Proceedings IPI-OUAT-IPNI International Symposium (2009)

Food security - Indian scenario

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

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

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

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

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

Introduction

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

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

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

Source: Chand 2007

The projected demands for other food items are also high. Achieving desired food targets is a challenging task, seeing the trend of stagnation or deceleration in the growth of Total Factor Productivity in agriculture since 90s, especially in the Indo-Gangetic Plains (Murgai 2000; Singh 2003; Kumar et al. 2004). The required growth rates per annum for cereals and pulses (2%), oilseeds (6%) and sugarcane (0.6%) to meet the projected demands are much higher than the realized growth rates for the last ten years (Chand 2007). There was depression in rates of production and productivity of major crops including pulses and oilseeds (Anonymous 2004a). The slowdown in growth of food grains production notably after mid-nineties posed a virtual threat to food security in the country. The stagnating productivity got reflected in falling agricultural growth rate, reaching about 2 percent during Tenth Plan period (2002-07). The National Agricultural Policy identifies food security as one of the major challenges and aims to attain annual growth rates in excess of 4 percent over the next decades. As high growth of non-agricultural sector has not brought about any significant improvement in the socio-economic conditions of rural people, an inclusive higher growth in agricultural sector is the hallmark of agricultural policy of the Indian government. It envisages conservation and efficient management of natural resources amongst development of horticulture, livestock, fisheries, food processing and marketing infrastructure etc in rural areas. The Government of India has recently launched several initiatives including National Rainfed Area Authority (2006), Centrally Sponsored Scheme of Micro-irrigation (2006), National Agricultural Development Scheme (2007), the National Food Security Mission (2007) and *Rashtriya Krishi Vikas yojana* (RKVY) to have an increased and equitable agricultural growth. The primary objective of National Food Security Mission is to increase production and productivity of wheat, rice and pulses by focusing on districts having high potential for productivity gains. A number of technologies have been identified to minimize the yield gaps of 40-100 percent between experimental farms and farmers' fields (ICAR 2007). The new initiatives will also go a long way in fulfilling the United Nations Millennium Development Goals of Eradicating Extreme Hunger and Poverty in the Asian region.

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

Managing soil health

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

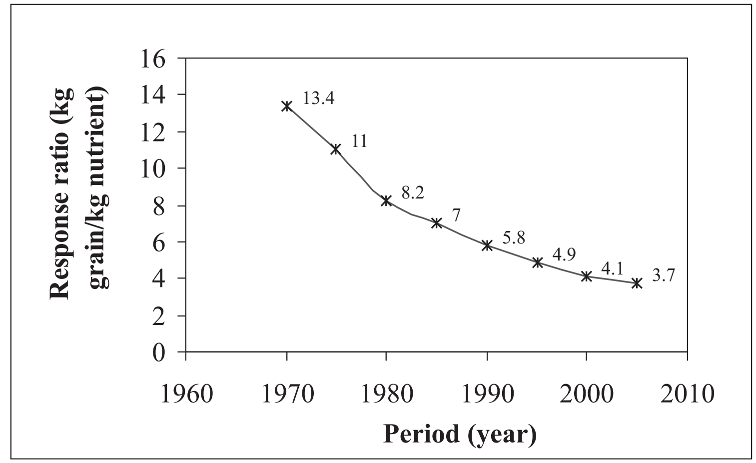
Declining fertilizer response

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

Integrated balanced nutrient management

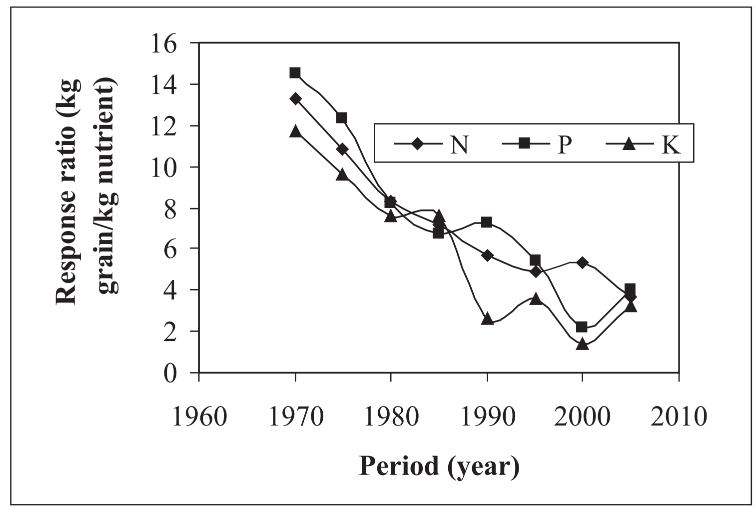
The Integrated nutrient management encompassing conjunctive use of chemical fertilizers including secondary and micronutrients, organic manures, composts / vermicomposts, bio fertilizers and green manures is the most ideal system of

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



(Source: Biswas and Sharma 2008a)

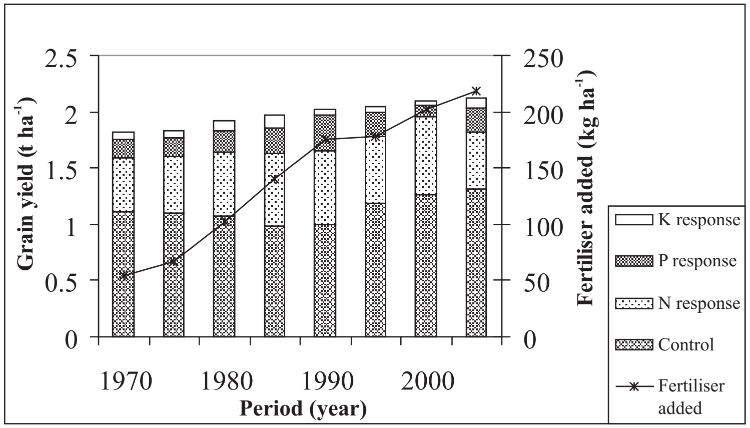
Fig. 2 NPK responses of foodgrain crops in irrigated areas in India.



(Source: Biswas and Sharma 2008a)

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

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



(Source: Biswas and Sharma 2008a)

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

Ensuring adequate supplies of fertilizers

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

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

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

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

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

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

Augmenting supplies of organic manures

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

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

Promoting bio-fertilizers

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

Developing nutrient-use efficient cultivars

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

Nanotechnology for slow release fertilizer

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

Ensuring nutritional security

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

The high incidence of Zn deficiency in Indian population is primarily due to more consumption of cereal-based foods and less of animal based-foods or pulses. The rice and wheat, constituting major staple foods in India, contribute about 60-70 % of daily calorie intake. The cereal grains are not only low in Zn, but also contain antinutritive compounds like phytates which reduce bio-availability of Zn. Growing of cereals on Zn deficient soils will further reduce the availability of Zn in grains. This has been very well demonstrated by a study in Central Anatolia, Turkey facing problem of Zn-deficiency. The Zn concentration in grains of 54 wheat cultivars grown on a Zn deficient soil averaged 9 mg Zn kg^{-1} compared to 26 mg Zn kg^{-1} on normal soils (Cakmak 2008). The application of Zn fertilizers on these soils has increased substantially the wheat yields and Zn content in grains. The consumption of Zn containing fertilizers has increased from nil in 1994 to about 400,000 tonnes per annum in Turkey. The economic benefits in terms of crop productivity and human health enhancement are enormous. The Anatolian experience, therefore, merits its replication in other Zn-deficient areas to address public health while improving crop production. Zinc is one of the nutrients depleted significantly under intensive agriculture, especially in rice-wheat cropping sequence, in India (Tandon 1995) and requires its replenishment through fertilizers for food and nutritional security.

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

Augmenting water resource

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

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

Rain water harvesting

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

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

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

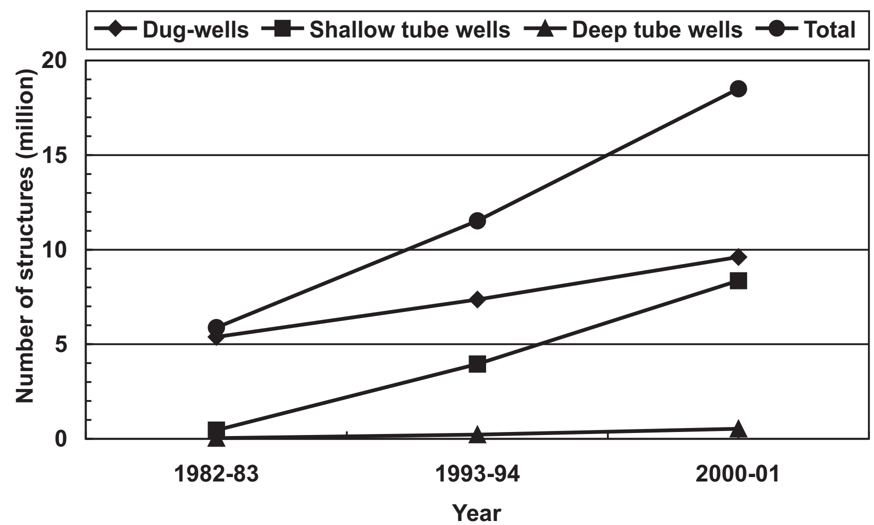
Rainfall zone (mm)	Area (m ha)	Rainfall for effective surface storage (%)	Harvestable runoff in water harvesting structure (m ha-m)
110-500	52.1	5	0.8
500-750	40.3	6	1.5
750-1000	65.9	7	4.0
1000-2500	137.2	6	14.6
> 2500	32.6	4	3.3
Total			24.0

Source: CSWCRTI 2007

Checking fall in water table

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

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



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

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

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

Source: CSWCRTI 2007

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

Use of waste water

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

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

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

Enhancing water-use efficiency

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

Amelioration of degraded lands

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

Table 4 Degraded lands in India (M ha)

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

Source: NBSSLUP 2008

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

Eroded land

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

Table 5 Area affected by potential soil erosion in India

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

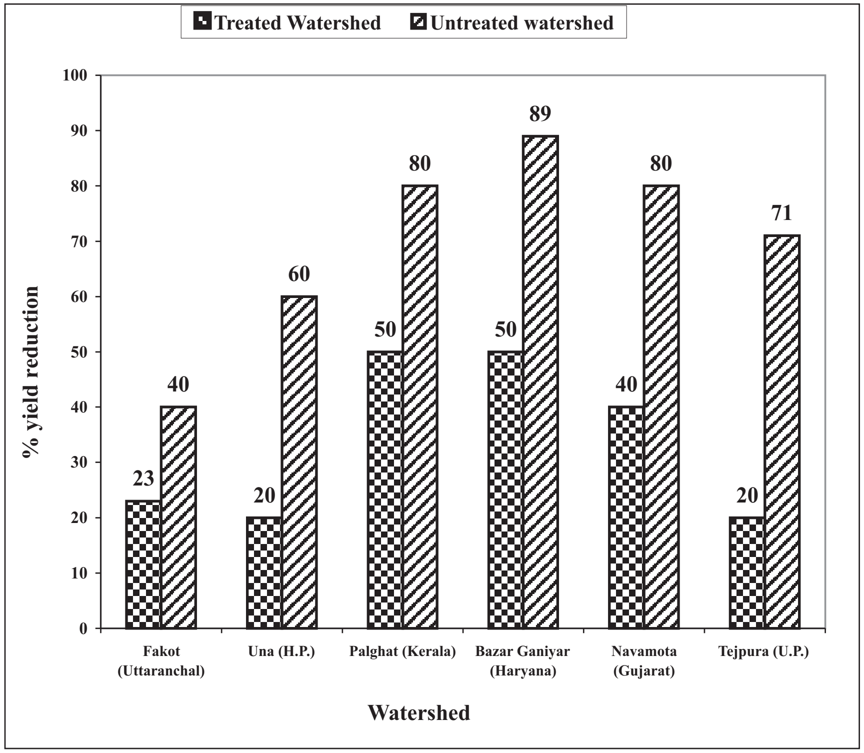
Source: NBSS&LUP 2008

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

Watershed management in rainfed areas

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

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



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

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

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

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

Bio-industrial watershed management

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

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

The bio-industrial watershed management system could be viewed on the parlance of Amul cooperatives in Gujarat, Kuppam vegetable farming and processing cooperative in Andhra Pradesh, Kokam fruit concentrate production cooperatives in Maharashtra and Goa, sugar mills co-operatives in Maharashtra and Gujarat, Leh Berry fruit concentrate production cooperative in Leh (J&K) and many other ventures in different parts of the country. As animals are essential component of farming system in rural India, the bio-industry based on milk, poultry, wool, meat and other animal products could be a great success. The development of cold storage /cold chain to store and transport perishable produce to the markets at appropriate time to avoid distress sales should be part of the bio-industrial development programme.

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

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

Reclamation of salt affected soils

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

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

Amelioration of acid soils

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

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

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

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

Source: Sharma and Sarkar 2005

Mitigating climate change

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

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

Table 7 Basin wise loss in glacial area

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

Source: Kulkarni et al. 2009

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

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

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

Epilogue

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

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

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Global impacts of human mineral malnutrition

Alexander J Stein

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

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

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

Introduction

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

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Presented at IPI-OUAT-IPNI International Symposium.
Published in Plant Soil 2010.335:133-154. Printed here with permission from Plant Soil.

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

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

Impacts of human mineral malnutrition

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

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

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

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

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

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

	IOM (2001)	JN (2009)
Arsenic (*As*)	No biological function, although animal data indicate a requirement.	Has been shown to have beneficial actions when fed in very small amounts to laboratory animals, but its physiological role has not been clearly defined.
Boron (*B*)	No clear biological function, although animal data indicate a functional role.	May be essential for humans based on recent experimental evidence showing that boron affects blood biochemical markers of energy and mineral metabolism.
Calcium (*Ca*)	Essential role in blood clotting, muscle contraction, nerve transmission, and bone and tooth formation.	Structural function (stores in the skeleton), electrophysiological function (carries charge during an action potential across membranes), intracellular regulator, and cofactor for extracellular enzymes and regulatory proteins.
Chloride (*Cl*)	As sodium chloride (salt) required to maintain extracellular volume and plamsa osmolality (IOM 2004: 269).	As sodium chloride (table salt) required for maintenance of extracellular fluid volume.
Chromium (*Cr*)	Helps to maintain normal blood glucose levels.	Required for normal sugar and fat metabolism, potentiates the action of insulin.
Copper (*Cu*)	Component of enzymes in iron metabolism.	Part of enzymes that help biochemical reactions in every cell, involved in the absorption, storage and metabolism of iron.
Fluorine (*F*)	As fluoride inhibits the initiation and progression of dental caries and stimulates new bone formation.	As fluoride serves as catalyst for the mineralization of developing tooth enamel and for remineralization of surface enamel; reduces occurrence of dental decay (caries).
Iodine (*I*)	Component of the thyroid hormones; and prevents goiter and cretinism.	Essential component of thyroid hormones, which regulate cell activity and growth in virtually all tissues and are essential for normal embryonic and postnatal development.
Iron (*Fe*)	Component of hemoglobin and numerous enzymes; prevents anemia.	Carries oxygen and forms part of hemoglobin in blood and myoglobin in muscles; component of various enzymes.
Magnesium (*Mg*)	Cofactor for enzyme systems.	Important role in 300+ fundamental enzymatic reactions, in the activation of amino acids, the synthesis and degradation of DNA, in neurotransmission and immune function.
Manganese (*Mn*)	Involved in the formation of bone and in enzymes in the metabolism of amino acid, cholesterol and carbohydrate.	Part of several enzymes (preventing tissue damage, breaking down carbohydrates, nitric oxide synthesis, urea formation); activates numerous enzymes (cartilage formation).

	IOM (2001)	JN (2009)
Molybdenum (*Mo*)	Cofactor for enzymes involved in catabolism of sulfur amino acids, purines and pyridines.	Component of a number of enzymes (metabolism of sulfur amino acids, oxidation of purines and pyrimidines, production of uric acid, oxidation of aldehydes).
Nickel (*Ni*)	No clear biological function identified; may serve as a cofactor of metalloenzymes and facilitate iron absorption or metabolism in microor-ganisms.	Cellular effects documented but no deficiency disease in man; found in highest concentrations in lung, kidney and some hormone-producing tissues; can activate or inhibit a number of enzymes that usually contain other elements.
Phosphorus (*P*)	Maintenance of pH, storage and transfer of energy and nucleotide synthesis.	The metabolism of all major metabolic substrates depends on its functioning as a cofactor in a variety of enzymes and as the principal reservoir for metabolic energy.
Potassium (*K*)	Required for cellular function; deficiency can cause cardiac arrhythmias, muscle weakness, glucose intolerance, high blood pressure, salt sensitivity, risk of kidney stones, high bone turnover and risk of cardiovascular diseases (IOM 2004: 186).	The most essential cation of the cells; because of its association with the metabolizing, oxygen-consuming portion of the body, a decline in total body potassium is usually interpreted as a loss of muscle mass due to a catabolic condition.
Selenium (*Se*)	Defense against oxidative stress and regulation of thyroid hormone action.	Functions as a component of enzymes involved in antioxidant protection and thyroid hormone metabolism.
Silicon (*Si*)	No biological function identified; in animal studies involved in bone function.	May play a role in structure of glycosamino-glycans and their protein complexes; no human data available.
Sodium (*Na*)	As sodium chloride (salt) required to maintain extracellular volume and plamsa osmolality (IOM 2004: 269).	Predominant cation in extracellular fluid; acts in consort with K, the chief cation of intracellular fluid, to regulate body water distribution and blood pressure; important for acid-base balance and the transmission of nerve impulses.
Sulfur (*S*)	As inorganic sulfate required for the synthesis of PAPS, which is required for synthesis of many important sulfur-containing compounds (IOM 2005: 424).	n/a
Vanadium (*V*)	No biological function identified.	No specific biochemical function has been identified.
Zinc (*Zn*)	Component of multiple enzymes and proteins; involved in the regulation of gene expression.	Structural, catalytic and regulatory roles; role in the coding for zinc finger proteins; required by over 60 enzymes for activity, incl. RNA polymerases; supports synaptic vesicles.

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

Health consequences of human mineral malnutrition

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

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

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

Burden of disease of human mineral malnutrition

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

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

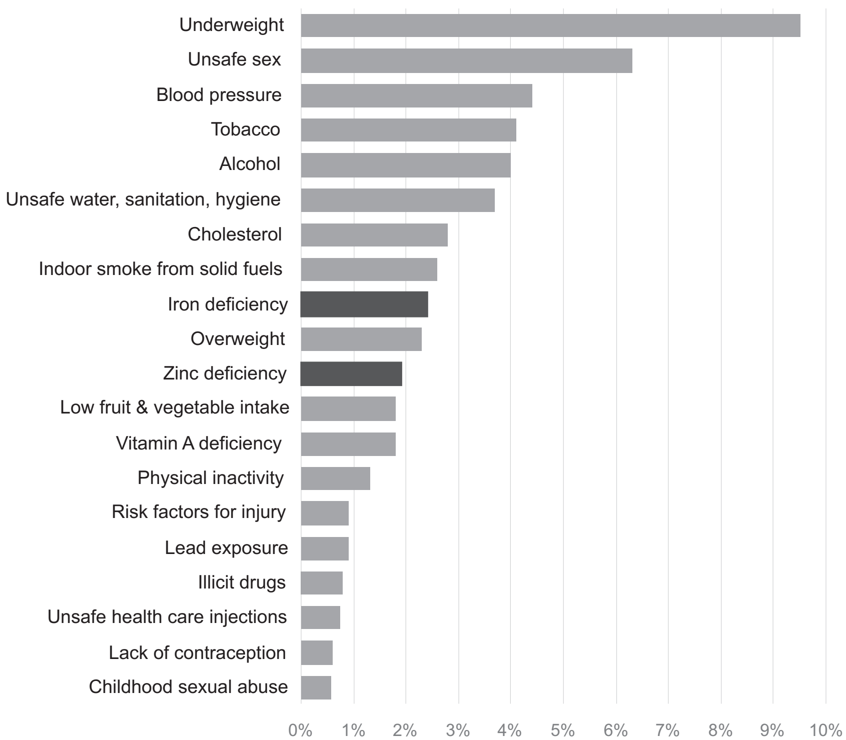
$$\text{DALYs}_{\text{lost}} = \text{YLL} + \text{YLD}_{\text{weighted}}$$

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

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

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

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

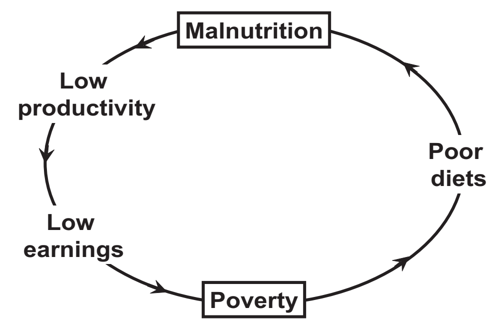


ranking of the burdens of disease caused by each health risk, FeD represents the 9th and ZnD the 11th biggest health risk worldwide (Fig.1). In this study only FeD, ZnD and ID were considered; no comparable analysis is available for other mineral deficiencies. Given that ID, the third mineral deficiency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

Socio-economic impact of human mineral malnutrition

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

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



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

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

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

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

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

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

Causes and determinants of malnutrition

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

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

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

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

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

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

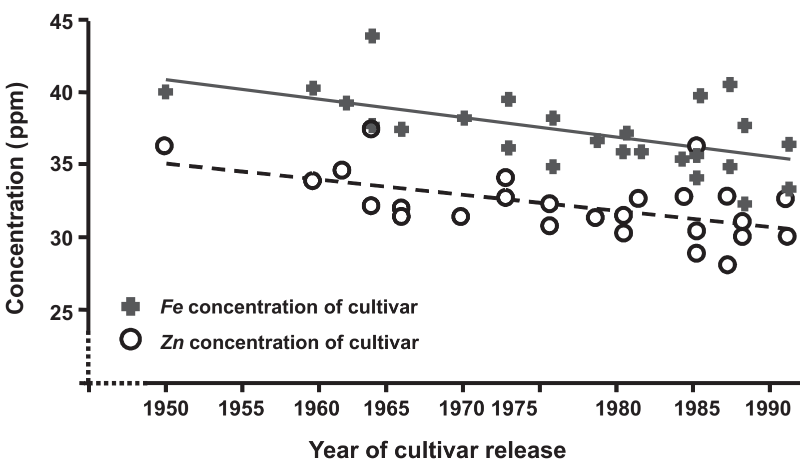
[5] Other authors suggest that causal relationships may exist between micronutrient deficiencies and obesity in different populations (García et al. 2009).

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

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

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

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



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

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

Interventions against mineral malnutrition

Conventional and novel, agricultural approaches

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

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

Table 3. Overview of micronutrient interventions

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

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

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

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

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

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

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

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

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

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

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

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

projects that cover specific micronutrients, crops or regions:

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

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

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

Current developments and constraints

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

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

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

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

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

Conclusions

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

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

Acknowledgements The author thank Thomas Fellmann for revising the manuscript.

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

Samuel B St Clair • Jonathan Lynch

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

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

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Presented at IPI-OUAT-IPNI International Symposium.
Published in Plant Soil 2010.335:101-115. Printed here with permission from Plant Soil.

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

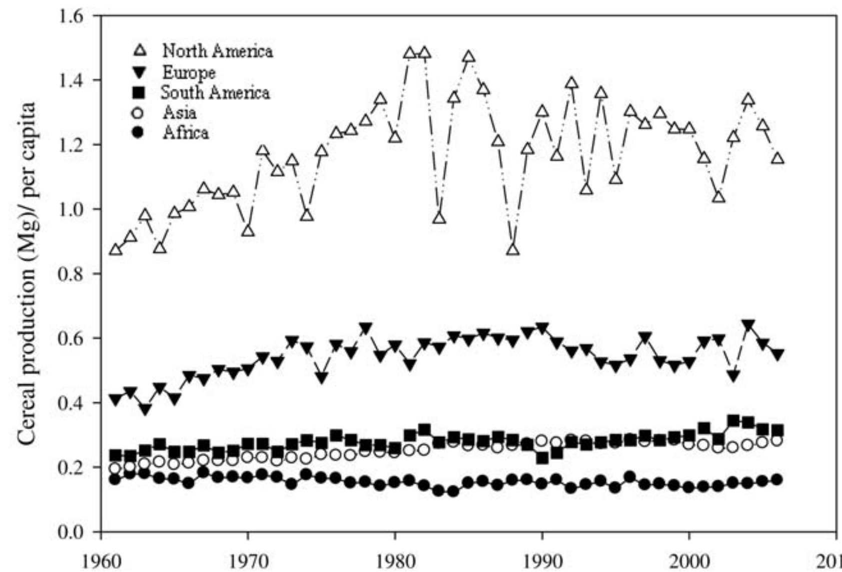
The world in general and developing countries in particular face major challenges of food security in the 21st century. Current estimates suggest that more than 1.02 billion people on our planet are underfed or malnourished including a 10% increase over the last 3 years due to rising food costs (FAO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

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

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

Nutrient impoverished soils contribute to human malnutrition in two

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



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

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

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

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

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

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

Soil limitations to crop productivity in developing countries

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

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

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

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

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

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

Climate change impacts on crop productivity and quality in developing countries

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

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

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

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

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

Key climate-nutrient interactions in cropping systems of developing countries

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

Drought effects on nutrient acquisition

Crop yields on soils in developing countries decrease exponentially with increasing aridity (Lal 2000). Soil moisture deficit directly impacts crop productivity but also reduces yields through its influence on the availability and transport of soil nutrients (Table 3). Drought increases vulnerability to nutrient losses from the rooting zone through erosion (Gupta 1993). Because nutrients are carried to the roots by water, soil moisture deficit decreases nutrient diffusion over short distances and the mass flow of water-soluble nutrients such as nitrate, sulfate, Ca, Mg, and Si over longer distances (Mackay and Barber 1985; Barber 1995). Roots extend their length, increase their surface area and alter their architecture in an effort to capture less mobile nutrients such as phosphorus (Lynch and Brown 2001). Reduction of root growth and impairment of root function under drought conditions thus reduces the nutrient acquisition capacity of root systems (Marchner 1995).

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

Effects of Intense precipitation on nutrient acquisition

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

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

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

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

Effects of temperature on nutrient acquisition

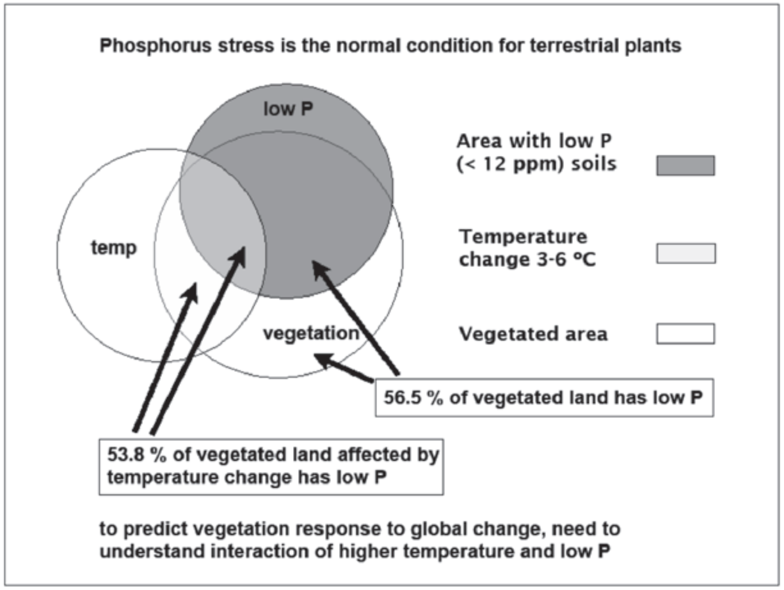
Soil warming can increase nutrient uptake from 100-300% by enlarging the root surface area and increasing rates of nutrient diffusion and water influx (Ching and Barber 1979; Mackay and Barber 1984) (Table 3). Water soluble nutrients including nitrate, sulfate, Ca, Mg primarily move towards roots through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

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

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

Climate warming contributes to the degradation of freshwater quality and

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



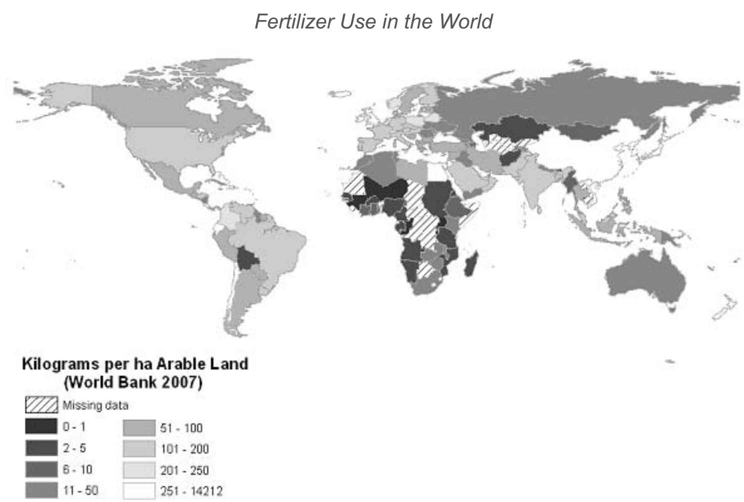
availability (IPCC 2007b). A major way in which this happens is through salinization, an important limitation to agriculture productivity in semi-arid regions that is expected to intensify through the 21st century (Yeo 1999). Increases in demand for irrigation in semi-arid regions such as the Indo-Gangetic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

Adaptation/mitigation strategies and limitations

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

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

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



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

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

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

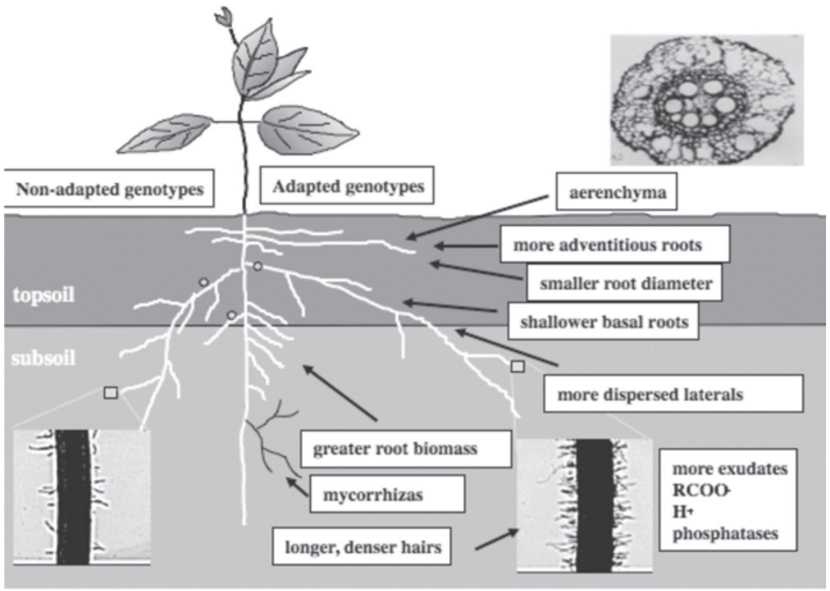
The second leg of ISFM is soil management to conserve and enhance soil fertility, including erosion control, maintenance of soil organic matter (Fernandes et al. 1997), and enhancing nutrient bioavailability by promoting beneficial root symbionts, most notably via biological nitrogen fixation (Hubbell 1995) and mycorrhizal associations (Plenchette et al. 2005). Although the critical importance of these management tools has been known for decades, other than nitrogen fixing food legumes they are rarely used in the poorest countries. Indeed, many poor farmers use soil resources abusively, without apparent regard for the longer-term

consequences of practices such as deforestation, residue burning, cultivation of steep slopes without runoff barriers. In some cases this is due to ignorance, compounded by disruption of traditional cropping practices by war, disease, and migration. Soil resources may be devalued because of the transitory nature of the cropping system, such as in the 'slash and burn' agriculture at retreating forest margins, or because the land is not owned by the farmer. In other cases soil fertility may be recognized as a resource but valued less than competing imperatives such as labor requirements for fuel wood collection, or the need to maximize food production in the short term. Many of the poorest farmers have little access to technical information or government services, and lack the exogenous incentives for soil conservation as a public good enjoyed by farmers in rich countries. The capability of this leg of ISFM to address the soil fertility crisis in the third world is therefore problematic, because of poor diffusion and adoption.

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

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

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



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

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

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

Conclusions

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

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

Annangi Subba-Rao • Kotha Sammi Reddy

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

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

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

Introduction

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

Declining crop response to fertilizer application

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

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

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

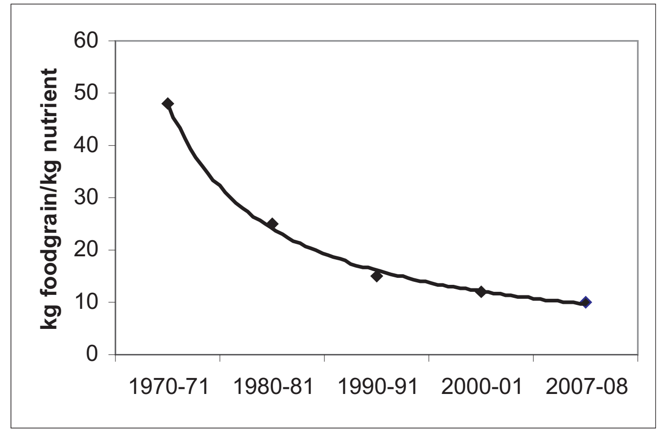
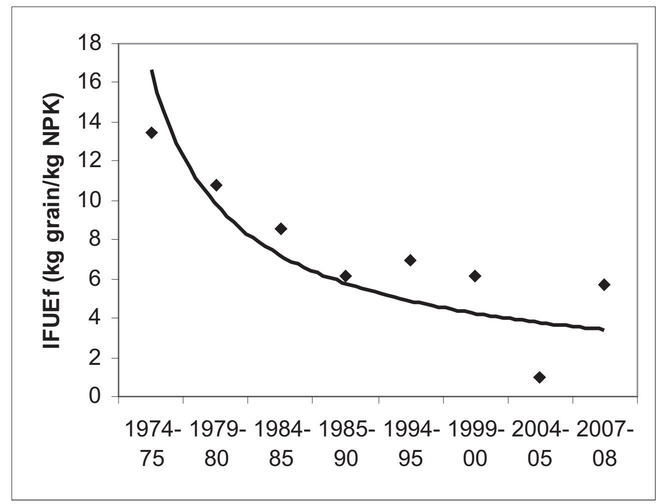


Fig. 2 Incremental fertilizer use efficiency over a period of time in India (Based on data from FAI 2008)



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

Table 1 Compound growth rates of productivity of foodgrains

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

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

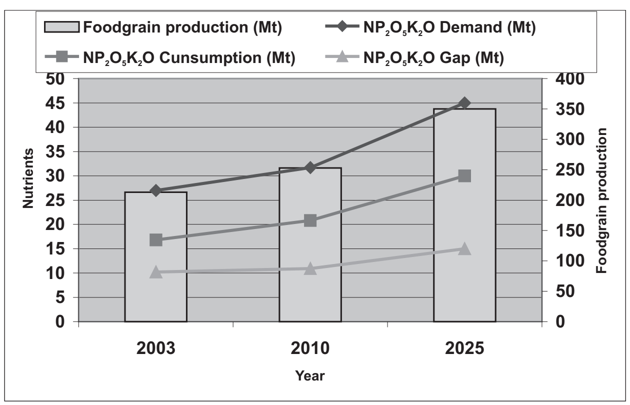
efficiency; soil organic matter depletion and loss of soil fauna and flora; insufficient input of organic sources because of other competitive uses; acidification and aluminum toxicity in acid soils; soil erosion.

Emerging issues of soil fertility

Wide nutrient gap between nutrient demand and supply

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

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



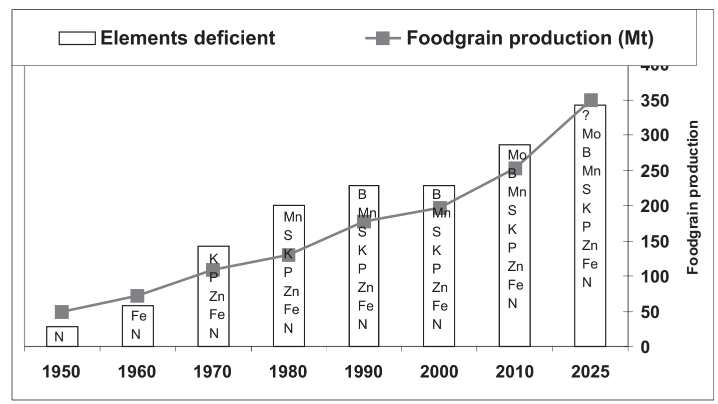
High nutrient turnover in soil-plant system coupled with low and imbalanced fertilizer use

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

Emerging deficiencies of secondary and micronutrients in soils

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

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



Poor nutrient use efficiency

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

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

Table 2 Nutrient use efficiency in India

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

Source: Sammi-Reddy et al. 2007)

Declining organic matter status

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

Acidification and aluminum toxicity in acid soils

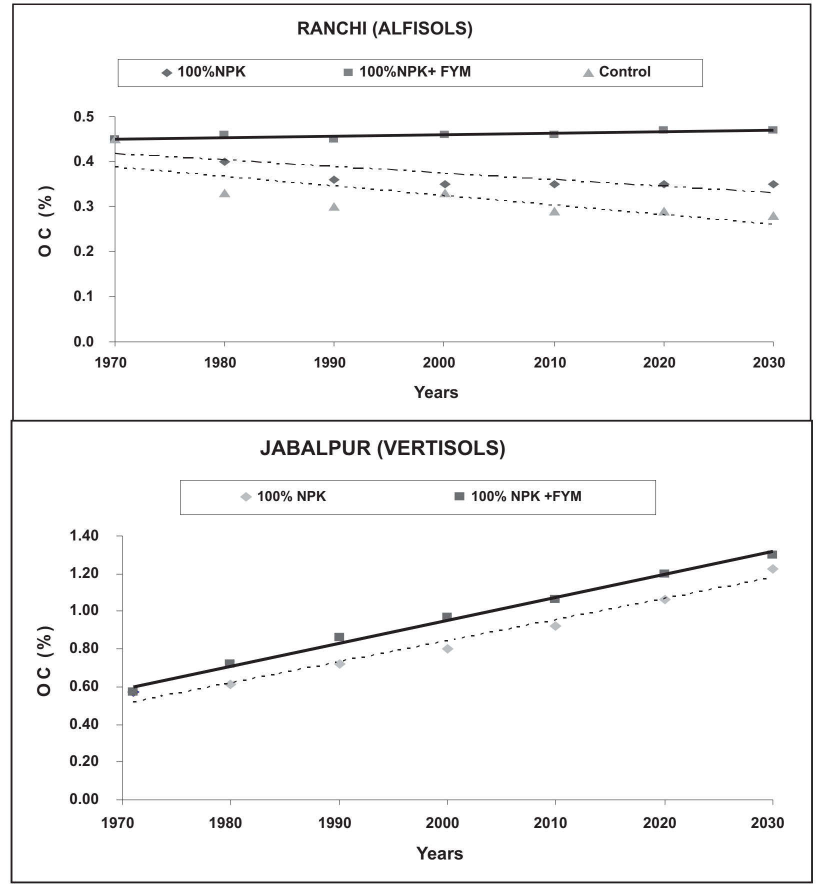
Nutrient imbalance is one of the main reasons for low productivity in acid soils. Solubility of Al, Fe and Mn being high in acid environment, these elements are available quite in excess at times causing toxicity. Soil acidity causes shortage of Ca and Mg. Ordinarily, B should be available under acid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

Emerging soil fertility management strategies for meeting future demands

Integrated nutrient management strategies

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

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



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

Table 3 IPNS strategies for major cropping systems.

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

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

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

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

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

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

*SYI- Sustainable yield index; **RSQI- Relative Soil Quality Index, RDF:Recommended dose of Fertilizer, FYM:Farmyard Manure, GLM:Greenleaf Manure

Source: Sharma et al. (2005)

Future prospects of integrated nutrient management in India

Potential availability of organic resources

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

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

Prospects of organic solid waste recycling

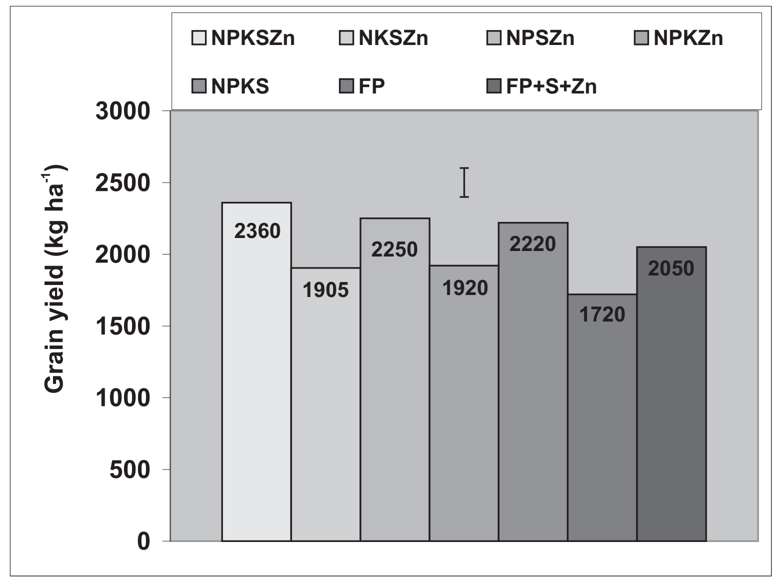
Organic solid wastes generated in large quantities by domestic, commercial and industrial activities are often indiscriminately disposed on the soils. It has been estimated that a large amount of urban compost is being generated every year from different cities of India which will reach to around 10.4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

Balanced fertilization through inorganic fertilizers

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

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

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



Soil test based fertilizer recommendations

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Efficient use of applied nutrients in biological systems

Nitrogen management strategies

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

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

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

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

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

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

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

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

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

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

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

Source: Yadvinder- Singh et al. 2007

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

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

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

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

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

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

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

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

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

Source: Subba-Rao et al. 2004

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

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

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

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

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

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

Source: Reddy 2007

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

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

Sulphur management strategy

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

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

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

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

Source: Singh 1999

Micronutrient management strategies

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

Table 12 Components of balanced fertilization under different situations

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

Source: Tandon and Narayan 1990

Improved agronomic practices

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

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

Conclusions

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

The future research should aim at

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

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