure that the required products are made available to the farmers in adequate quantity and at the time needed by them. It goes without saying that they will have to ensure the quality of the product also. Industry must involve the dealers/retailers/cooperative salesmen in their promotional and educational programmes also. In fact, if possible, the dealers/retailers/cooperative salesmen should organize some educational/extension programmes on their own also. Their involvement in the programmes will be very effective in communicating messages to the farmers.

The industry has been conducting these Training Programmes for a long time. However, in the present context, they need to be done on a much larger scale and their contents also need to be modified as per the changed concept of Balanced Fertilization.

Development of Facilities for Soil Testing

The need of the hour is to apply the fertilizer nutrients in accordance with what is needed by the crops keeping in view the variety sown, the soil status and the targeted yield and climatic conditions to be more precise. The Task Force on balanced use of fertilizers set up under the chairmanship of the Addl. Secretary, Department of Agriculture and Cooperation, has also recommended that to ensure balanced use of fertilizers at micro level, the application of nutrients will have to be soil, crop and climate specific. We have been talking of soil analysis based application of fertilizers nutrients for so many years but its adoption, in its extended form, covering the secondary and micro nutrients has assumed much greater significance now.

In order to adopt location specific/crop specific/yield specific/climate specific approach for application of fertilizers, it is essential to have precise information on the status of the soil. Soil testing, therefore, becomes a vital tool in the process of adoption of balanced use of fertilizers. As reported by the Task Force, not only the number of soil testing laboratories in the country is grossly inadequate, but also more than 75% of them do not have the equipments to analyse the secondary and micro nutrients. As reported, there are only 544 soil testing laboratories in the country (414 static and 130 mobile) with annual analyzing capacity of 7.06 million samples against 115.58 million farm holdings. In the given situation; the industry has to play a big role. In its own business interest and in the interest of improvement in crop productivity, the industry should come forward in providing soil testing facilities (with analysis of secondary and micro nutrients) by establishing soil testing laboratories. The fertilizer industry has been playing its due rule in the area of soil testing in the past. The industry has set up 40 soil testing laboratories (28 static and 12 mobile) and more than 4,00,000 samples are being tested annually. Intensive efforts are being made by the industry to make the farmers understand the need and importance of soil testing. During the FAI Golden Jubilee lecture delivered on the 1st December, 2005, Prof. M. S. Swaminathan had given a call that the FAI should make the agriculture year 2006-07 as the year of the Soil Health Enhancement. In response to the suggestion of Prof. Swaminathan, the FAI with the help and support of its member companies, has launched a nation wide campaign on Soil Health Enhancement during the current year (2006-07). Response to the campaign has been very encouraging. A number of activities covering soil testing, preparation of soil health cards, conducting demonstrations on balanced and integrated use of fertilizers, organizing trainings for fertilizer dealers, farmers etc. are being undertaken by the fertilizer companies.

With the limited resources available with it, the industry has been doing its level best. However, in the present circumstances, the industry needs to undertake this activity on a still larger scale as the gap between the existing facilities and what is needed is really large.

In addition to substantially adding to the capacity of soil analysis testing facilities, the industry will have to make extra efforts in winning the confidence of the farmers in the soil analysis results and the corresponding fertilizer recommendations. For whatever be the reasons, the farmers' experience has not been very happy and they have lost their faith in soil testing. The industry will have to re-establish the faith of the farmers in the activity of soil analysis by providing quality and timely soil analysis results and fertilizer recommendations.

Make Available Appropriate Fertilizer Products:

It has been mentioned in this paper else where that if the industry is really interested in promoting balanced use of fertilizers, then in addition to doing the educational and promotional work with the farmers, training the dealers' and providing soil testing facilities etc. it will have to ensure availability of appropriate products to the farmers. In view of the fact that the deficiency of secondary and micro nutrients is proving to be a limiting factor in giving response to application of the primary nutrients, the secondary and micro nutrients have to be accorded due priority in terms of their application in addition to the application of primary nutrients. One of the approaches being seriously considered to make it happen, is to make such fertilizers available to the farmers which will contain secondary and micronutrients along with the primary nutrients N, P and K. Composition of nutrients in these fertilizers will be in accordance with the requirement of the crops, based on the soil status, climatic conditions and targeted yields etc. One of the policy interventions and incentives for development of new products recommended by the Task Force on Balanced use of fertilizers reads as: "modifications in fertilizer policy to create a policy environment so that the industry is motivated towards the development of new products based on soil and crop requirement. For example, fortification of fertilizers with appropriate grade of secondary/micronutrients, customized and value added fertilizers etc. Such products should be approved by the Central Government and the manufacturers may be allowed to charge additional cost by selling at a higher MRP". Further, the report reads "The Task Force has noted the latest government initiative to grant approval for new products under the newly created clause 20 A of the FCO for large scale commercial trial". However, there is further need to accelerate this process in consultation with ICAR to approve new and efficient products speedily.

Keeping these developments in view, the industry has started working in the direction of coming out with the new mix of fertilizer products. The Department of Fertilizers and the industry have been working together to provide an enabling environment for manufacturer of customized fertilizers which will be the multi nutrient carriers precisely tailored to meet the specific nutritional needs at the time of sowing of the crops backed by sound scientific plant nutrition principles. The technology used in manufacturer of such fertilizer blends will make them of very high quality so that all the fertilizer granules will be uniform in size as well as in chemical composition.

At present, there is no exclusive provision for customized fertilizers in the Fertilizer Control Order. The Central Fertilizer Committee is already seized of the issue. It is hoped that it will soon come out with appropriate provisions in the FCO which will enable the industry to take up the manufacturing and marketing of the customized fertilizers.

The role of the industry is to keep itself in readiness to manufacture and market the customized fertilizers soon after the enabling provisions are notified under the FCO. As the customized fertilizers are knowledge driven, the industry has to educate the farmers on adoption of new nutrient package and its application technology also. Further, it is a well known fact that no nutrient source, be it mineral fertilizer, organic manure, bio-fertilizer or green manure is in a position to meet the nutrient demand of the country. In fact, it is the combined use of all sources of plant nutrients which provides an ideal solution to the problem of imbalanced use of fertilizers. The combined use of organic and inorganic sources increases the efficiency of applied fertilizers. Therefore, the industry should promote the concept of integrated plant nutrient supply (IPNS) which involves the combined use of all sources of plant nutrients. In fact, merely promoting the concept will not do, the industry will have to play a role in making them available also.

Pricing

Pricing of fertilizers plays an important role in balanced fertilization. Disproportionately lower use of P and K is being attributed to their comparatively higher prices. Since, for all practical purposes, fertilizer prices of almost all the fertilizer products are controlled by the Government, there is virtually no role that the fertilizer industry can play in fixing the prices conducive to the balanced use of fertilizers. What the industry can do and should keep doing is to continue to take up this issue with the Government particularly in view of the fact that the issue was on the agenda of the Alagh Committee and the Working Group on Balanced use of Fertilizers has also made specific recommendations in this regard.

Extension as an Effective Tool to Disseminate Research to Farmers: Success and Shortcomings

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As scientists, you are well aware of the essence of 'time' in performing various agricultural operations: matching soil to seed and product to market. And one good thing that the green revolution has done is that it has taught farmers the value of 'time' for an array of farm operations they perform. Same way, 'on time' dissemination of information is essential.

The image of today's farmer is different from that of yesteryears. Today's farmer may not be as rich as he ought to have been, consequent to the gains accruing from the first green revolution. And there still are a substantive percentage of farmers, particularly, small and marginal, who continue to be poor and uneducated. In fact, claims notwithstanding, development has bypassed vast segments of rural India.

Nevertheless, there is a silver lining that things would change given the breakthrough in Agri-tech, coming up of Info-tech, quicker means of communication and extension education methodologies in vogue. However, for this change to happen, it is imperative to first change the mindset of the stakeholders: policy-makers, scientists and farmers involved in transforming the rural landscape.

There is need to improve rural health delivery system, ensure quality education and correct skewed sex ratio. For such desired change, again timely dissemination of knowledge and information is important. For effective communication, we now have the multi-media and extension education specialists to act as facilitators: catalysts of change at the cutting edge. These foot-soldiers are the crucial link, passing the baton of not only scientific agriculture to farmers but also making them aware of social issues. Together, these enable farmers to enhance production and productivity, improve their economies and incomes and help them to lead a quality life.

We intend to focus on the efficiency and efficacy of extension education and communication methodologies and technologies that Punjab Agricultural University has successfully put to use to widen the knowledge and information base of farmers and their families. Based on experience and feedback, the extension education and communication tools have been redefined and modified.

PAU was the first state agricultural university to have realized the need for opening a window to farmers. It had set-up a full-fledged Centre for Communication in 1970, though, the concept of farmers' fair or 'Kisan Mela' struck roots when the University was established in 1962. Besides direct contact with the farmers and their families through Kisan Mela, field days are also organized in different agro-climatic zones of Punjab to demonstrate to the farmers crop production and protection technologies, introduce cost-effective farm power machinery and lay out experiments showing package of practices required to be followed for reducing cost of production and obtaining remunerative returns.

Apart from the two two-day Kisan Mela at Ludhiana in March and September, four one-day regional Kisan Melas are also held. While, this helps to impress upon farmers the concept of crop-specific and region-specific farming, it also saves them travel expenses to visit Ludhiana. The response to these fairs is tremendous. An estimated 1.25 lakh farmers visited Ludhiana campus in September last. This is one event where farmers rub shoulders with scientists, put searching questions at the face-to-face question-answer session, bring 'sick' plants or samples of different crops 'damaged' either by diseases or insect-pests for on-the-spot diagnosis and also go around the demonstration and experimental area. For farmers, 'seeing is believing'. At PAU scientists talk 'with' the farmers and not 'to' them. PAU and farmers have developed a symbiotic relationship even PAU and agriculture are synonymous.

PAU makes full use of the media, print, electronic and Radio to pass on timely information, news and views related to agriculture, besides, of course, other means: exhibitions, seminars, workshops, field days etc. Farm literature also plays a key role as an extension education tool to create awareness. The two monthly farm magazines: Changi Kheti in Punjabi and Progressive Farming in English are immensely popular. Other literature includes books on different and specific subjects besides the Package of Practices for Rabi and Kharif crops updated after deliberations between PAU and state departments of agriculture and horticulture.

In fact, the Centre has liaison with state development departments. Consequently, state co-operation department Joint Registrar, Kamaldeep Singh Sangha enrolled over 700 agricultural and multi-purpose co-operative societies as permanent members of monthly magazine Changi Kheti and Rabi, Kharif Package of Practices. This means extending benefits to 2,500 villages. In fact Joint Registrar Co-operation, Jalandhar, is instrumental in activating co-operative societies to establish village libraries with prominence to farm literature. The Minister, Amarjit Singh Samra has announced to cover the state under this movement through co-operative societies and banks. This is yet another example how communication of extension education net-working with the state instruments helps disseminate research knowledge and information to farmers.

Centre for Communication, Languages and Culture is an important component of the Directorate of Extension Education. The Centre is responsible for mirroring the University. It showcases the research activities. Its twin objectives are to supply timely information to farmers and educate general public as well through the media what agriculture is all about. And agriculture is not the only 'culture' Punjabis know of. Who can deny that agriculture is the 'mother' of all cultures?

The Centre has 10-sub units: editorial, business, art and exhibition, TV and photo section, reference and training, media centre and publicity, design, printing press, public relations and a Museum of Rural Life. Please visit that. In fact, the Centre also has a postgraduate diploma course in agricultural journalism and mass communication. This is not the usual run-of-the-mill course. This is a specialized course, wherein, students are trained to report on 'development' journalism. They are trained to report on science and technology and interpret the research activities for the benefit of farmers as well as urban readers, who must also understand the hardship faced by rural people and how important agriculture and allied sciences are in day-to-day life.

The Centre remains in touch with the Directorate's plant clinic at PAU, its farm advisory service scheme experts in the field and 16 Krishi Vigyan Kendras in the state, which provide unalloyed feedback on what goes on in rural society and on farms. Sending out flash messages through TV, Radio and newspapers on happenings that are likely to impact agriculture is a daily routine. Popular articles by scientists are distributed to daily language newspapers and magazines for the benefit of farmers. The Centre also organizes TV and Radio talks for the benefit of farmers.

We need not go into the micro-details as to how effective communication or extension education is for required returns from agriculture. However, let us give you a bird's eye-view of problems that beset Punjab agriculture, its contribution to central food grain kitty, shortcomings in dissemination of information and talk of successes achieved, as a consequence of persistent campaigns and the like. In this respect we can say that our slogan, "Save water, save Punjab" has immensely helped motivate and educate farmers not to transplant paddy before June 15. It is no mere flash in the pan to say that at least 75 per cent area under paddy this year was not sown before June 15.

You are aware that Punjab has been the engine of agricultural growth that India has seen and acknowledged. PAU has also carved a niche even at international level. Despite a host of problems it today faces, one can not deny its contributions to national endeavours to achieve self-sufficiency in food grains. Punjab is a spec of a state with just 1.53 per of country's geographical area. Yet, of country's total production, Punjab produces 20 per cent wheat, 11 per cent rice, 13 per cent cotton, 10 per cent milk, 26 per cent honey and 45 per cent mushroom. State's contribution to the central buffer stock is around 60 per cent wheat and 40 per cent rice.

We have all heard the alarm bells rung by country-wide fall in production of wheat. We also know that agriculture is the biggest private economic activity in India. We are aware that the land holdings are small, average size being one hectare. In fact, 66 per cent of all farm holdings are one hectare or less. Also, only 54 per cent land has assured irrigation facilities. Returns are low and farming is fast becoming economically unviable, while debt burden is rising and so are farmers' suicides.

In fact, holdings are getting either fragmented or gobbled up by urbanization and industrialization. Yet, we can not pull out large sections of farmers from their land and give them alternate means of livelihood. At the same time, while overall farm production is stagnating, population is galloping. There is a mismatch between the two. If all Indians are to be given plenty of food and also good nutrition, we have to produce 360 million tonnes of food grains by 2020. It is a stupendous and difficult task to face new challenges and opportunities that science offers. But it is not impossible to achieve what we have to. Lot is required to be done and much more undone. We have also to factor climate changes and global warming. While, these changes precipitate woes of farmers these also pose new challenges to scientists.

Problems of Punjab are unique: declining productivity, increasing indebtedness, injudicious use of inputs, environmental pollution, shrinking holdings, degrading natural resources: falling water table, sick soils that show signs of nutrient deficiencies and technological fatigue. Having identified its problems, Punjab has to find solutions to these problems of its own. In this, self-help is the foremost coupled with government policy support mechanism. There is need for a sound farm infrastructure and to exploit info-technology. We shall also have to worry about marketing Punjab farm produce and products through value addition and processing.

We discussed the above issues expecting that scientists would come out of his or her field of specialization and subject-cocoon, although the assigned topic was: "Extension education as a tool to disseminate research to farmers: Success and shortcomings". Let's join hands to work in sync for humanity. Remember even the eight UN millennium goals the world has set for it is rooted in agriculture. As we tackle the identified problems, let's brace ourselves to meet new challenges and harness upcoming opportunities and let's not forget that we have to work for posterity.

In all our endeavours, extension education, communication, info-tech, multi-media, newspapers, television, radio, farm literature, audio and visual aids, exhibitions, field days, workshops, demonstrations, Kisan Melas have a crucial role to play. Science and technology are service-oriented tools in the hands of mankind. Let's make effective use of these by being in constant dialogue with our clients: farmers and policy makers. Among the stakeholders that we referred to in the beginning, let's not forget that industrialists and communicators too have to work hand-in-hand, shoulder-and-shoulder with policy-makers, scientists and farmers and keep the people informed, caution and warn them from time-to-time and prepare them to understand and appreciate the future challenges and opportunities. Our clients must be enabled to rise to the occasion and not get caught napping or unawares.

Research cannot be kept in moth balls. Each scientist has to be a skilled extension educationist and communicator. Each has to talk in the language and idiom of the farmer and also convince policy-makers, politicians and bureaucrats to give wings to his research findings for socio-economic transformation of the society. Scientists would do well to take short-term courses on scientific writing for common people or what is called popular writing to disseminate knowledge and information. Society has invested hopes and expectations in scientists. They must articulate the aspirations of the society by talking and writing about its problems and also appraise it of their research works.

We can say with a degree of fairness and conviction that at the Punjab Agricultural University, extension education as a tool has proved to be an instrument of change for farmers that led to socio-economic transformation of the state in particular and northern zone of the country in general. I am sure, extension education would retain its effectiveness and efficacy in transferring research from lab to land in times to come.

Summary and Future Research Needs

The doctrine of modern nutrient management practice is not a new comer to this world.... 178 years ago, famous German scientists Carl Sprengel (1787-1859) and Justus von Liebig (1803-1873) understood that soil may be favorable (for growing plants) in almost all respects, "yet may often be unproductive because it is deficient in one single element that is necessary as a food for plants". This basic massage is still to be vigorously disseminated to many farmers around the world.

During the last decade, the total factor productivity in the Indo-Gangetic Plains (IGP) is decreasing under intensive agriculture due to gradual depletion of soil fertility, rising and falling of water tables, land degradation and associated environmental problems. The soil health is being impaired due to larger and imbalanced use of fertilizer and emerging secondary and micro-nutrient deficiencies. In contrast, demand for food, especially, nutritious food is steadily increasing due to population growth coupled with rising standard of living.

Keeping this background in mind, the International Potash Institute (IPI) and Punjab Agricultural University (PAU) organized an International Symposium on the 'Balanced Fertilization for Sustaining Crop Productivity' at the Punjab Agricultural University, Ludhiana, India during November 22-25, 2006.

The symposium, which was attended by more than 300 delegates from 13 countries, consisted of 9 technical sessions with 32 oral presentation papers on various themes. Two poster sessions with 198 posters complemented these presentations. The symposium was inaugurated by Dr. G.S. Kalkat, Chairman, Punjab State Farmers Commission and presided over by Dr. K.S. Aulakh, Vice Chancellor, Punjab Agricultural University, Ludhiana. Dr J.S. Samra, Deputy Director General (NRM), Indian Council of Agricultural Research was the Guest of Honour and delivered a special address. The valedictory session was chaired by Dr. J.S. Samra with Hillel Magen, Director IPI and Dr. Patricia Imas, Coordinator, IPI as Co-Chairpersons. Dr. M.S. Brar Organizing Secretary proposed the vote of thanks.

At the valedictory function, highlighting the problems of plateauing of food grain production in India, especially in the grain bowl region consisting of Punjab, Haryana and Utter Pradesh, Dr J.S. Samra pointed out that nitrogen, phosphorus and potassium are being applied in a ratio which is widely divergent from an ideal ratio of 4:2:1. Several papers presented in the symposium pointed out excess application of nitrogen and very little application of potassic fertilizers to field crops. Dr. Samra emphasized the need to improve fertilizer use efficiency through balanced fertilization. He endorsed the views of the scientists that continuous mining of potassium may alter the mineralogy of clays in the soils in a way that after a time period, it may be difficult to supply adequate amounts of potassium to crop even by applying heavy doses of potassium fertilizers. The issues related to export of nutrients in the form of grains from the production zones to the regions where these are consumed should also be effectively taken care of.

Finally, Dr. Samra called upon the scientists to reorient farm research by taking ecological regions as functional units for overcoming production constraints in relation to environment.

Hillel Magen and Dr. Patricia Imas urged scientists and policy makers to understand the increasing role of potassium in agriculture.

Through the whole symposium, during the presentations and poster sessions, the following points emerged

- A general thinking in the symposium presentations was that rice-wheat farming without adequate K fertilization in IGP of India poses a threat to the sustainability of the production system. Fertilizer management practices with balanced supply of nutrients based on indigenous soil supply and crop demand can ensure high and stable overall productivity on a long-term basis.
- Some presentations indicated a highly skewed fertilizer use with declining soil K levels even in soils with medium to high K status. As nutrient balance sheet has been negative for years, it may spiral further especially in intensive cropping systems. A negative K balance has an adverse impact on the mineralogy of K in soils due to the formation of edge-wedge sites in K bearing minerals. This scenario is alarming in view of advancement of weathering front in illite-vermiculite or illite-vermiculite-smectite phases. The incorporation of K through canal and tube well water containing substantial amounts of K (approx 100 kg K_2O ha^{-1} $year^{-1}$) is very significant, and that may slow down the weathering of K containing minerals, particularly illite.
- There is a wide gap between fertilizer recommendations made by the scientists and those adopted by the farmers. This unsatisfactory scientific utilization of knowledge leads to severe impairment of productivity and prevents farmers from the scope of improvement. Immediate action must be taken to improve the link between research and extension.
- Many long term fertilizer experiments demonstrate the superiority of the NPK balanced fertilization treatment with additional organic matter on soil health and yield sustainability. The long term decline in grain productivity has been associated mainly with the sub optimal K application.
- Potassium plays a major role in reducing the photooxidative damage that develops under environmental stress. Potassium also plays a major role in alleviating biotic and abiotic stresses, and thus its application serves in many cases as an 'insurance policy'.

- Plants grown under high light intensity require more K than plants which are grown under low light. Similarly, plants grown under elevated CO_2 conditions require greater amounts of K as compared to plants grown under ambient CO_2 levels.
- The fertilization measures for high yields of rice include: balanced input of N, P and K; co-application of organic and inorganic fertilizers; rational distribution of fertilizers in the rotation crop, adjustment of fertilizer amounts at different growth stages and variable-rate application to place fertilizers in fields according to spatial patterns of soil productivity.
- Fertigation in banana saves up to 50% of the nutrients along with 30-50% increase in yield. This, and other fertigation experiments, clearly confirm that fertigation technology significantly improve Nutrient Use Efficiency (NUE) and Water Use Efficiency (WUE).
- Site specific nutrient management (SSNM) enables a dynamic adjustment in fertilizer N, P and K to accommodate field- and season-specific conditions; an effective use of existing (indigenous) nutrients coming from the soil, organic amendments, crop residue, manure, and irrigation water. Efficient fertilizer N management through the use of the leaf colour chart (LCC) ensures that N is applied at the time and in the amount needed by the rice crop and therefore reduces environmental risks.
- Good fertilizer K recommendations should integrate between reliable soil and plant tests, and must also consider nutrient use efficiency of the specific crop, adverse soil factors (compaction, low temperature, low soil water content) and nutrient balance sheets. It is also obvious that even K-rich clay soils require a regular K fertilization under frequently occurring stress conditions. K fertilization recommendation needs to consider 'removal' of K (in grain, product, straw etc.) and 'uptake' of K, to meet both the replacement and availability of K during the entire cropping season.
- European experience showed that countries with large number of animals suffered from high positive N and P balance. For the last 30 years, various directives were issued by the EU to combat and reduce the level of water pollution. The farm gate balance caused significant reduction in N inputs with better and more accurate calculation of N inputs from organic sources. This also affected the level of K in soils. In 1990-1994, only 4% soils were classified as low, 17% as medium, and 79% as high; 10 years later, 18% are now classified as low, only 17% as medium and only 42% as high in available K. Thus in 10 years time, half of the soils rich in K lost much of their reserve K. This negative balance is of much concern, and may pose a risk to sustainable crop production.
- A proper K and Mg nutrition by foliar application results in optimal

photosynthetic activity with low formation of oxygen radicals, particularly at high light intensity (heat and drought stress).

- Greenhouse agricultural systems are characterized as high inputs-output systems (e.g. 1000 kg N ha^{-1} applied to greenhouse grown pepper, to achieve 90 tons of pepper for export). Nevertheless, with all sophistication of fertigation systems, there is a significant measured loss of N to groundwater, causing steady increase in nitrate content (during the period 1982-2006).
- The potential of developing genotypes that utilize nutrients efficiently was stressed. Manipulating N metabolism using specific genes involved in nitrate uptake and assimilation (transporter genes and NR genes) has already been done in few plants.
- Knowledge transfer to the farming community is identified as a key tool to further increase the productivity of the Indian agriculture.

Future Research and Activity Needs

The main tools to achieve higher, sustainable productivity are: 1) Better soil health and fertility management, 2) Improved water management, 3) Integrated plant health management, 4) Efficient energy management and 5) High-quality post-harvest management. In the near future, it is assumed that increasing nutrient demand in the developing countries will follow the trend of growth in production.

Summing up the various opinions and discussions made during the symposium, it emerges that research for achieving increased sustained productivity is needed in the following fields:

- Productivity:
  - Strive for increases in both crop yield and nutrient use efficiency at the same time.
  - There is a need for a better synchronization of nutrient supply and crop demand.
  - Similar to the concept of SSNM in rice which is based on assessing the colour of the leaf (as an indicator for N application), there is a need for assessing the flag leaf in wheat for the precise decision making for N application.
  - There is a need for optimization of nutrient application with regards to soil moisture, uptake curves in specific conditions, development of nutrient balance sheets and development of farmer friendly diagnostic techniques that aids in rapid correction of the nutrient status.
  - The technology of Integrated Nutrient Management (INM) for harmonizing sustainable resource use, crop yield enhancement and environmental protection has to be widely adopted.

- There is a need for a multidisciplinary approach for better integration of data needed for breeding genotypes for high nutrient use efficiency.

- Sustainability:
  - The measures suggested for tackling the decline in productivity are soil and plant tests to improve site-specific recommendations, balanced fertilization, integrated nutrient management, use of manures and various types of composts and judicious use of inorganic fertilizers.

- Technology:
  - At initial stages of crop development, priming seeds with K may be highly beneficial. This approach needs to be tested and evaluated further.
  - There is a need to develop and adopt technologies for maximizing water and nutrient use efficiency. For example, collection of drainage water for recycling, correct time and quantity of irrigation with the use of tensiometers, as well as supplying farmers with precise recommendations based on sophisticated uptake curves of plants under greenhouse farming system.

- Management:
  - It is quite relevant to workout which crop in a rotation should preferentially be fertilized with K, at what development stage of plant K should be applied, which form of K fertilizer should be used, and whether foliar application has advantage over soil application.
  - A proper consideration of the various general and specific functions of K in crop growth, yield formation and stress avoidance will help to develop effective and innovative strategies for K fertilization.
  - Further development of K fertilization strategies for farmers will be a great challenge for a better plant and soil health and thus for crop sustainability.

- Policy
  - Supporting policies for agricultural production, extension and fertilizer inputs should be constantly optimized to ensure the highest efficiency of the whole agricultural sector.