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

N Panda

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

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

Introduction

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

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

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

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

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

Development of acid soil

Acid soils occupy about 30 percent of cultivated land in India, whereas 70 percent of the cultivated land in Orissa is acidic. Acid soils have poor base saturation; which generally varied from 16 to 17 percent in the pH range of 5.0 to 6.0. The active species of naturally occurring ions bound to the clay are H^+ and Al^+. The KCI extractable Fe has minor role in soil acidity compared to Al. Humic acid, hymetamalonic acid, fulvic acid and humus contribute to acidity in various ways. The total acidity of the soil extracted by $BaC1_2$–TEA comprises pH dependent acidity and exchange acidity. The pH dependent acidity (variable charge) calculated as the difference between total and exchange acidity increased linearly with increasing free Fe_2O_3+$A1_2O_3$ plus organic carbon in soil (Mishra et al. 1989). Since the organic carbon contents were lower (0.29–1.19%) than the sum of free oxides of Fe+A1 (0.7–11.0%), the pH dependent acidity, constituting more than 81 percent of total acidity in the soil was ascribed mainly to inorganic compounds.

Problems associated with acid soils

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

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

Plant nutritional problems associated with soil acidity

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

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

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

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

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

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

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

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

Liming acid soils: Scopes and limitations

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

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

Industrial wastes as amendment for acid soils

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

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

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

Management of acid soils having iron toxicity

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

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

Selection of crop species and cropping systems for acid soil region

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

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

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

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

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

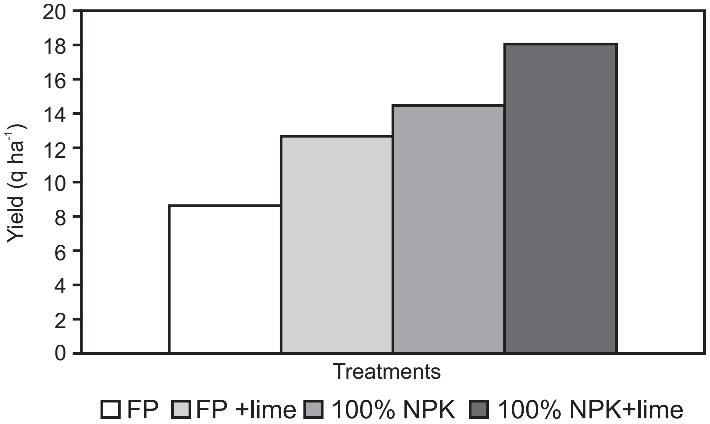

Fig. 1 Response of groundnut to liming and fertilization in acidic soils of Orissa

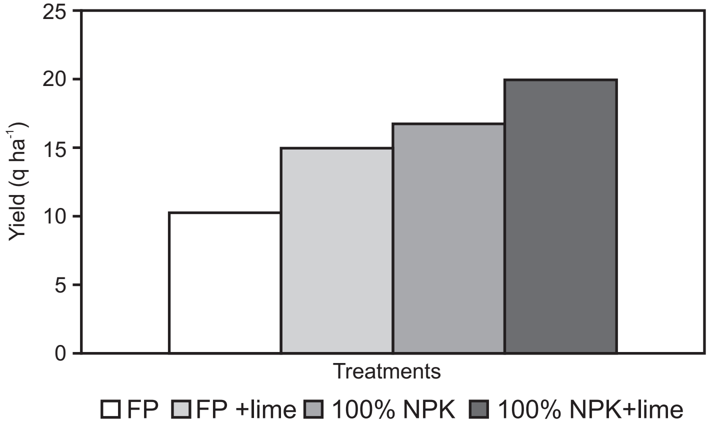

Fig. 2 Response of pigeonpea to liming and fertilization in acidic soils of Orissa

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Potassium nutrition of crops under varied regimes of nitrogen supply

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

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

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

Introduction

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

Many long term experiments have shown that high yields can be achieved from balanced NPK supply (Belay et al. 2002; Cai and Qin 2006; Wang et al. 2007a). To ensure sustained crop production under intensive cropping, application of recommended doses of NPK plus FYM is required (Rupa et al. 2001). Nitrogen application rate, timing and N source influence the K nutrition of crops and the interaction of these factors with K nutrition has been found to be significant in numerous studies**.** Optimal N and K application is propitious to best nutrient management in agriculture. A nitrogen-potassium interaction generally exists in agricultural ecosystems (Gething 1993; Johnston and Milford 2009). In this paper we review K in crops under varied N regimes, including effects of N-K interaction on crop yields, and processes of N-K interaction such as K uptake, transport, recycling and reutilization within plants under different levels of N supply. We also consider N-K interactions in relation to soil-K fixation and release under varied N regimes as well as their influence on crop yield, quality and stress tolerance in order to provide a guide to best nutrient management in agriculture.

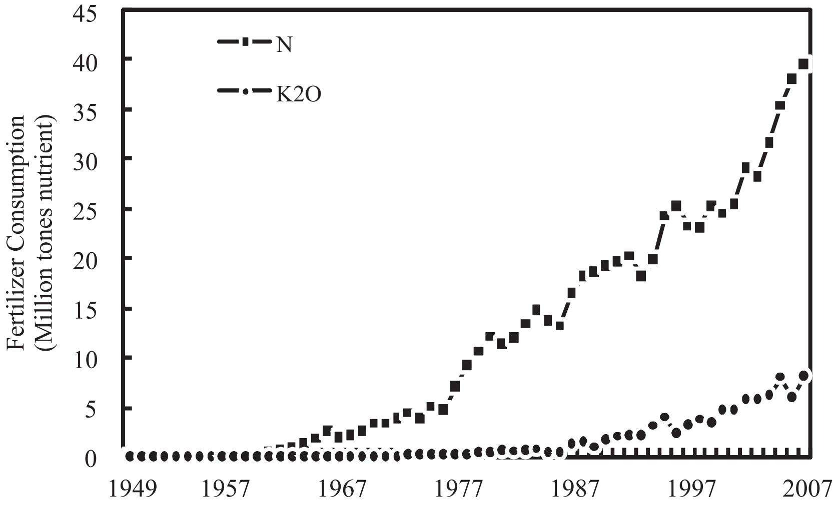

Fig. 1 Trends in fertilizer consumption in China from 1949 to 2007 (According to China Agriculture Yearbook)

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

Soil-K fixation and release under variable N regimes

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

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

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

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

NH_4^+ fixation was increased with increased N rates and was reduced with increased K rates with urea. With NH_4Cl application, an increase in fixed NH_4^+ was noted with increasing K rate (Chen and MacKenzie 1992). By contrast, K^+ fixation was enhanced consistently with increasing K application rate and decreased with increasing N application rate (Chen and MacKenzie 1992; Du et al. 2007). But other research found that the fixation of NH_4^+ was reduced by K addition before NH_4^+, and the reduction was proportional to the amount of K previously fixed (Kenan et al. 1999). In the presence of K, NH_4^+-N concentrations increased 4.1 fold when N fertilizer was applied and 3.5 times in the absence of N application (Tung et al. 2009). Compared with application of K^+ alone, addition of NH_4^+ did not show any effects on diffusion distance of fertilizer K but did increase the concentration of water extractable K in fertilizer microsites (Du et al. 2007). In the soil close to the fertilizer placement site the concentration of exchangeable K decreased as a result of the NH_4^+ addition, and this was less apparent in Flurvo-aquic soil than in red soil. The addition of NH_4^+ reduced K fixation in soil crystal lattices, thereby increasing the risk of K leaching in the soil (Du et al. 2007).

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

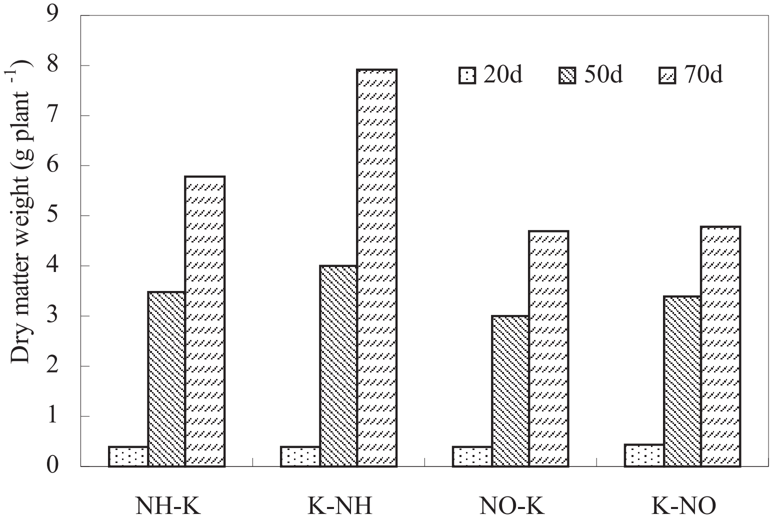

Fig. 2 Effects of N source and the order of N and K application on rice growth (adapted from Chen et al. 2007) NB: NH-K, K-NH, NO-K, and K-NO indicate NH_4^+-N application before K fertilization, NH_4^+ application after K fertilization, NO_3^--N application before K fertilization and NO_3^--N application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

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

K uptake and content in plants under variable N regimes

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

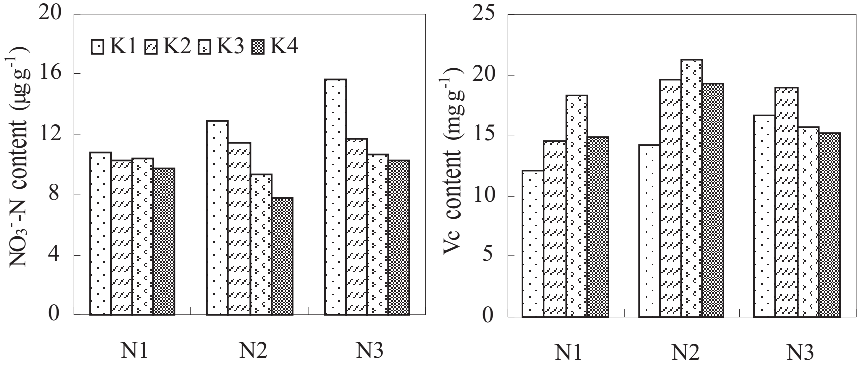

Fig. 3 Effects of K fertilization on nitrate and Vc content of tomato at different N levels (adapted from Sun et al. 2000)

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

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

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

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

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

Effects of N-K interactions on crop yields

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

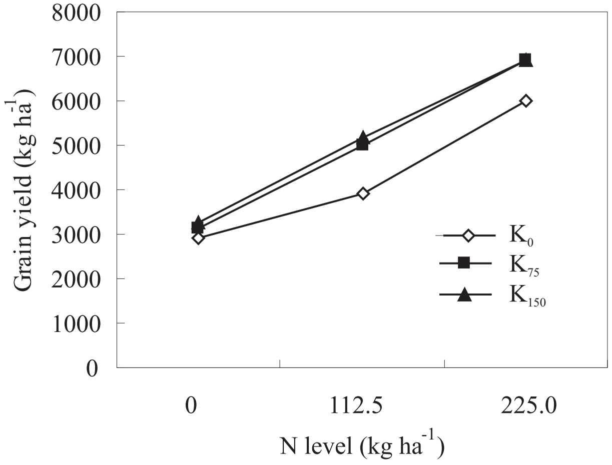

Fig. 4 Effects of K fertilization on wheat yield under variable N regimes (adapted from Zou et al. 2006a)

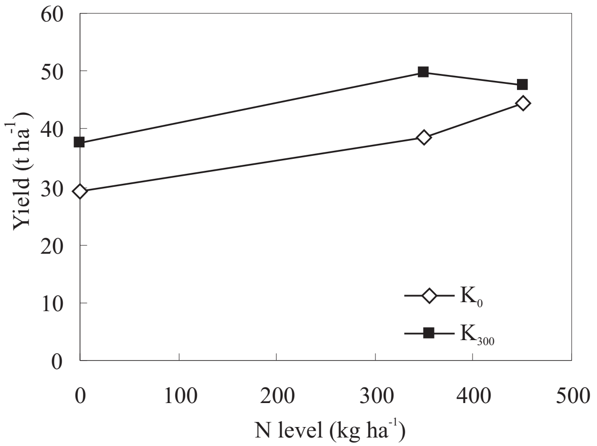

Fig. 5 Effects of K fertilization on cabbage yield under variable N regimes (adapted from Guo et al. 2004)

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

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

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

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

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

Conclusions

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

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

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

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

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Mineral nutrition under salt stress

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

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

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

Keywords Crop management • inland salinity • salt-affected soils

Introduction

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

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

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

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

Source : NRSA and Associates 1996

Nitrogen

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

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

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

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

Source: Yaduvanshi 2001a

Symbiotic nitrogen fixation in salt-affected soils

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

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

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

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

Phosphorus

The plant roots largely absorb it as dihydrogen orthophosphate ion ($H_2PO_4^-$), however, under neutral to alkaline environments, it is also taken up as monohydrogen orthophosphate (HPO_4^{2-}) ion. The high amounts of Na_2CO_3 and Na_2HCO_3 react with native insoluble calcium phosphates to form soluble sodium phosphate and hence, give a positive correlation between the electrical conductivity and their soluble P status. Due to high pH and the presence of soluble carbonates and bicarbonates, water soluble sodium phosphates are formed in these soils. Sodic soils are reported to contain high amount of soluble phosphorus. Research conducted at CSSRI revealed lack of response to added phosphorus in sodic soils during early years after reclamation. However, other studies, indicated that sodic soils are not always high in available phosphorus and significant increase in yields of some crops was obtained with application of P fertilizer**.** When these soils were reclaimed by using amendments and growing rice under submerged conditions, Olsen's extractable P of surface soil decreased due to its movement to lower sub-soil layers, uptake by the crop and increased immobilization (Chhabra et al. 1981; Swarup 1986; 1994). In freshly reclaimed alkali soils, crops did not respond to application of phosphatic fertilizers in the initial 3 to 5 years. During this period, continuous cultivation also improved the soils considerably in the upper 15-cm (pH_2 8.5-9.0). It was observed that if the Olsen's P of the surface 15-cm soil falls below 7.5 kg P ha^{-1}, rice yields may suffer. Nutrient uptake in rice (a shallow–rooted crop) is dependent on the fertility status of the surface 30-cm layer, which becomes depleted and start responding to P fertilization. On the other hand, wheat plants, with a relatively deeper rooting system, can extract P from the lower layers to meet their needs, therefore, do not respond to applied P for another 3 to 5 years. Long-term field studies were conducted on a gypsum amended alkali soil (pH_2 9.2, ESP 32) with rice wheat and pearl millet cropping sequence and NPK fertilizer use for 25 years (1974-75 to 1999-2000). Phosphorus application enhanced the grain yield of rice (Yaduvanshi 2003) when Olsen's extractable P in 0-15 cm soil depth had reduced from the initial level of 33.6 kg ha^{-1} to 12.7 kg ha^{-1}, and wheat responded to applied P when available P came down close to 8.7 kg P ha^{-1}. Crop responses to applied P were limited to the application of 11 kg P ha^{-1} in the initial years of cropping and that too only to rice crop in a rice-wheat cropping sequence. Subsequently, application of 22 kg P ha^{-1} significantly improved the rice and wheat yield. Recent studies on integrated nutrient management showed that continuous use of fertilizer P, green manuring and FYM to crops significantly enhanced the yield of rice and wheat as well as improved the available P status of the alkali soils (Yaduvanshi 2000).

The available P status of saline soils is highly variable and does not show any trend or relation to level of soil salinity. The availability of fertilizer phosphorus in the soil may be modified by soil salinity due to higher precipitation of added soluble P (Taylor and Gurney 1965), higher retention of added P by the soil (El Mahi and Mustafa 1980) and due to antagonistic effect of excess Cl on the P sorption by the plants (Manchanda and Sharma 1983). Wheat responded significantly to P application up to 50 kg ha^{-1} (0, 25, 50 and 75 kg ha^{-1}) in terms of grain yield at the site irrigated with Cl^- dominated water (EC 15-19 dS m^{-1}), but there was no response to applied P on the SO_4^{--} irrigation water site although the former (irrigated with Cl^- dominant water) had more Olsen's P than the latter (Manchanda et al. (1982). Barley crop irrigated with Cl^- dominant water also showed higher requirement of P. It has been generally observed that application of P fertilizers increased crop yields in saline soils (Singh et al. 1990, 1992). Higher plant responses to applied phosphorus occurred on moderately saline soils than on non-saline soils. Manchanda and Singh (1982) and Manchanda and Sharma (1983) reported that P requirement under SO_4^- dominated saline conditions ($SO_4 >$ 70%) was either less or at the most equal to the non-saline soil, whereas in case of under Cl -dominated salinity (Cl > 70%), it was considerably more than that of the non-saline soil. Application of P helped rice plants to restrict increase of Na^+ concentration under salinity (Naheed et al. 2008). Rice genotypes showed higher requirement of P with increase in sodicity stress (Qadar 1998). Seedlings of CSR13 and Jaya (moderately tolerant to sodicity) did not show any problem of survival and growth at pH_2 8.0, with Olsen's-P 8.5 kg ha^{-1} but failed to survive at pH_2 9.7 and 9.9 where Olsen's-P was 12.5 and 14.8 kg ha^{-1}, respectively. However, there was no problem of survival or growth at these sodicity levels when Olsen's-P was raised to 17.6 and 20.8 kg ha^{-1}, respectively, and plants attained maturity and produced grain (Table 3). CSR10, a sodicity tolerant genotype showed less response to added P. Plants fertilized with P had less Na^+, a potentially toxic ion in the shoot. It is likely that internal plant requirement of P is higher under stress for restricting uptake of Na^+ at root level and its better regulation at tissues/cellular levels (sequestering in the vacuole). This is reflected with higher chlorophyll contents in the leaves of P fertilized plants in sodic soil (Table 4) (Qadar and Ansari 2006).

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

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

* Plants failed to reach maturity, Source: Qadar 1998

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

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

Source: Qadar and Ansari 2006

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

Potassium

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

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

Sulphur

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

Calcium

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

Sodium

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

Zinc

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

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

Iron

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

Manganese

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

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

Boron

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

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

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

Molybdenum and Copper

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

Conclusions

Plants/crops growing in salt affected soils are exposed to a number of unfavorable conditions like moisture stress, element toxicity, poor soil physical conditions, nutrients imbalance and their deficiency. Plants responses to these adverse conditions are complex and their requirement of different nutrients may not be same under salt stress conditions compared to that of non-stress. The relationships between salt stress and mineral nutrition of plants are equally complex as activity of nutrient elements is altered because of excess of potentially toxic ions (Na^+, Cl^-, SO_4^{2-}, CO_3^{2-}, and HCO_3^-) present in salt affected soils. These ions cause toxicity in plants after their uptake, and also have antagonistic effects on uptake of other nutrient elements like K, N, and P. pH induced changes in the solubility and availability of nutrients is another important factor. Salt affected soils have inadequate levels of some of the nutrients like N, whereas, availability of others such as Zn may be very low. A good number of published results both under controlled as well as field conditions, have shown that improving the soil nutritional status helped plants to grow and yield better under salt stress. However, in some of the reports increased application of nutrients (N, P, and K) did not produce the desired results, which is likely to be because of differences in growing conditions, level of salt stress, crops and their varieties used in the study. The present paper has focused on one of the major reasons for the aggravation of the adverse effects of salt stress on plant growth and yield because of inadequate supply of mineral nutrients, namely, nitrogen, phosphorus, potassium, calcium and zinc. To get the maximum advantage from the applied mineral nutrients, they must be given in the right quantity, at the appropriate time and place, from a proper source and in the right combination. Nutrient application should synchronize with the growth stage of the plants when the requirement of nutrient is maximum. This is true for any situation, but more important under stress environment as adequate level of nutrients may alleviate, to some extent, the adverse effects of salinity and sodicity. Crops especially the horticultural crops, which are highly sensitive to Cl^- toxicity are likely to be benefited by adding more N as NO_3 to offset the adverse effects of Cl^- on its uptake. Similarly, Na induced Ca deficiency or K in plants could be corrected by adding Ca and K as nutrients

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

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Role of potassium in water stress management in dry land agriculture

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

Keywords Potassium nutrition • K deficiency • water stress

Introduction

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

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rising population trend continues.

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

K status in rainfed agriculture

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

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

Release studies indicated that despite the larger reserves of K in alluvial soils of U.P., Bihar and Rajasthan, the rate of K release is much slower as compared to black soils. Hence under intensive cropping with high-yielding short duration genotypes, the soil K supply may not match with K demand by crop. Therefore, application of K to crops particularly in light textured acidic alluvial soils is essential to sustain higher productivity. Similarly, K application is essential on red and lateritic soils, as these soils possess low levels of soil K status as well as its buffering capacity (Sriniviasa-Rao et al. 1998).

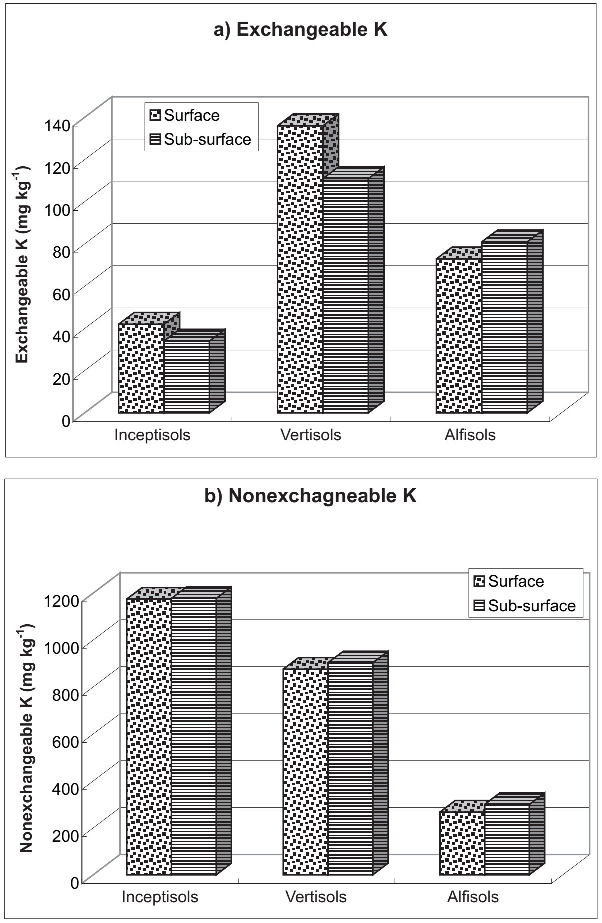
In rainfed agro ecosystems, the soils are characterized by low to high available K status. Surface soils of Agra, S.K.Nagar, Bangalore, Hoshiarpur and Rakh Dhiansar were low in K, Faizabad, Phulbani, Ranchi, Anantapur, Akola, Hisar and Arjia were medium and at Rajkot, Indore, Rewa, Kovilpatti, Bellary,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

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

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

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

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



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

K requirements of different dry land crops

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

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

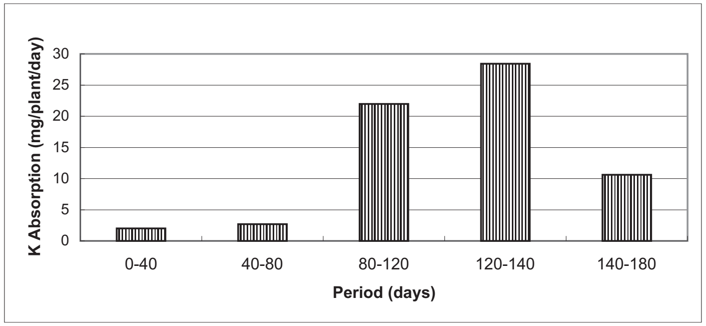
Crop	Produce	kg nutrient tonne^{-1} produce		
		N	P_2O_5	K_2O
Sorghum	Grain	22.4	13.3	34.0
Pearl millet	Grain	42.3	22.6	90.8
Rice	Grain	20.1	11.2	30.0
Chickpea	Grain	46.3	8.4	49.6
Groundnut	Grain	58.1	19.6	30.1
Soybean	Grain	66.8	17.7	44.4
Sunflower	Grain	56.8	25.9	105.0
Cotton	Seed	44.5	28.3	74.7

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

K nutrition and water stress

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

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



Source: Narasimhachary 1980

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

Potassium has substantial effect on enzyme activation, protein synthesis, photosynthesis, stomatal movement and water relations (turgor regulation and osmotic adjustment) in plants (Marschner 1995). Increased application of K^+ has been shown to enhance photosynthetic rate, plant growth, yield, and drought resistance in different crops under water stress conditions (Egilla et al. 2001; Pervez et al. 2004; Thalooth et al. 2006; Yadav et al. 1999). K-fed plants maintained higher leaf water potential, turgor potential and relative water content and lower osmatic potential as compared to untreated plants of Vigna radiata (Nandwal etl al.1998), maize (Premachandra et al. 1991), and wheat (Pier and Berkowitz 1987; Sengupta et al. 1989) grown under water stress. Nodulation, nitrogenase activity and dry matter yield increased with incremental K^+ supply in broad bean grown at moisture level of only ¼ of field capacity (Adb-Alla and Wahab 1995). K^+ is predominant in accumulating solute during drought in tropical grasses (Ford and Wilson 1981), soybean (Itoh and Kumura 1987), maize (Premachandra et al. 1991), cotton (Pervez et al. 2004) and olive trees and sunflower (Benlloch-Gonzaliz et al. 2008) and significantly contributed to osmotic adjustment.

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

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

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

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

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

K nutrition and water stress management

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

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

The amount of soil moisture available to plants in arid and semi-arid regions is a major limiting factor for crop yield. Under such conditions, potassium fertilization proved helpful in mitigating the adverse effects of water stress. The interaction of plant K status and water stress in mustard, sorghum and groundnut (Umar 2006) showed that water content of the leaf tissue was significantly increased by K application and the highest increase in RWC was 14.7 percent, 17.4 percent and 22.8 percent under normal conditions, and by 8.7 percent, 19.9 percent and 17.7 percent under water stress conditions in mustard, sorghum and groundnut, respectively. Water stress caused grain yield reductions and K application could enhance yield to a great extent. Production of above ground biomass, grain yield and RWC were highly correlated with the tissue K concentration, showing that concentration of K^+ in leaves played a vital role in increasing water stress resistance and stabilizing yield in the crops studied. Cakmak (2005) reported several examples emphasizing the role of K in alleviating the adverse effects of drought on crop production.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Conclusions

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

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

GN Mitra • SK Sahu • RK Nayak

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

Keywords Iron toxicity • potassium • soils of Orissa

Introduction

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

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

Iron rich soils of Orissa and the problem of iron toxicity

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

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

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

Classification of iron toxic soil and status of nutrients

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

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

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

Source: Nayak 2008

The profile distribution of different forms of iron

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

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

Table 2 Profile distribution of different forms of iron

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

Source: Nayak 2008

Table 3 Classification of iron toxic soils of Orissa

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

Source: Nayak, 2008

Physical properties and nutrient status

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

Interaction of DTPA-Fe with other soil nutrients

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

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

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

Fe contents in rice leaf

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

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

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

* Values in parenthesis indicate number of samples

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

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

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

Tolerance of iron toxicity by rice varieties

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

Recent concepts on mechanism of Fe uptake by plants

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

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

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

Effects of iron toxicity on plants

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

Defense mechanisms by plants for metal detoxification

There are cellular mechanisms for metal detoxification and tolerance by higher plants. These are: Restriction of metal movements to roots; binding to cell wall and root exudates; reduced influx across plasma membrane; active efflux into apoplast; chelation in cytosol by various ligands; repair and protection of plasma membrane under stress conditions; transport of phytochelatin-metal complex into the vacuole and transport and accumulation of metals in the vacuole. Upon exposure to heavy metals, plants often synthesize a set of diverse metabolites that accumulate in the mM range, such as amino acids: proline and histidine, peptides: glutathione and phyto-chelatins (PC), and the amines: spermine, spermidine, putrescine, nicotianamine, and mugineic acids. These metabolites bear functional significance in the context of metal stress tolerance. Tseng et al. (1993) showed that, in rice, both heat stress and heavy-metal stress increased the levels of mRNAs for low molecular mass HSPs (Heat shock proteins) of 16–20 kDa. HSPS act as molecular chaperones in normal protein folding and assembly, but may also function in the protection and repair of proteins under stress conditions.

Recent concepts on genetic regulation of K^+ uptake

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

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

Amelioration of iron toxicity through application of K

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

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

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

Source: Sahu and Mitra 1992

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

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

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

Source: Sahu and Mitra 1992

Potassium and symptoms of iron toxicity, grain yield and quality

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

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

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

	K	V	Kx V	K	V	Kx V	K	V	Kx V
C.D (0.05)	3.12	9.43	N.S	8.79	7.47	7.47	2.42	1.56	N.S

Source: Sahoo 1989

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

K, and Fe contents at different stages of growth

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

Conclusions

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

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Role of nutrient management in reduction of greenhouse gases

CS Snyder • AM Johnston

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

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

Introduction

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

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

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

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

GHG mitigation by agriculture

An estimated 20 percent of GHG emissions are thought to be due to clearing and burning of forests, largely as a result of development pressures and human demand for food and fuel (Baumert et al. 2005). Safe-guarding and storing carbon (C) in agricultural systems is one means of mitigating GHG emissions. Increasing the agricultural productivity per unit of existing land area can help preserve and protect natural areas (Cassman 1999) and help minimize anthropogenic CO_2 emissions. Intensification of agricultural production on existing lands may also lower the risk of accelerated N_2O emissions be preventing heightened decomposition of soil organic matter and subsequent N mineralization which may be associated with cultivation of former wetlands, forests, or grasslands (IPCC 2006). There is evidence that net GHG emissions can be kept low in agricultural cropping systems with optimized management that exploits the realistic, attainable yield potential (Adviento-Borbe et al. 2007). Intensive crop management systems may have increased GHG emissions per unit land area, but they do not necessarily increase GHG emissions per unit of crop or food production (Snyder et al. 2007; 2009). Using the economic optimum N rate (EONR) for crop production might increase emissions of CO_2 compared to a no N or 50 percent of the EONR scenario, but the increased land area that would be required to compensate for the yield loss under these two lower input scenarios would result in CO_2 emissions as much as four times greater than those of the intensive EONR system (Brentrup and Palliere 2008).

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

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

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

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

Methane emissions and rice paddy management

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

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

Nitrous oxide emissions associated with nitrification and denitrification

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

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

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

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

Increasing fertilizer N consumption and N_2O emission implications

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

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

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

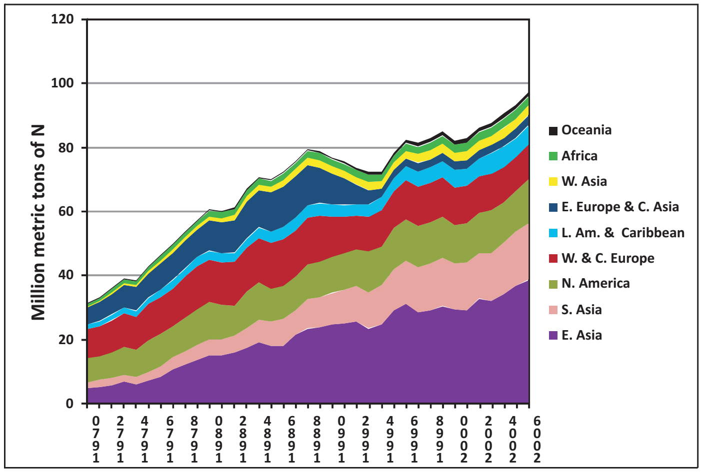
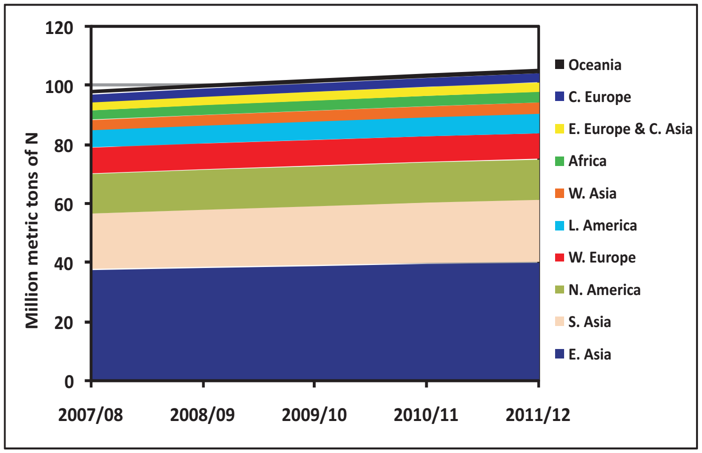


Fig. 2 Projected world fertilizer N consumption (FAO 2009)



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

Fertilizer management for nutrient use efficiency and effectiveness

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

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

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

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

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

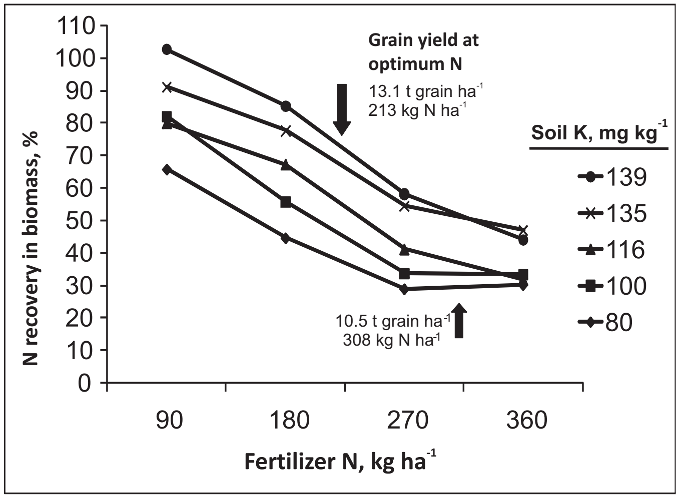
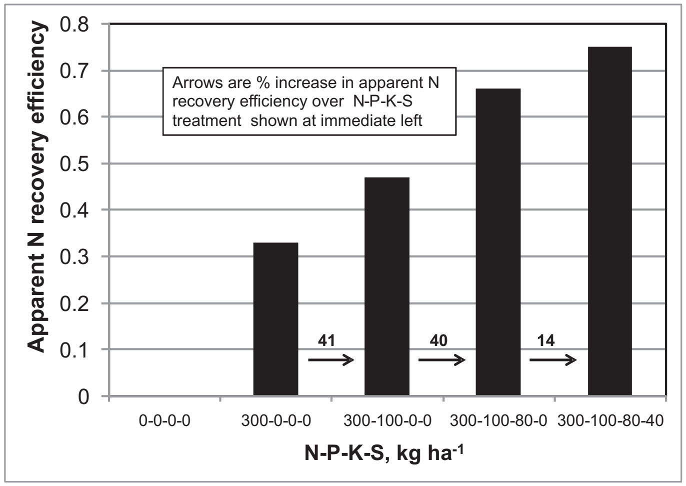


Fig. 4 Balanced fertilization effects on apparent N recovery by maize using balanced fertilization (assuming 25 kg of N uptake per ton of grain (Gordon 2005).



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

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

Nutrient management practices that improve RE_N of applied N are likely to minimize the risks of N loss via the various loss pathways (immobilization, ammonia volatilization, runoff, leaching, denitrification) (Chien et al. 2009). Nutrient managers should consider the risks for reductions in N loss via one pathway being offset by increased N loss via another pathway (Snyder 2008; Snyder et al. 2009). For example, reductions in the direct loss of N via ammonia (NH_3) volatilization, could conserve N and increase the inorganic soil N supply and lead to an increased risk for elevated NO_3^- in water resources; which may elevate the potential for direct and indirect N_2O emissions (Crutzen et al. 2008; Del Grosso et al. 2006; Galloway et al. 2003; Sutton et al. 2007). The combination of fertilizer source, timing and placement that produces the greatest yield with the least amount of N is likely to help optimize agronomic goals and minimize environmental impacts. Continued in-field assessment of new practices for optimum crop N use efficiency, and measurements to assess progress, are essential to production and environmental goals (Dobermann 2007; Snyder and Bruulsema 2007).

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

<table>
<tr><td></td><td colspan="3">Plant available soil P</td><td colspan="3">Plant available soil K</td></tr>
<tr><td>Level</td><td>U.S.</td><td>China</td><td>India</td><td>U.S.</td><td>China</td><td>India</td></tr>
<tr><td></td><td colspan="3">% of soil samples</td><td colspan="3">% of soil samples</td></tr>
<tr><td>Low</td><td>24</td><td>46</td><td>46</td><td>14</td><td>58</td><td>13</td></tr>
<tr><td>Medium</td><td>23</td><td>25</td><td>49</td><td>29</td><td>18</td><td>53</td></tr>
<tr><td>High</td><td>53</td><td>29</td><td>5</td><td>57</td><td>23</td><td>34</td></tr>
<tr><td colspan="7">North America[a]</td></tr>
<tr><td colspan="3">Median soil test
P (mg kg^{-1})</td><td colspan="4">Median soil test
K (mg kg^{-1})</td></tr>
<tr><td>2001</td><td colspan="2">27</td><td colspan="4">154</td></tr>
<tr><td>2005</td><td colspan="2">31</td><td colspan="4">154</td></tr>
<tr><td colspan="2">% of soil samples with < 25 mg kg^{-1} soil test P in 2005</td><td>42</td><td colspan="3">% of soil samples with < 160 mg kg^{-1} soil test K in 2005</td><td>53</td></tr>
</table>

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

Fertilizer N management for reduced methane emissions

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

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

Fertilizer management for reduced nitrous oxide emissions

Right source

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

In contrast to the global summaries and modeling approaches mentioned above, Chen et al. (2008) stated, "Since ammonia or ammonium producing compounds are the main sources of fertilizer N, maintenance of the applied N in the ammonical form should result in lowered emissions of nitrous oxide from soils". Harrison and Webb (2001) also reported that relative N_2O emissions from NO_3-based sources may be greater than those from NH_4-based sources and differences may increase with increasing soil wetness. Higher N_2O emissions with NH_4-based fertilizers may be related to potential NO_2^- accumulation or N_2O production during nitrification (Venterea and Stenanas 2008). These conflicting reports and the summary by Snyder et al. (2009) raise questions about the importance of N source in addressing N_2O emissions, and they illustrate the need for continued research.

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

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

[1] Bouwman et al. 2002a, 2002b

[2] Stehfest and Bouwman 2006

[3] Values followed by a common letter are not significantly different, based on two-tailed statistical tests (Stehfest and Bouwman 2006)

[4] Includes potassium nitrate, calcium nitrate, sodium nitrate (Bouwman et al. 2002a; 2002b)

[5] Includes ammonium bicarbonate, ammonium chloride, ammonium sulfate (Bouwman et al. 2002a; 2002b)

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

Right rate

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

It is quite challenging to manage fertilizer N at an appropriate amount because each agro-ecosystem and specific growing season will differ as to what is most appropriate. Residual soil N estimation has proven useful in some regions, but wide ranges in yield response to a given N rate often occur when attempting to calibrate soil NO_3^- tests or mineralizable N tests (Dahnke and Johnson 1990; Follett 2001; Stanford 1982). A scatter or “cloud' of data points instead of a distinct response curve is often observed in research calibration efforts because of the large spatial and temporal variability in soil NO_3^- (Meisinger 1984). Nitrous oxide emissions began to increase significantly compared to unfertilized check

treatments with N rates above 100 kg ha^{-1} in an irrigated corn study (Grant et al. 2006; Kachanoski et al. 2003). In the less humid areas of the world where upland crops predominate, farmers may minimize the potential for N_2O emissions by following a nutrient management plan (NMP) which includes soil testing to determine residual NO_3^- in the soil; where it is appropriate and has been properly calibrated by research. By considering the normal N mineralization potential from SOM for soils in a field and the residual soil NO_3^-, the deficit between the sum of these two N-inputs and the expected N uptake demand for realistically attainable crop yields can be calculated; which allows estimation of an appropriate amount of timely and well-placed N fertilizer.

Right time and right place

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

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

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

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

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

Enhanced efficiency of fertilizers

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

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

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

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

Conclusions

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

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