INTERNATIONAL POTASH INSTITUTE

Optimizing Crop Nutrition

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Electronic International Fertilizer Correspondent (*e-ifc*). Quarterly correspondent from IPI.

Editorial

Dear readers,

In this edition we are pleased to include papers presented at IPI's special session entitled "Nitrogen and Potassium Interaction in Plant Nutrition", held during the 5th International Nitrogen Conference in Delhi (3-7 December 2010) and organized by the Indian Nitrogen Group (ING-SCON) and the International Nitrogen Initiative (INI).

Non-leguminous crop plants, take up nitrogen almost exclusively in two ionic forms (NH_4^+ and NO_3^-). This uptake drives plant growth with dry matter N concentration ranging from 0.5-6 percent, a value only slightly lower than that of potassium at 0.8-8 percent. These N containing ions are derived from mineral fertilizers, mineralization of organic matter, and soil microbiological processes including nitrification. Additionally, with the rise of reactive nitrogen in the environment, some N inputs come directly from atmospheric deposition as well as indirectly from irrigation water.

Legumes fix atmospheric nitrogen contributing a significant amount of soil N, which benefits other crops when planted in mixed cropping systems. These multiple factors all make calculations of Nitrogen Use Efficiency (NUE) rather complex. Until it is possible through biotechnology to create a "super non-legume plant" which absorbs N from the atmosphere (will this ever be achieved?), management of the fertilization process clearly plays a key role in improving NUE. In this respect, potassium, via its role in the uptake and translocation of N and protein formation in the plant, deserves special attention.

What is the energy cost of potash production? See more on page 28 (Weidberg, R.). Photo by IPI.

The papers included in this edition from IPI's special session relate to the improvement of NUE through N-K interaction. Brar *et al.* discuss this topic in cereals, with a sound agronomic approach; Cai *et al.* examine the physiological and molecular responses of rice to N, P, K and Mg deficiencies, and Bar Tal looks at NK interactions in the soil.

Finally, we look at the energy cost (in terms of GHG or CO_2 equiv. emissions) of potash production. The report shows that in comparison to other nutrients, the greenhouse gas (GHG) footprint of potash is relatively low. In times when energy costs and GHG are of major concern, this type of calculation provides a valuable extra tool to make the right decision for efficient nutrient management.

We trust this eclectic collection will prove interesting and informative, and wish you all an enjoyable read. ■

Hillel Magen

Director

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Introduction

Nitrogen-Potassium Interaction in Soil-Plant Systems: A Special Session of the IPI-INI-ING at N2010, New Delhi, India

Raghuram, N.(1)

Issues of balanced potassium fertilization and plant nutrition, especially in the context of nitrogen (N) and potassium (K) interactions, have been the focus of a special IPI-INI-ING session in the 5th International Nitrogen Conference (N2010), held during 3-7 December, 2010 in New Delhi, India. The conference on “Reactive nitrogen management for sustainable development - science, technology and policy” brought together over 400 delegates from 36 countries. The conference was coordinated by M.S. Sachdev for the Indian Nitrogen Group of the Society for Conservation of Nature, headed by Y.P. Abrol (President) and N. Raghuram (Secretary).

The nitrogen cycle is the most anthropogenically altered nutrient cycle, which has adverse impacts on food security, energy, industry, health, biodiversity, environment and climate change. Responding to these issues, the conference provided a comprehensive agenda under five sub-themes: food security, ecosystem services and biodiversity, health, energy security and industry and climate change, along with a separate session that integrated all these subthemes.

Prof. Xu Guohua (Nanjing Agric. Univ.) delivers his paper on “Different Strategies for Improving Nitrogen and Potassium Use Efficiency by Biological Approaches” at the IPI-INI-ING special session during the N2010 conference, New Delhi, India. Prof. Dr. J.S. Samra (CEO, National Rainfed Area Authority Planning Commission, Government of India) and Mr. H. Magen (Director, IPI) chaired this session. Photo by E. Sokolowski.

The interactions of N with other nutrients, such as K and P, are central for integrated nutrient management programmes. The special session of IPI-INI-ING on “Nitrogen-potassium interactions in soil and plant systems” was held under the Food Security theme with three oral presentations and as many posters. A USD 500 award was also announced for the best poster presented in this session.

A Delhi Declaration was also adopted by the conference that summarized the current knowledge base and made policy and research recommendations for action under each of the five subthemes. The Declaration called upon “the UN bodies such as UNEP, FAO, UN-Habitat, WHO, UNDP, UNFCCC, CBD, CLRTAP and other regional organizations, national governments, scientific communities, including CGIAR, industries, policymakers, International Nitrogen Initiative (INI) and the civil society to address nutrient deficiencies, move towards increased efficiencies in each segment of nitrogen cycle management, in order to reduce the adverse effects. Approaches should consider the use of incentives, make full use of recycling and ensure the treatment of discharges…. Identification, communication, and promotion of best practices require collaboration among many stakeholders including governments, scientists, practitioners, and policymakers at global, regional and national levels. The formation of the Global Partnership on Nutrient Management (GPNM), facilitated by UNEP, is a welcome development in this regard.” ■

The paper “Nitrogen-Potassium Interaction in Soil-Plant Systems: A Special Session of the IPI-INI-ING at N2010, New Delhi, India” appears also at:

Regional Activities/India and

N-K Interaction Center

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INI: International Nitrogen Initiative

ING: Indian Nitrogen Group

The Effects of Nitrogen Form on Interactions with Potassium

Bar Tal, A.⁽¹⁾

Abstract

Nitrogen and potassium are major nutrients in crop fertilization. The monovalent cation K^+ is the ionic form of K in soil and is taken up as such by plants. For N there are several ionic and non-ionic forms in soil but plant uptake by non-legumes is usually restricted to the two main monovalent ionic forms: NH_4^+, a cation and NO_3^-, an anion. The source of N available to plants and N transformations within the soil, influence K reactions in soil, K absorption by roots, short and long-distance transport within the plant, as well as K demand by crops. NH_4^+ and K^+ share similar valence and size properties, and consequently compete for the same exchangeable and non-exchangeable sites of soil particles. The form of N fertilizer can thus affect K availability in both the short and long-term. In the short-term, K concentration in the soil solution may increase following NH_4^+ fertilization, whereas long-term NH_4^+ fertilization has been reported to deplete exchangeable and non-exchangeable K in soil. The available N form affects K adsorption to root surfaces and plant membranes. Transport of K^+ through plant membranes is affected both by NH_4^+ and NO_3^- by direct competition between K^+ and NH_4^+ for transporters, as well as by indirect effects of electrical balance following NH_4^+ assimilation. K^+ transport to plant shoots decreases with an increasing NH_4^+/NO_3^- ratio in the root zone; the long distance transport of NO_3^- in plants is related to K^+ recycling within the plant. The effects of K^+ on fruit quality have been shown to be dependent on the N source. Consequently, the interactions of K^+ with N forms have practical implications for fertilization of crops.

Table 1. Comparison of different properties of nitrogen and potassium in soil and plant.

Property	Nitrogen	Potassium
Soil-composition	A component of organic matter, anion and cation forms, solid, dissolved and gases forms	Inorganic cation or component of soil minerals
Soil-reactions	Complex chemical reactions in soil, involving microorganisms	Simple chemical reactions in soils
Plant-uptake mechanism	Taken up in two main ionic forms: NH_4^+ and NO_3^-	Taken up only as K^+
Plant-physiological role	A major component of proteins, nucleic acid and numerous other organic compounds	An osmotic-regulator

Introduction

Nitrogen and potassium are major crop nutrients and fertilizer components. Römheld and Kirkby (2010) recently reviewing the subject of K in agriculture considered topics including soil K availability, K uptake by plants, as well as physiological and practical aspects of plant K status. General interactions between N and K in crop fertilization have been described by Milford and Johnston (2007). The main focus of this work was to draw attention to the requirement for adequate K supply to crops in order to optimize yield response to N fertilization. Potassium status of the soil was shown to exert a considerable influence on crop uptake and response to N, as a consequence of the physiological role of K in plants. Recently, the K nutrition of crops under varied regimes of nitrogen supply was reviewed by Zhang *et al.* (2010). The present mini-review focuses on the effect of N form on crop response to K in agriculture. The paper specifically discusses the interactions of NH_4^+ and NO_3^- with K^+ in the entire soil-plant system. It includes the following areas of interest: the influence of N source and the effects of N transformations within the soil on soil K reactions; K absorption by roots; short and long-distance transport of K in plants; and whole plant response to K supply and K demand.

Ammonium and potassium interactions in soil

The main broad differences between K and N properties in relation to their chemical reactions in soil, uptake by plants and their roles in plant physiology are presented in Table 1. The exclusive monovalent ionic form of K in the soil contrasts to the several ionic and non-ionic forms of N which are present. This means that potassium is taken up by plants as K^+ whereas nitrogen can be absorbed as NH_4^+, a cation and as NO_3^-, an anion. Nitrogen is a major constituent of organic molecules in plants which include amino-acids, proteins and nucleic acids. On the other hand, K remains exclusively as an inorganic cation, with one of its major physiological roles as an osmotic-regulator in plant tissues. This difference between plant N and K raises the question of possible interactions or competition between these two nutrients. NH_4^+ and K^+ are both univalent cations and have a similar ionic radius ($2.8A^0$). Consequently, they compete for the same exchangeable and non-exchangeable sites of soil particles. The form of N fertilizer can thus affect K availability both in the short- and long-term.

Potassium availability to plants in soil is governed by the transfer between four main pools in the soil: structural, fixed (non-exchangeable), exchangeable and soluble (Römheld and Kirkby, 2010). The soluble and exchangeable phases

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exist in all soils, the latter providing negative charge sites on clay mineral surfaces and organic matter. The fixed or non-exchangeable phase exists only in micaceous type clays (2:1 layers like illite, vermiculite and other clays from this group) (Römheld and Kirkby, 2010; Zhang *et al.*, 2010). In soils, equilibrium exists between these different pools and the relationship between them is presented in Fig. 1. The size of the soil solution pool is very small, about 5 percent of total crop demand at any given time (Mclean and Watson, 1985), and 0.1-0.2 percent of the total soil K. However, it plays a crucial role in the K cycle as can be seen in Fig. 1. It is the only pool that is available for plants and it is in equilibrium with exchangeable K (1-2% of the total soil K) and fixed K (1-10% of the total soil K). These pools are the main contributors to K supply to plants because of the very rapid rate of exchange of soluble ions with exchangeable ions, occurring in less than seconds (Eick *et al.*, 1990; Bar-Tal *et al.*, 1995; Sparks, 2003). When K$^+$ is removed from the solution by plant uptake or leaching, the soil solution is rapidly replenished by K$^+$ from exchangeable sites, whereas the fixed clay replenishes the exchangeable sites slowly by a diffusion controlled process. The main K pool in soil (90-98%) is the structural K in minerals like micas and feldspars, but the release of this form to the soil solution during the process of weathering is very slow. Microbial biomass provides an additional K pool in soil which contains from 2.1-25.4 µg K g^{-1} soil or 0.1 percent of the $NH_4^+NO_3^-$ extracted K (Khan *et al.*, 2009). This pool and the role of micro-organisms is not crucial for the K cycle, as it is in the N cycle, because the main form of K in living tissues is the ion K$^+$ which is readily transferred to the soil solution.

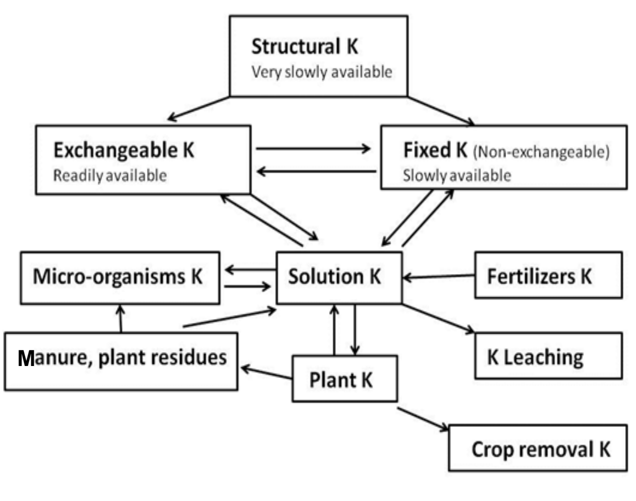

Fig. 1. The potassium cycle in soils.

Soil K status influences K uptake by plant roots. The amount of K in the soil depends on soil type, production level, retention or removal of crop residues and the input of K as fertilizer or as a component of irrigation water. Imbalance in fertilizer application, especially N fertilizers with no K, is very common. This leads to a deficiency in K due to the continuous removal of K during crop uptake that alters the amount and status of remaining K (Römheld and Kirkby, 2010). Release and fixation rates of K in soil are highly dependent on soil K balance, confirming that these are reversible processes that depend on plant uptake and fertilizer inputs (Bar-Tal *et al.*, 1991; Simonsson *et al.*, 2007). In a greenhouse experiment, where corn was grown in pots (3 kg soil) for one season, the control treatment (nil K input) resulted in the release of 2.6 and 1.1 mmol kg^{-1} from loess and sandy loam soils, respectively (Bar-Tal *et al.*, 1991). In the same experiment, application of 30 mmol K per pot resulted in fixation of 1.33 and 1.20 mmol kg^{-1} to a loess and a sandy loam soil, respectively. These changes in non-exchangeable K are quite considerable when compared to the initial levels of 7.6 and 1.9 mmol kg^{-1} in the loess and the sandy loam soils, respectively. This may be explained by the use of small volume pots which enhanced the rate of changes in the soil. Under field conditions, however, the same processes would be expected to induce these changes at a much slower rate; taking several years to obtain similar results. Crop uptake of K under a negative soil K balance due to imbalanced NPK fertilization in the field is mainly met through K released from non-exchangeable sources (Römheld and Kirkby, 2010; Lal *et al.*, 2007). On the other hand, a considerable increase in fixed K is observed in permanent plot experiments in high K input treatments (Benbi and Biswas, 1999) and in pot experiments (Bar-Tal *et al.*, 1991).

The NH_4^+ ion is also present in soil solution and in exchangeable and fixed soil pools. There is also equilibrium between these forms as was described for K. The main chemical difference between K$^+$ and NH_4^+ is that the latter can also be oxidized to nitrite and NO_3^-, mainly through microbial activity. Only the fixed phase NH_4^+ is relatively protected from the oxidation process and can be retained in the clay inter-layers for long periods. The similar properties of the K$^+$ and NH_4^+ ions leads to strong interactions between them in the soil. Both ions are held by the same non-exchangeable sites in the interlayers and edges of interlayers of the 2:1 clay minerals. Consequently, a simple competition where application of one ion should displace the other and increase its fraction in soil solution is to be expected. However, the reality is more complex and application of NH_4^+

or K^+ to soil may lead to increases as well as decreases in the non-exchangeable pool of the counter ion. Some examples and the possible explanations are presented below.

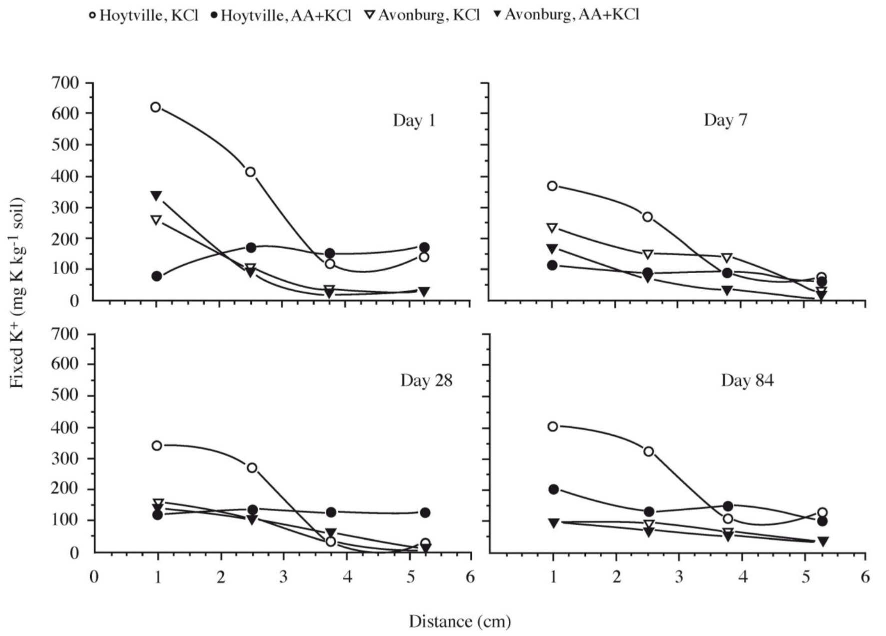

Fig. 2. Distribution of fixed K^+ fertilizer over time and distance from the injection point in Hoytville and Avonburg soils following injection of KCl or anhydrous ammonia (AA) + KCl.

Adapted from (and redrawn): Stehouwer and Johnson, 1991; Soil Science Society American Journal 55:1374.

Simultaneous injection of anhydrous ammonia (AA) and a KCl solution in a silty clay loam soil decreased K^+ fixation, whereas the concentrations of the exchangeable and soluble K^+ increased (Stehouwer and Johnson, 1991). The decrease in K^+ fixation was attributed to preferential NH_4^+ fixation blocking K^+ fixation and the increased exchangeable K^+ explained by a decrease in K^+ fixation (Fig. 2) and to pH-induced increases in cation-exchange capacity (primarily in the organic fraction) (Stehouwer and Johnson, 1991). Liu *et al.* (1997) reported that in field experiments, the soil fixation capacities for both NH_4^+ and K were significantly reduced by sustained high rates of K fertilization, but not by N fertilization. Kenan *et al.* (1999) also found that the fixation of NH_4^+ was reduced by K addition before NH_4^+ was added, and that the reduction was proportional to the amount of K previously fixed. Enhanced K^+ fixation with increasing K application rates and reduction with increasing NH_4^+ application rates was reported by Chen and MacKenzie (1992) and Du *et al.* (2007). The sequence of NH_4^+ and K^+ application may influence K fixation. Chen *et al.* (2007) reported that NH_4^+ at high rates of application before K fertilization to rice plants resulted in poor growth and reduced K uptake compared to NH_4^+ application after K fertilization. However, when NO_3^- was used as the N source, plant growth was not affected by the order in which N and K were applied. The explanation for the negative effect of the early NH_4^+ application on K availability was that the NH_4^+ blocked the non-exchangeable sites, thus reducing the capacity of the soil to store K to meet the continuous consumption by the plants. Evangelou and Lumbanraja (2002) reported that the surface of vermiculite clay exhibits high specificity for K^+ at low-K fractional loads which cause the clay interlayer to collapse and thus a large proportion of interlayer NH_4^+ most likely becomes fixed. The available exchange sites appear to have relatively lower affinity for NH_4^+. Therefore, the data indicates that availability of applied NH_4^+ in vermiculitic soils would depend on the presence or absence of applied K^+.

Clay minerals of the smectite type have a unique structure that enables a high exchangeable cation capacity in the interlayers. The size of the hydrated exchangeable cation affects the interlayer distance. Changes in the composition of the exchangeable cations affect the interlayer distance or swelling of the clay. However, the high affinity of K^+ and NH_4^+ ions to exchangeable sites leads to their gradual fixation, a process which results in transformation of smectite to illite. The transformation from smectite to illite is a pedological or geological process that takes thousands of years to complete. When one considers transformations on a geological scale, the effect of temperature on this transformation was found to be critical, starting at 50 to 60°C. In the past few decades, new observations have indicated that the transformation of smectite to illite occurs also under ambient air temperature conditions with the relatively short time scales associated with soil cultivation. Such fast transformation has been shown in laboratory conditions under cycles of wetting and drying (Eberl *et al.*, 1986 and 1993). Sandler and Harlavan (2006) suggested that high K concentrations may lead to this transformation without wetting and drying cycles. In vitro experiments of K^+ and NH_4^+ fixation under wetting and drying cycles were conducted and the illitization of the original smectite by both ions was similar (Miklos and Cicel, 1993). The formation of illite from smectite in experimental field plots (Versailles) fertilized by inorganic K fertilizer and manure have been reported by Pernes-Debuyser *et al.* (2003). Additional laboratory experiments showed that the changes over one growing season were measureable (Barré *et al.*, 2007a, 2007b and 2008). The opposite process of fast release of interlayer K and decomposition of illite clay due to agricultural activity has also been reported. The most extreme cases were observed in a rice field where wetting and drying cycles are common and the potassium is easily leached, leading to measureable changes over a relatively short time of 30 years (Li *et al.*, 2003). Continuous maize cropping over several decades resulted in decomposition of soil illite, whereas no change was obtained under a corn-oat-hay rotation with the same fertilization treatment (Velde and Peck, 2002).

Numerous published data indicate that K^+ and NH_4^+ are attracted by the same exchange sites with similar affinity. A slight preference for K^+ over NH_4^+ has been demonstrated in laboratory exchange isotherms (Fig. 3, Chung and Zasoski, 1994). They also reported that similar exchange isotherms were obtained in the bulk solution and rhizosphere, independent of the solution pH and ionic strength. Consequently, the concentration of NH_4^+ in the soil solution has a strong and direct impact on the distribution of K^+ between the soil solution and the exchange complex and vice versa. The situation becomes more complex when the soil contains additional cations. In a laboratory study, Evangelou and Lumbanraja (2002) investigated the exchange of K^+ - NH_4^+ - Ca^{+2} on vermiculite and hydroxy-aluminium vermiculite. They found that in the case of vermiculite, binary exchange data alone may not be able to predict ternary exchange data. However, in the case of hydroxy-aluminium interlayered vermiculite, binary data may be able to predict ternary data as long as the third cation's distribution between exchange and solution phases remains constant across the isotherm. Liu *et al.* (1997) found that K^+ application enhanced NH_4^+ fixation but reduced the amount of exchangeable NH_4^+ on the clay surface. Wang *et al.* (2010) reported that the application of the fertilizer ammonium sulfate to different soil types from China in incubation experiments significantly altered the distribution between pools of native K and added K in the soils. Addition of ammonium sulfate significantly increased water-soluble K^+ and decreased exchangeable K^+ in almost all the soils except the paddy soil that contained considerable amounts of 2:1 type clay minerals with K^+ added. Added ammonium sulfate also reduced the formation of fixed K^+ in the soils with K^+ added and suppressed the release of fixed K^+ in the three studied soils without K^+ added.

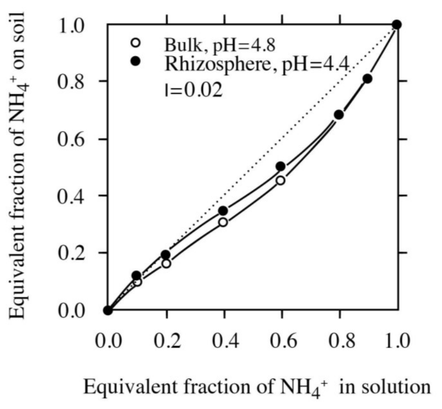

Fig. 3. Exchange isotherm for NH_4^+-K exchange in bulk soil of peach seedling at solution ionic strength of 0.02. The dotted line is non-preference line.

Adapted from (and redrawn): Chung and Zasoski, 1994; Soil Science Society American Journal 58:1368-1375.

The nitrogen source may significantly affect rhizosphere pH (Nye, 1981; Marschner, 1995; Marschner and Römheld, 1996; Bar-Yosef, 1999; Bloom *et al.*, 2003). The common N fertilizer sources in soil systems are urea, NH_4^+ and NO_3^-. Urea is the cheapest N source (per N unit) and is the most concentrated N fertilizer (46%); it is highly soluble, moves easily in irrigation water and is therefore widely used in agriculture. The hydrolysis process of urea yields the derivative NH_4^+ ions - and thus urea is a source of the NH_4^+ form for plant nutrition. Rapid adsorption on the surface sites of the solid phases, and nitrification reactions diminish the NH_4^+ content in soils and media, and hence, rhizosphere NH_4^+ concentrations are commonly low even under irrigation with a high NH_4^+-N/ NO_3^--N ratio.

In the field, the transformation of NH_4^+ to NO_3^- is usually a rapid process, between days to weeks, depending on temperature, soil moisture and pH. Therefore, in most fertilizer application methods the form of N should not have a strong impact on K distribution between the exchangeable and solution phases. However, when continuous fertigation is used it is expected that the N source will effect K concentration in the solution in the wetted soil, and several studies have validated this assumption. For example, during the irrigation season, K^+ concentration in the soil solution of a citrus orchard increased when N was applied as ammonium sulfate, as opposed to ammonium nitrate (Fig. 4, Erner *et al.*, 2011, submitted). The application of a nitrification inhibitor enhanced the effect of the ammonium sulfate on soil solution K^+ concentration, indicating that the effect of the fertilizer on K concentration was via the NH_4^+ - K^+ exchange process.

Another mechanism by which the N source influences K availability and leaching is unique to calcareous soils common in arid and semi-arid regions. In carbonate-bearing soil, the acid produced by nitrification of NH_4^+ gives rise to an increase in the concentrations of Ca^{2+} and Mg^{2+} in the soil solution, which can exchange with K^+, leading to higher K^+ solution (unpublished data of the author, Kolahchi and Jalali, 2007).

Potassium and nitrogen interactions in plants

Nitrogen is a unique nutrient that can be absorbed either as the cation NH_4^+ or the anion NO_3^- (Marschner, 1995). This characteristic of nitrogen influences plant nutrition in general and the uptake

Research Findings

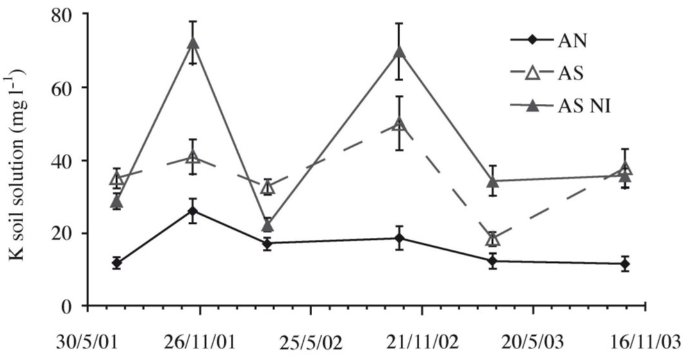

Fig. 4. The effect of N source on K concentration in the soil solution of a citrus orchard.

Adapted from (and redrawn): Erner *et al.*, 2011, submitted.

of other elements that are taken up as ions as well as numerous physiological processes in plants (Marschner, 1995; Forde and Clarkson, 1999; Mengel and Kirkby, 2001; Epstein and Bloom, 2005). The cation-anion balance in plant tissues is maintained by diffusible and non-diffusible organic and inorganic ions, and has been found to be notably affected by the sources of N nutrition (Marschner, 1995; Mengel and Kirkby, 2001; Epstein and Bloom, 2005). It has been widely reported that NH_4^+ nutrition depressed the uptake of cations, especially in leaves and petioles, and that NO_3^- nutrition depressed that of anions (Kirkby and Mengel, 1967).

The nitrogen source has a strong impact on soil rhizosphere and the rhizosphere pH *via* three mechanisms (Marschner, 1995; Marschner and Römheld, 1996; Bar-Yosef, 1999): (i) displacement of H^+/OH^- adsorbed on the solid phase; (ii) nitrification/denitrification reactions; and (iii) release or uptake of H^+ by roots in response to NH_4^+ or NO_3^- uptake, respectively. Mechanisms (i) and (ii) are not associated with any plant activity, and affect the whole volume of the fertigated substrate, whereas mechanism (iii) is directly related to the uptake of nutritional elements, and may be very effective in changing the pH because it affects a limited volume in the immediate vicinity of the roots (Moorby *et al.*, 1984; Gahoonia and Nielsen, 1992; Gahoonia *et al.*, 1992; Marschner and Römheld, 1996; Taylor and Bloom, 1998; Bloom *et al.*, 2003). The extent of the pH changes caused by the three mechanisms described above depends on soil properties, plant activity, and all the environmental factors that affect nitrification rate.

Transport through membranes and long-distance transport in plant

The selective transport of nutrients through plant membranes is mainly regulated by transporters (Hirsch *et al.*, 1998). Two distinct membrane transport systems for K uptake by plants have been described: high and low affinity transport systems (HATS and LATS); (Maathuis, 2007; Maathuis and Sanders, 1997; Nieves-Cordones *et al.*, 2007). At low external K^+concentrations (<1 mM), HATS are dominant; while at higher external K^+ concentrations (>1 mM) LATS become dominant, mostly via ion channels (Maathuis and Sanders, 1997; Hirsch *et al.*, 1998). Over the past two decades, the complex system of K^+ transporters and the genes encoding them have been identified (Szczerba *et al.*, 2009).

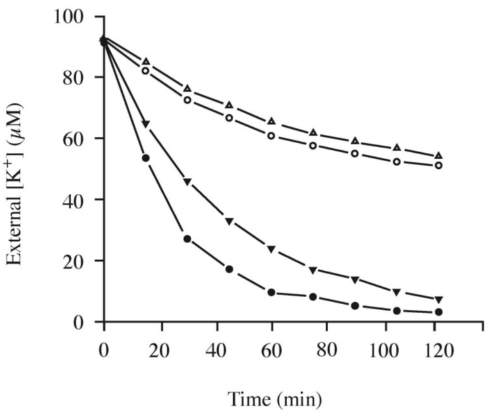

Fig. 5. Effects of NH_4^+ on high affinity K^+ uptake in plants grown with or without NH_4^+ in the absence or in the presence of NaCl.

Adapted from (and redrawn): Nieves-Cordones *et al.*, 2007; Plant Science 172:273-280.

After K^+ starvation for seven days, K^+ depletion experiments were performed in the absence of NH_4^+ (closed symbols) or in the presence of 1 mM NH_4^+ (open symbols). One group of plants received the NaCl treatment (50 mM final NaCl concentration) (triangles) and the other remained in the NaCl free solution (circles).

NH_4^+ inhibits HATS which operate primarily at low external K^+ concentrations (<1 mM), while LATS, which dominates at higher K+ external concentrations, are relatively NH_4^+ insensitive (Hirsch *et al.*, 1998; Nieves-Cordones *et al.*, 2007 and others) (Fig. 5). On the other hand, NO_3^--grown plants regulate cytosolic K^+ concentrations at high K^+ external concentration better than NH_4^+-grown plants by potassium efflux through LATS (Szczerba *et al.*, 2006).

NO_3^- is a univalent anion that can serve as a counter ion to K^+ (Abdolzadeh *et al.*, 2008; Guo *et al.*, 2007; Jarvis *et al.*, 1990; Lu *et al.*, 2005; Mathuis, 2007; Pettersson, 1984) and *vice versa*. Ivasshikina and Feyziev (1998) reported that the rate of NO_3^- uptake by maize seedlings was faster when K^+ served as the accompanying counter ion, rather than the other main cations, Ca^{2+}, Mg^{2+} and Na^+ (Fig. 6). It was found that growing sugarcane seedlings in a K^+ depleted nutrient solution for a 3 1/2-month period reduced the roots' capacity to absorb NO_3^- (Subasinghe, 2006). On the other hand, growing sugarcane seedling in an N depleted nutrient solution reduced the initial K^+

Research Findings

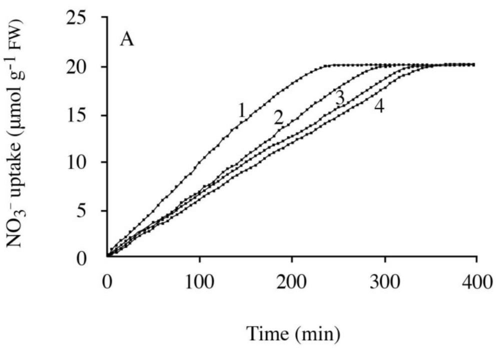

Fig. 6. The time course of NO$_3^-$ uptake by maize seedlings from solutions, containing Ca^{2+} K$^+$ (1); Ca^{2+}Mg^{2+} (2); Ca^{2+} Na$^+$ (3); Ca^{2+} (4) as accompanying cations.

Adapted from (and redrawn): Ivasshikina & Feyziev, 1998; Plant Science 131:25-34.

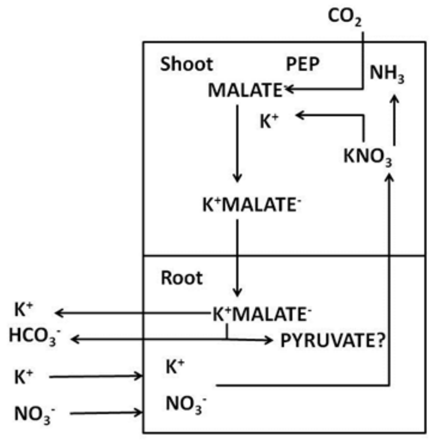

Fig. 7. NO$_3^-$ uptake by roots as regulated by NO$_3^-$ reduction products of the shoot and K$^+$ cycling in plant.

Adapted from (and redrawn): Ben Zioni *et al.*, 1971; Physiolgia Plantarum 24:288-290.

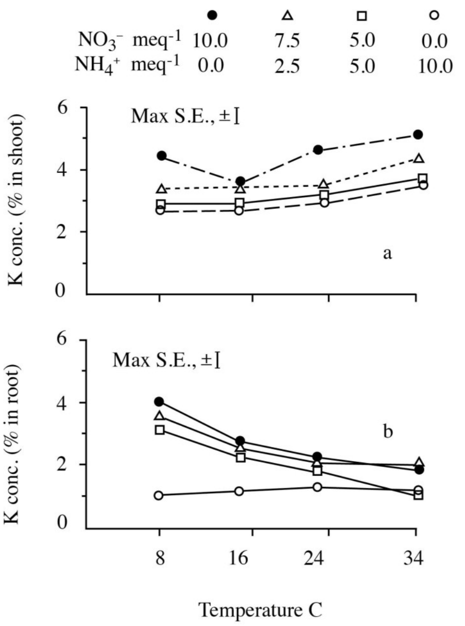

Fig. 8. Nutrient solution temperature and percentage NO$_3^-$/NH$_4^+$ effect on percent K in the tomato plants. a. shoot; b. root.

Adapted from (and redrawn): Ganmore-Neumann and Kafkafi, 1980; Agronomy Journal 72:762-766.

uptake rates and decreased the affinity of roots for K$^+$.

The potassium ion is easily mobilized in the whole plant because it is not assimilated in organic compounds. Like other cations, it is transported from the root system upward to the canopy via the xylem, but it also has the property of high phloem mobility and, as a result, a high degree of re-translocation via the phloem (Marschner, 1995). K uptake and re-translocation play an important role in NO$_3^-$ transport from roots to shoots as a counter ion and assimilate loading in the phloem (Maathuis, 2007). A conceptual model of K circulation and NO$_3^-$ uptake was suggested by Ben Zioni *et al.* (1971). According to this model, NO$_3^-$ is absorbed by roots and transported via the xylem to the shoots with K$^+$ as the counter ion. In the shoot, NO$_3^-$ is reduced and assimilated into organic compounds, whereas K$^+$ is transported downward to the roots with malate via the phloem (Fig. 7). Then the root takes up more NO$_3^-$ and exudes HCO$_3^-$ to maintain electro-neutrality or takes up more K$^+$, according to the external and internal K concentrations and the N form. The rate of uptake and partitioning of K in plants can be modified depending on the N forms supplied. NH$_4^+$-N as the sole N source caused a decrease in potassium uptake relative to the NO$_3^-$-N supply in tobacco (Lu *et al.*, 2005) and (Ganmore-Neumann and Kafkafi, 1980) tomato plants. In tobacco plants, using NH$_4^+$ as the sole N source resulted in more K translocated to leaves than NO$_3^-$ in terms of the amounts of xylem-transported K (Lu *et al.*, 2005). In contrast, Ganmore-Neumann and Kafkafi (1980) reported that increasing the NO$_3^-$/NH$_4^+$ ratio in the solution resulted in higher K concentrations both in roots and leaves of tomato plants (Fig. 8), in agreement with 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.*, 1990). Ganmore-Neumann and Kafkafi (1980) showed that temperature elevation from 8 to 34°C resulted in a gradual decrease and increase of K content in roots and shoots, respectively, due to enhanced transport from increased temperatures (Fig. 8). Engels and Kirkby (2001) reported that cycling and recycling of K^+ increased with increasing shoot growth rate, which is in accordance with the suggested model by Ben Zioni *et al.* (1971). Cytosolic K^+ concentrations vary between 40 and 200 mM, depending on K^+ supply and nitrogen form (NO_3^- or NH_4^+) demonstrating the strong impact of N form on potassium dynamics in plants (Szczerba *et al.*, 2006).

Effects on whole plant, crop yield and quality

The nitrogen form is an important factor for plant development and yield. Increasing the N-NH_4^+:N-NO_3^- ratio in the N fertilizer reduced the uptake of K^+ and other mineral cations, but increased the uptake of mineral anions by tomato (Kirkby and Mengel, 1967; Ganmore-Neumann and Kafkafi, 1980) and other crops as has been reported in numerous publications. Bar-Tal *et al.* (2001b) demonstrated that the uptake of Ca^{+2} and K^+ increased quadratically as the N-NO_3^-:N-NH_4^+ ratio increased, throughout the studied range of 0.25 to 4.0 (Fig. 9).

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, while simultaneously lowering leaf nitrate reductase activity (NRA). 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). K^+ activates plant enzymes functioning in NH_4^+ assimilation and transport of amino acids (Hagin *et al.*, 1990). Therefore, an adequate supply of K^+ enhances NH_4^+ utilization and thus improves yield when both N forms are applied together. Potassium has been shown to strongly stimulate carboxylic acid accumulation in fruits (Erner *et al.*, 1993). This is because the high rate of K^+ uptake increases the cation-anion balance in the plant tissue and, in order to maintain electro-neutrality, carboxylates are synthesized (Marschner, 1995). NO_3^- uptake also stimulates carboxylation in plant tissue in order to remove hydroxyls produced in the NO_3^- reduction process and to balance the excess accumulation of cations over anions (Marschner, 1995). Thus, both K^+ and NO_3^- have similar effects on organic acids production in plants leaves and fruits (Serna *et al.*, 1996).

The NH_4^+:NO_3^- ratio is an important N-management tool, particularly in soil-less culture (Silber and Bar-Tal, 2010) and in soil under fertigation (Bar-Yosef, 1999). For a given N dose and irrigation regime, the N-NO_3^-:N-NH_4^+ ratio affects Ca, Mg, and K uptake (Bar-Tal *et al.*, 2001a, b; Kirkby and Mengel, 1967; Neilsen *et al.*, 1995), and carboxylic acid biosynthesis (Kirkby and Mengel, 1967; Mengel and Kirkby, 2001). However, in a recent experiment investigating the effect of N source on grapefruit, no effect on fruit quality and acid concentration in the fruit was found (Erner *et al.*, 2011, submitted). A possible explanation for this result is: in soil grown plants, two confounding effects of NH_4^+ take part, on the one hand a higher NH_4^+ concentration increases K^+ concentration in the soil solution (Fig. 4) and on the other hand the competition between NH_4^+ and K^+ on root uptake reduced the uptake of K^+ by the trees.

Conclusions

The N form and K application modes have short and long-term effects on potassium availability in soil through exchange and fixation reactions, respectively.

N form effects K^+ absorption by plants through several mechanisms: NH_4^+ and K^+ competition, long distance transport of K^+ - NO_3^-, specific effects of N metabolism on K uptake and vice-versa.

The overall interactions of N form and K^+ application on whole plant response and crop yield are a product of the above described effects.

Proper K^+ application can improve N fertilizing efficiency, increase yield and reduce environmental pollution.

Further studies on the mechanisms of K^+ and NH_4^+ fixation in soil clay minerals are required for better understanding of long-term effects on their availability to plants.

Further studies on the interactions of K^+, NH_4^+ and NO_3^- at the molecular and whole plant levels are required for improving N and K fertilization.

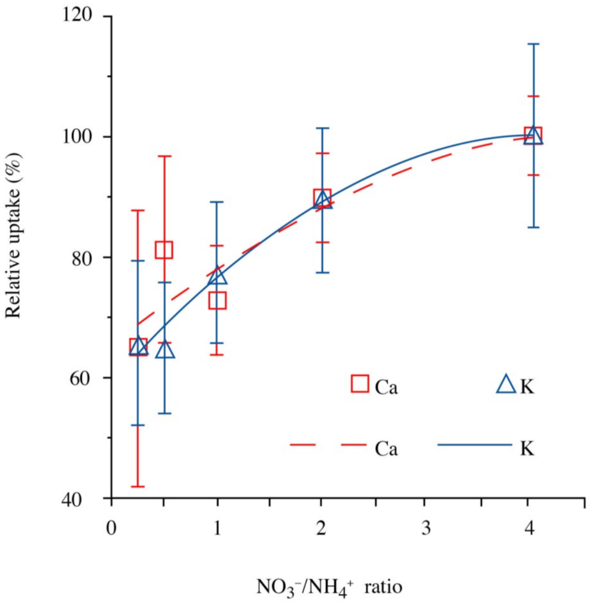

Fig. 9. The Effect of the mineral N form on K and Ca uptake by pepper plant.

Adapted from (and redrawn): Bar-Tal *et al.*, 2001. *HortScience* 36:1252-1259.

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Regional Activities/India **and**

N-K Interaction Center

Research Findings

Physiological and Molecular Responses of Rice to N, P, K and Mg Deficiencies

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Abstract

Nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg) constitute the most important nutrient elements of plant cells. Their physiological functions have been intensively investigated in the past. However, interactions between these nutrients are not fully understood and the underlying processes are largely unclear at the molecular level. In this study, we detected both physiological and molecular responses of rice (*Oryza sativa* L. ssp. *Japonica* cv. *Nipponbare*) to N, P, K and Mg starvation. Deficiencies of these nutrients, particularly N and P, resulted in the accumulation of soluble sugar and starch in the leaves. The root to shoot biomass ratio was increased by N and P deficiencies, but decreased by K and Mg deficiencies. In addition, our data showed that deficiency of either K or Mg induced the accumulation of the other. Moreover, K starvation markedly decreased both K and soluble sugar concentrations in the roots. Reverse transcription polymerase chain reaction (RT-PCR) analysis showed that expression of two sugar transporter (*SUT)* genes in the leaves was orchestrated with the sugar accumulation induced by the nutrient shortages. Expression of a putative high affinity K transporter gene (*OsHAK1*) and a putative Mg transporter gene (*OsMGT*) showed opposite up- or down-regulation by K and Mg supply status. These findings suggest that deficiencies of the major nutrients suppressed the export of carbohydrates from source leaves, and that the regulated sugar and nutrient transporter genes detected in this study could be used to elucidate the molecular mechanism of plants in their adaption to varied nutrient supply.

Introduction

Nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg) constitute the most important nutrient elements in plant cells. Their physiological functions have been intensively investigated in the past (Hermans *et al.*, 2006; Maathuis, 2009). At the cellular level, N is the main nutrient constituent of protein which makes up a high percentage of the plant organic material. Compared with N, a much lower percentage of P is present in the cellular composition. However, P plays a predominant role in genetic materials such as DNA and RNA. Moreover, it is also essential in energy metabolism and in regulating cellular activity (Maathuis, 2009).

In contrast to N and P, K is not an integral constituent of any plant metabolite and is present as a cation, making up the highest cation concentration in the plant cell (Karley and White, 2009; 2010). Besides its action as an osmoticum, K functions in phloem loading of sucrose, facilitates photosynthesis and sustains water content (Karley and White, 2010). Plants suffering from deficiency of K are vulnerable to biotic stress such as disease infection or abiotic stress including mechanical pressure, and fruit quality is reduced (Tuncay *et al.*, 1999). Mg is another macro element which is essential for photosynthesis in the chloroplast. In addition, it functions as an activator of many enzymes during chemical reactions in the cell (Berkowitz and Wu, 1993).

Previous research has demonstrated that plants utilize different strategies in response to deficiencies of the various nutrients. Lee (1982; 1993) showed that uptake of N, P or S in barley is dependant on plant nutrient status, with efflux playing only a minor part in the regulation of nutrient uptake. In 1994, Cakmak *et al.* reported differences in partitioning of dry mass and carbohydrate between shoot and root in beans suffering from P, K, Mg deficiencies. In the model plant *Arabidopsis*, translocation of carbohydrate and sugar differed between plants deprived of N, P, K and Mg (Hermans *et al.*, 2006). Under N deficiency, carbohydrates were accumulated in shoots, whereas root systems expanded to increase their potential for nutrient acquisition. Starvation of P resulted in similar changes in *Arabidopsis*. By contrast, deficiency of K did not increase plant root systems, and carbohydrate was accumulated in the shoot to a much lesser degree than that under N and P deficiencies (Hermans *et al.*, 2006).

In addition to these physiological adaptations, a micro-array analysis by Hermans *et al.* showed that related categories of gene are over-represented or down-regulated in the processes. For example, photosynthesis and sucrose synthesis related genes change their expression when plants become P-deficient (Hermans *et al.*, 2006). Sucrose is usually the main form in which carbohydrate is moved in long distance transport in plants (Hayashi and Chino, 1990). It also acts as a signal to control gene expression and plant development (Li *et al.*, 2003; Gibson, 2005). Increasing data from tomato, *Arabidopsis* and *Plantago major* demonstrate that SUT/C genes play pivotal roles in sucrose transport (Stadler *et al.*, 1995; Barker *et al.*, 2000; Matsukura *et al.*, 2000; Barth *et al.*, 2003; Carpaneto *et al.*, 2010). In rice, five SUC transporter genes have been cloned, and these genes show different expression profiles in embryo, pollen, and tonoplast (Matsukura *et al.*, 2000; Hirose *et al.*, 2010; Sun *et al.*, 2010; Eom *et al.*, 2011). Whether these genes are involved in translocation of sugar in

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plants under nutrient starvation is an intriguing question. There is some support for the idea in that several lines of evidence have shown that expressions of high-affinity K transporters can be enhanced under K deficiency (Okada *et al.*, 2008; Qi *et al.*, 2008; Horie *et al.*, 2010). It is not clear, however, whether monocot plants, e.g. rice, respond to the starvation of different nutrients in a similar way to *Arabidopsis* and which changes in gene expression accompany the physiological changes taking place in the plants.

In *Arabidopsis*, two gene families might relate to Mg uptake, one is *AtMGT*s, a group of 10 family members that complement the mutant of the Mg transporter in yeast or bacterium (Li *et al.*, 2001). The other is *AtMHX*, which encodes a protein located on the tonoplast and acts as an antiporter of H^+ and Mg^{2+} (Galili, 1999; Shaul *et al.*,1999). By a similarity search in the rice database with amino acids of AtMHX and AtMGT as the queries, we retrieved their homologs, OsMGT and OsMHX, respectively. However, little is known about the functions of OsMGT and OsMHX.

In this study, we investigated physiological changes of rice grown hydroponically, deprived of different nutrients with the aim of identifying the interaction between nutritional status and related gene expression, to increase our understanding of plant mineral nutrition.

Materials and methods

Growth conditions

Rice (*Oryza sativa* L. *ssp japonica*) seeds were sterilized in 10% H_2O_2 for 30 mins, then subsequently washed five times before being immersed in deionized water in the dark for 24 hours. The seeds were transferred into plastic trays to germinate in a growth cabinet, with a light/dark cycle of 14 h/10 h and a day/night temperature regime of 32°C/22°C. After 15 days the seedlings were transplanted into 3-L plastic boxes and cultivated gradually from 1/4, 1/2, to full strength nutrient solutions (modified based on the protocol of International Rice Research Institute) (Yoshida *et al.*, 1976). The seedlings were cultivated for one month before the P, K and Mg starvation treatments were introduced, while the seedlings for the N deficiency were grown in the full strength nutrient solution for one more week before beginning the treatment. Under the different nutrient starvation treatments, $NaNO_3$, $KHPO_4$, KCl and $MgSO_4$ were replaced by equivalent molar concentrations of NaCl, KCl, and $CaSO_4$ for four weeks (three weeks for the N treatment). Plant samples for RNA extraction were stored at -70°C immediately after harvest.

Measurements of plant samples

Plant samples were harvested after four weeks (three weeks for the N treatment) of the nutrient starvation treatment. Roots were washed with de-ionized water three times to remove adhering nutrients, followed by desiccation in a forced-air oven at 70°C for about 48 h to a constant weight. The dried samples were ground into powder. About 0.05 g of dried powder was digested by 5 ml of 98% H_2SO_4 and 1 ml of 30% H_2O_2 at 270°C. After cooling, the digested sample was diluted to 100 ml with distilled water. The P, K, Mg concentrations were determined by an ICP-emission spectrometer (Perkin Elmer Optima 2100DV), N concentration was determined by colorimetric continuous flow analysis (AutoAnalyser 3, Bran+Luebbe, Germany) as described by Ding *et al.* (2006).

Soluble sugar and starch concentration

The measurement of starch and soluble sugar concentration of shoot and root was based on the method of Hansen and Møller (1975), as described in detail by Ding *et al.* (2006).

To visualize the distribution of starch in rice plants, iodine staining of whole plants was perfomed. After nutrient starvation treatments, the rice samples were immersed in 70% ethanol and incubated overnight at 70°C to remove chlorophyll. Afterwards, they were stained in iodine solution (0.5% KI+0.1% I_2) for five hours before observation.

Determination of active root surface area

Root activity can be evaluated by determination of active root surface area and percentage of the active root surface area of the total root surface area. Active root surface is the root surface capable of assimilating the ions from the outside of the plasma membrane into the cytosol. In this study, active root surface area was determined based on Zhang's methods (1994) by use of the dye Methylene Blue ($C_{16}H_{18}N_3SCl{\bullet}3H_2O$) which is adsorbed to the surface of roots. The principle of the method is that by treating the roots with a given amount of methylene blue then determining how much of it remains in solution after the treatment, the dye adsorbed by the roots was worked out and the active root surface area was calculated according to the adsorbed dye mass. The rice roots were immersed in three beakers in sequence, each beaker containing 10 ml 2 mM Methylene Blue solution. The time in each beaker was 1.5 min. Afterwards, 1 ml solution from each beaker was extracted and diluted to 10 ml. Absorbance at 660 nm (A_{660}) of the diluted solutions were determined by a universal Microplate spectrometer (SpectraMax M5). The mass of Methylene Blue adsorbed by the roots was calculated according to a standard curve on the base of the A_{600} of a series of Methylene Blue solutions with different concentrations. Three replicates were conducted for each treatment of the nutrient starved plants.

Research Findings

Expression of sugar, Mg and K transporter genes

Total RNAs of roots and leaves were extracted from a mixture of three separate groups of plants in each treatment by use of the Trizol reagent (Invitrogen). DNAse I (TaKaRa) was applied to remove residue genomic DNA in the total RNA. First-strand cDNA was synthesized with 5 µg total RNA as templates. To detect sugar transporter gene expression under the different nutrient starvation regimes, forward and reverse gene specific primers of the rice SUT family members (listed in Table 1) were synthesized according to their sequence on genebank (Os03g07480; Os12g44380; Os10g26470; Os02g 58080; Os02g36700, equal to SUT1-5, respectively). RT-PCR was performed in parallel with the samples under normal nutrient conditions as a control in triplicate. A housekeeping gene, Actin (*OsRac1*, accession number AB047313) was amplified in parallel as their internal control. The PCR primers were used to amplify putative Mg transporter genes *OsMHX* (Os11G43860), *OsMGT* (Os06g44150) and a high affinity K transporter gene *OsHAK1* (Os04G32920) as listed in Table 1.

Results

Different effects of N, P and K, Mg starvation on root to shoot biomass ratio and active root surface

Removal of N for three weeks and P, K and Mg for four weeks from the culture solution decreased biomass production and changed root morphology in comparison to adequate nutrient supply (Fig. 1). Shoot growth was decreased much more significantly by deficiency of N and P than by deficiency of K and Mg (Fig. 1; Fig. 2). However, there was only a small difference of total root biomass among the four treatments (Fig. 2). The root to shoot biomass ratio expressed on a fresh weight basis was increased by N and P starvation, but decreased by K and Mg starvation (Fig. 2).

Deficiencies of N, P, and K resulted in a decrease of the percentage (%) of active root surface (Fig. 3), representing an impairment of root activity. However, active root surface of the plants was larger under N and Mg deficiencies but smaller under P and K deficiencies in comparison with plants receiving adequate nutrient supply (Fig. 3). It is interesting to note that deficiency of Mg did not change the percentage of active root surface, although it increased the total active root surface of rice (Fig. 3).

Table 1. Primer pairs for amplification of sucrose transporters, Mg transporters *OsMGT, OsMHX* and K transporter *OsHAK1*, respectively.

Gene	Sequence
	Sucroze transporters
OsSUT1	F：CAGCCCTCCCAACAAAATCAA
	R：CGAGAACTACAAAGCTCACCA
OsSUT2	F：TTCCTCGCCGACCTCACCGAG
	R：CACCAGCCCACCGATAAAAGA
OsSUT3	F：TCTGTTCTTGGATGGCATTAGG
	R：GCACGACGATGGAGATGTTGA
OsSUT4	F：TTGGCTTTGTGGACCTATT
	R：GTCCCATCCAGTCAGTATCAA
	Mg transporters
OsMGT	F：TCACCCACAGAATCACGG
	R：TCAACAGCGTAGACGACAAT
OsMHX	F：TGGCAGATACTGTTCCTT
	R：CCTCCCATTTGTTCTTTA
	K transporters
OsHAK1	F：TCTACACCCTCATCATCATCCC
	R：TACACCTGCCCCTCGTACTTCT

Accumulation of carbohydrates in the nutrient deficit shoot and shortage of soluble sugar in the K starved roots

Deficiency of the four major nutrients resulted in a noticeable increase of soluble sugar in the shoot, particularly under N and P starvation conditions (Fig. 4). The soluble sugar in rice roots was increased slightly by N deficiency, but seems not to be affected by P and Mg deficiency (Fig. 4). In contrast, there was only very low soluble sugar in the K starved roots, representing the distinct impairment of sugar translocation from shoot source to the root sink (Fig. 4).

A similar trend of increases of starch concentration as that for soluble sugar in the shoot of rice was observed for the four nutrient deficiency treatments (Fig. 1; Fig. 4). The starch accumulation in the P deficient shoot was the largest among the four treatments. The difference of starch concentration in the roots between the four treatments was much less significant than that in the shoot (Fig. 4).

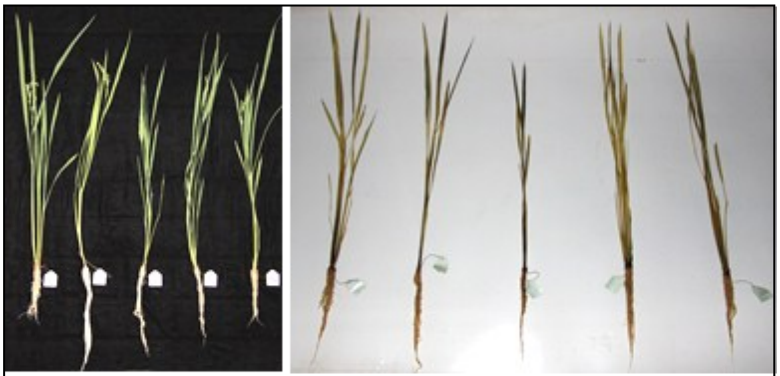

Fig. 1. Morphological comparison of rice plants grown in a complete nutrient solution or different nutrient-deficient solutions for three or four weeks. Period of N-deficiency treatment was three weeks; for P-, K- and Mg- deficiency four weeks. In the right panel, plants were stained with iodine solution (0.5% KI+0.1% I_2) for five hours to visualize starch accumulation. Before iodine solution staining, plants were incubated in 70% ethanol overnight to remove chlorophyll. From left to right: Control; -N; -P; -K; -Mg, respectively.

Research Findings

Interactive effects of N, P, K and Mg deficiency on their concentrations in rice

As expected, temporary removal of N, P, K and Mg supply in the culture solution decreased their concentrations respectively (expressed on a dry weight basis) both in the roots and shoots (Fig. 5). Total P concentration in the shoot was also decreased by lack of N, K and Mg supply (Fig. 5). The largest variation of K concentration occurred in the roots. Interestingly, under K starvation conditions, the K concentration in the shoot was much higher than in the roots, which showed very low concentrations of K implying rapid transfer of any K acquired from the outer medium from root to shoot (Fig. 5).

In comparison to Mg sufficient plants, removal of Mg supply resulted in lower K in the roots and higher K in the shoots, representing enhanced K transport from the roots to shoots (Fig. 5), similar to the effects of K starvation.

Notably, when rice plants grew under K starvation for four weeks, their Mg concentration increased markedly in the shoots but not significantly in the roots, compared with that of the control and N and P starvation treatments (Fig. 5). Likewise, plants under Mg starvation had a much higher K concentration than the plants deprived of N and P. The same was also true in comparison to the control. The data demonstrated a strong complementary relationship between K and Mg in plants. That is to say, deficiency of K enhanced uptake of Mg, and deficiency of Mg enhanced the uptake of K. In addition, K significantly inhibited Mg uptake in rice.

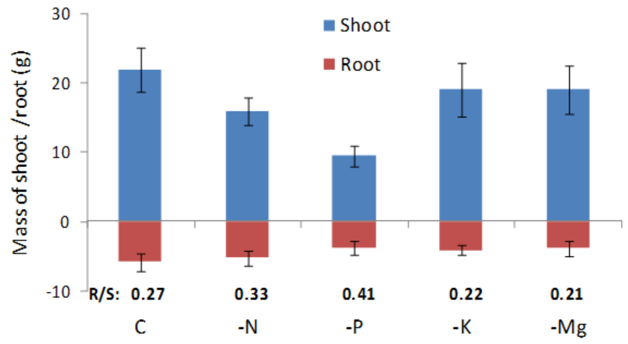

Fig. 2. Root and shoot biomass (fresh weight) and root to shoot biomass ratios of rice plants grown in a complete nutrient solution or in nutrient solutions deficient in N for three weeks or deficient in P, K and Mg for four weeks, respectively. Columns are means (±SD) of mass determined from four replicates.

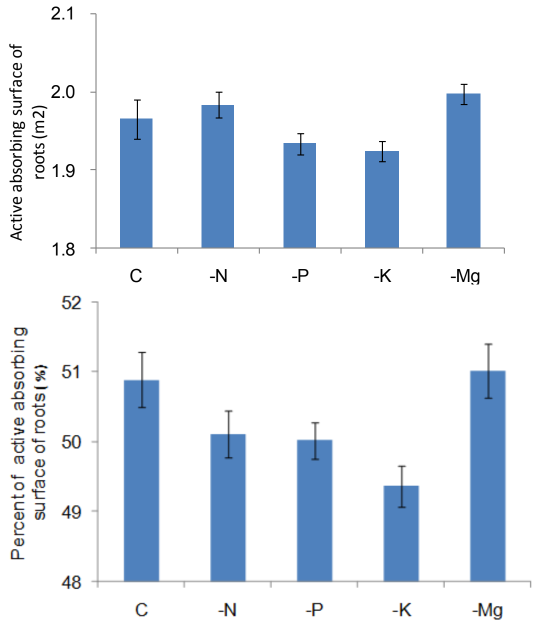

Fig. 3. Active root surface area (m^2) and percentage of active root surface area of rice plants grown in a complete nutrient solution or nutrient-deficient solutions for three weeks (N-deficiency) or four weeks (P-, K-, Mg-deficiencies), respectively. Columns are means (±SD) of active root surface or percentage of active root surface determined from four replicates.

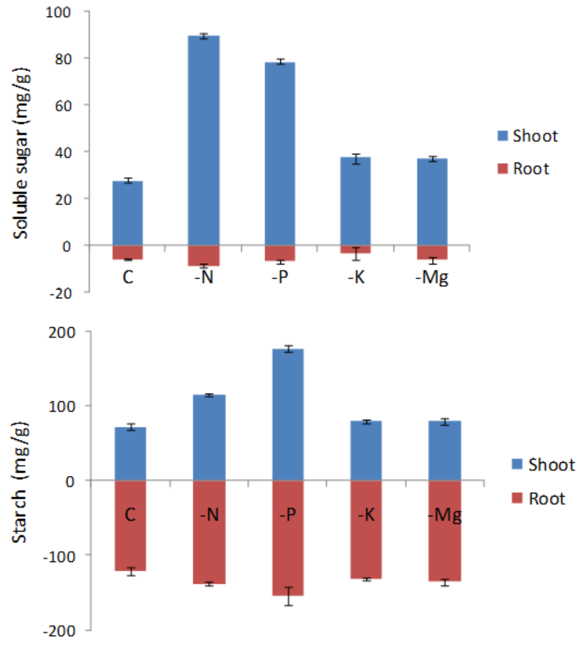

Fig. 4. Soluble sugar and starch concentrations in shoots and roots of rice plants (expressed on a dry weight basis) after growth in a complete nutrient solution or a nutrient solution deficient in N for three weeks, or deficient in P, K or Mg for four weeks, respectively. A: Soluble sugar; B: Starch. Columns are means (±SD) of soluble sugar or starch concentrations determined from four replicates.

Research Findings

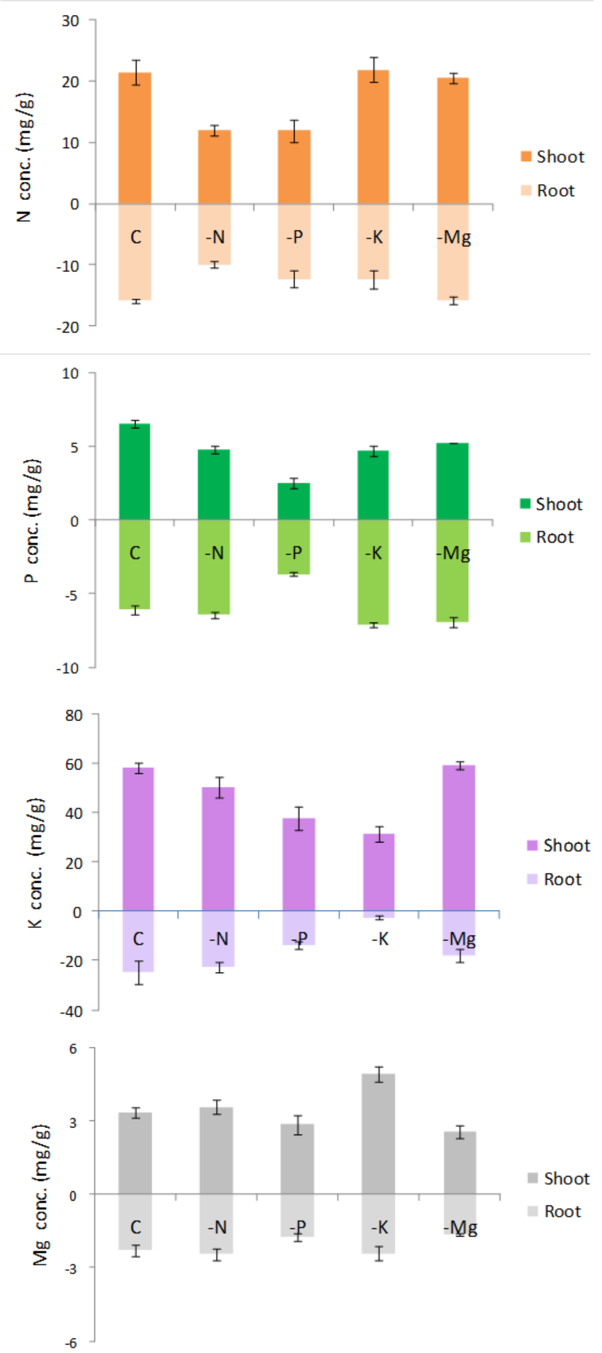

Fig. 5. N, P, K, Mg concentrations of rice plants (expressed on a dry weight basis) after growth in a complete nutrient solution or nutrient-deficient solutions for three weeks (N deficiency) or four weeks (for P-, K-, Mg- deficiencies). Columns are means (±SD) of ion concentrations determined by ICP-emission spectrometer (Perkin Elmer Optima 2100DV) from four replicates. N concentration was determined by colorimetric continuous flow analysis (AutoAnalyser 3, Brank Luebbe, Germany).

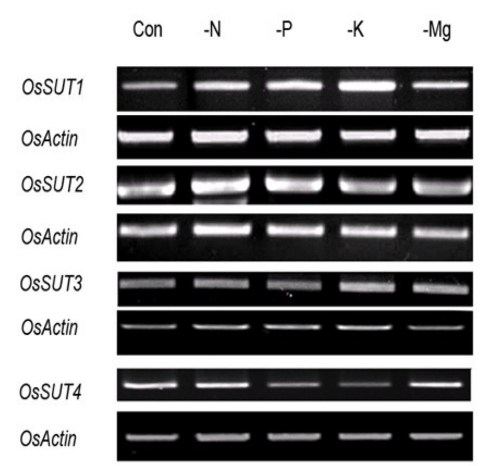

Fig. 6. Rice SUT genes expression detected by RT-PCR for a complete nutrient solution or deprived of different nutrients for three days. RT-PCR was performed in triplicate with a housekeeping gene, Actin (*OsRac1*, accession number AB047313) in parallel as their internal control.

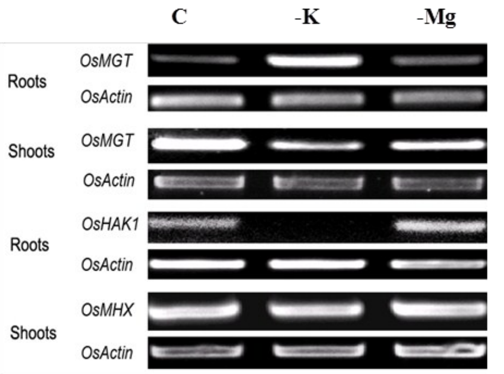

Fig. 7. Several rice K^+ and Mg^{2+} transporter genes expression detected by RT-PCR under complete nutrient solution or deprived of K^+or Mg^{2+} for three days. RT-PCR was performed in triplicate with a housekeeping gene, *Actin* (*OsRac1*, accession number AB047313) in parallel as their internal control.

Research Findings

Effects of N, P, K and Mg starvation on expression of sugar transporter (SUT) genes in shoots

In order to test if the sugar accumulation in the nutrient starved leaves was related to inhibition of sugar export to the root sinks, five sugar transporter genes were examined for their expression in rice leaves by RT-PCR. Interestingly, the expression of *OsSUT1* was up-regulated in the nutrient deficient leaves, particularly under K starvation (Fig. 6). In contrast, the transcripts of *OsSUT4* were decreased under deficiencies of P and K (Fig. 6). *OsSUT2* and *OsSUT3* were not apparently regulated by nutrient supply status. Expression of *OsSUT5* was not detected in our experimental conditions.

K and Mg starvation regulated putative K and Mg transporter genes expression

Since a strong interaction of K and Mg was shown by physiological data, we analyzed transcriptional expression of a putative high affinity K transporter gene (*OsHAK1*) and two putative Mg transporter genes (*OsMGT* and *OsMHX*). Very noticeably, *OsHAK1* expression was suppressed by K deficiency and up-regulated by Mg deficiency in the roots (Fig. 7). In contrast, *OsMGT* expression was up-regulated in the roots and down-regulated in the shoots by shortage of K supply (Fig. 7). Its expression was not apparently regulated by Mg supply status. No difference of *OsMHX* expression was observed under different K and Mg treatments (Fig. 7).

Discussion

Plants have developed various strategies to deal with different nutrient deficiencies, which are frequently encountered as environmental stresses. Using hydroponic cultivation, we investigated the response of rice to starvation of different nutrients. The consistency in carbohydrate partitioning and root to shoot ratio between rice and *Arabidopsis* suggests that dicots and monocots are comparable in their responses to different nutrient deficiencies. In addition, interaction revealed by physiological data between these nutrients and underlying genes expression provides new information to understand activities *in planta* during nutrient deficiencies.

In our experiment, soluble sugar and starch accumulated markedly in rice shoots under P and N deficiency (Fig. 4). By contrast, much lower amounts of these compounds were accumulated under K^+ and Mg^{2+} deficiency (Fig. 4), and their root to shoot biomass ratios decreased only slightly compared with the control (Fig. 2). These findings are consistent with the conclusions drawn by Hermans *et al.* (2006) from experiments with *Arabidopsis*. The photosynthetic rate of rice decreased notably under N and P deficiencies while it was affected only slightly under K^+ and Mg^{2+} deficiencies (Fig 8). According to Hermans *et al.* (2006), the arrest of photo-synthesis under N and P deficiencies is due to accumulation of carbohydrates in the shoot.

In *Arabidopsis*, a Ca^{2+} signaling pathway has been shown to regulate a K^+ channel for low-K response (Li *et al.*, 2006), implying an interaction between different cations in plants. Interestingly, Mg^{2+} concentration increased under K^+ starvation and *vice versa* (Fig. 5). This shows a complementary relation-ship between K^+ and Mg^{2+} concentrations in plants which confirmed our previous research (Ding *et al.*, 2006). A plausible explanation is that K^+ and Mg^{2+} are the most abundant uni-/divalent cations that have a

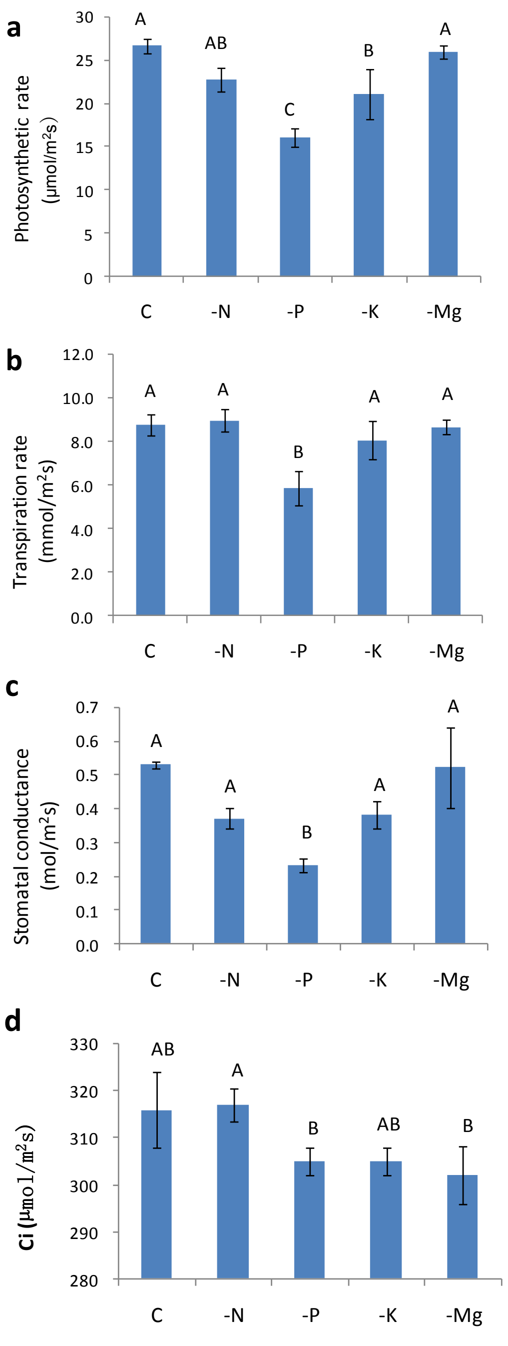

Fig. 8. Photosynthetic parameters including photosynthetic rate (a), transpiration rate (b), stomatal conductance (c), and intercellular CO_2 concentration (Ci) of rice plants (d). Rice plants were measured with a portable infrared gas exchange system (Li-6400) according to the manufacturer's instruction. The measurements were performed between 10 and 11 am in rice plants grown in nutrient deficient solutions for three weeks (for -N treatment) or four weeks (for control and -P, -K, -Mg treatments). The measurements were made in three repeated experiments. Different letters in large case in the figure indicated statistical differences among means by Duncan's multiple range test ($p \leq 0.01$).

pivotal role in sustaining ion homeostasis of the cell (Li *et al.*, 2001). Therefore, deficiency of one ion will induce accumulation of the other. Consistent with this assumption, our RT-PCR results showed that under Mg starvation, *OsHAK1* expression in roots was up-regulated notably. Likewise, under K starvation, expression of *OsMGT* in rice roots was up-regulated slightly (Fig. 7). These facts suggest that *OsHAK1* and *OsMGT* may be important for the interaction of Mg and K *in planta*.

Notably, under K^+ starvation of rice, K^+ concentration in the root was extremely low compared with the concentration of K^+ in the shoot (Fig. 5). This difference implies that the translocation efficiency from root to shoot is very high during K^+ starvation. Since *OsHAK1* decreased its expression in roots under K^+ starvation as compared with the control growing in a complete nutrient condition, it means that other transporter(s) may be involved in this process. Moreover, *OsHAK1* has previously been identified to increase its expression markedly in the roots of rice seedlings under K^+ starvation or Na^+ stress (Okada *et al.*, 2008; Horie *et al.*, 2010), whereas in our experiment, its expression decreased in six-week rice plants under K^+ starvation. This finding implies that the expression of this gene is differently regulated during the plant developmental stages.

It has long been established that loading of sucrose into the phloem of plants needs K^+ (Doman and Geiger, 1979). Increasing data show that SUT family members have an important function in long distance transport of sucrose (Stadler *et al.*, 1995; Matsukura *et al.*, 2000; Scofield *et al.*, 2007; Sun *et al.*, 2010). It has been suggested that OsSUT1 is a potential sucrose transporter in phloem loading (Hirose *et al.*, 1997; Matsukura *et al.*, 2000; Scofield *et al.*, 2007). Our data showed that expression of *OsSUT1* in shoot was up-regulated significantly under K^+ starvation. In accordance with the increase, soluble sugar concentration in the K^+-deficient rice was lower compared with that of the N and P-deficient plants. It should be noted that *OsSUT1* also increased its expression level slightly under N and P deficiencies. However, soluble sugar and starch concentration remained very high in the shoot of these plants which suggests that other regulators may participate in the process.

OsSUT4 is identified to be preferentially expressed in sink leaves (Aoki *et al.*, 2003). Decrease of *OsSUT4* expression by P and K starvation (Fig. 7) suggests that its down-regulation might be tuned to adapt to the situation since its substrate, sugar, was accumulated in source leaves.

In conclusion, we showed that rice, a monocot, gave a similar response to nutrient deficiencies as that of the dicot *Arabidopsis*, which suggests that higher plants adopt analogous means of dealing with nutrient deficiencies. Moreover, our physiological data revealed clearly that K^+ and Mg^{2+} interacted with each other during deficiency, and that K^+ was unique in partitioning between root and shoot during K^+ starvation. Detected expression regulation of both sugar transporter and K and Mg transporter genes under these nutrient deficiencies further support these physiological findings and facilitate understanding of activity of plants at the molecular level.

Acknowledgement

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The paper "Physiological and Molecular Responses of Rice to N, P, K and Mg Deficiencies" appears also at:

Regional Activities/China

Role of Potassium Nutrition in Nitrogen Use Efficiency in Cereals

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Abstract

Consumption of fertilizer nitrogen (N) is increasing quantitatively, but the corresponding yield increase per unit of N (N use efficiency, NUE) is substantially diminishing over the years. Improving NUE is of paramount importance both from an economic as well as an environmental point of view. Among several strategies to improve NUE, balanced nutrition, particularly balancing N and potassium (K) nutrition and tapping into the synergistic effect of N and K, is recently gaining importance. The efficiency of fertilizer N is only 30-40% in rice and 50-60% in other cereals. There are several reports indicating the positive effects of N and K interaction in terms of crop productivity and economics, but the balance of N and K application is not appropriately practiced in many parts of the world. Positive interaction of N and K has been reported in many rainfed cereals like sorghum, pearl millet, finger millet, maize, and minor millets. In a study based on 241 site-years of experiments in China, India, and North America, balanced fertilization with N, phosphorus (P), and K increased first-year recoveries by an average of 54% compared to recoveries of only 21% where N was applied alone. In several sorghum cultivars grown in Savannah regions, improved N content and N use efficiency with K application has been reported. It has also been demonstrated that with the application of PK, the agronomic efficiency of N (AE_N) improved substantially (6.7 kg grain/kg N) in sorghum and (10.3 kg grain/kg N) in pearl millet. Balanced fertilization improved both AE_N as well as partial factor productivity of fertilizer N at on-farm locations.

Introduction

Inadequate application of potassium (K) combined with over application of nitrogen (N) is a serious problem in modern intensive agricultural production systems. It leads to large N losses, environmental pollution and low nitrogen use efficiency (NUE). Although fertilizer consumption is increasing quantitatively, the corresponding yield increase per unit of nutrient has diminished over the years (Sharma and Sharma, 2011; Benbi and Brar, 2011). The response ratio (kg grain/kg nutrient) in food grain crops in irrigated areas in India (Fig. 1) substantially declined between 1960 and 2008 (Biswas and Sharma, 2008a). The need to improve NUE is therefore of paramount importance both for economical as well as environmental reasons.

K application has been neglected in many developing countries, including India, which has resulted in soil K depletion in agricultural ecosystems and a decline in crop yields (Regmi *et al.,* 2002; Panaullah *et al.*, 2006; Ladha *et al.*, 2003; Wang *et al.*, 2007b; Lal *et al.*, 2007). Higher yields and crop quality can be obtained at optimal N:K nutritional ratios. K is an essential macronutrient required for proper development of plants. In addition to activation of numerous enzymes, K plays an important role in the maintenance of electrical potential gradients across cell membranes and the generation of turgor. It is also essential for photosynthesis, protein synthesis, and regulation of stomatal movement, and is the major cation in the maintenance of cation-anion balances (Marschner, 1995).

N is probably the major agronomic stimulant to crop growth within the farmer's armoury. But to exploit its maximum use efficiently for increasing crop production, the crop must have access to, and take up, an adequate amount of K from the plant-available (exchangeable K) pool of K in the soil. This is because there is a strong interaction between these two nutrients in crop growth. Crop response to applied fertilizer N decreases when the exchangeable K content of a soil is below a critical target level. Because of this interaction, there is little point in applying large amounts of N when soil is low in available K, because N is used inefficiently and causes financial losses to the grower. There is also the risk that any excess unused fertilizer N lost from the soil will have adverse effects on the environment.

Among several strategies to improve NUE, balanced nutrition, particularly balancing N and K nutrition and tapping into the synergistic effect between N and K, is important both in irrigated as well as rainfed production systems

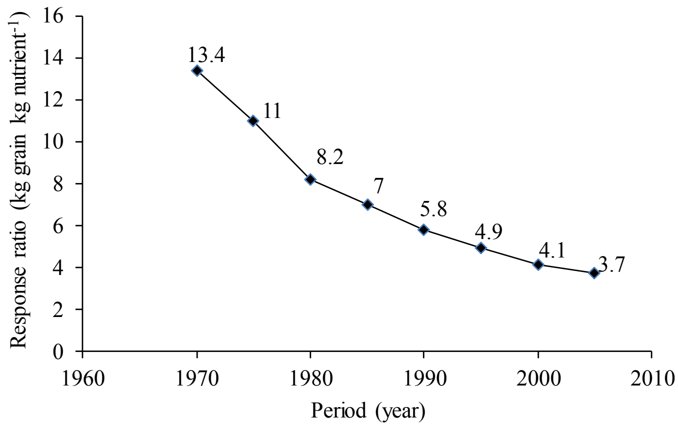

Fig. 1. Fertiliser response of food grain crops in irrigated areas in India.

Source: Biswas and Sharma, 2008a.

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(Ganeshamurthy and Srinivasarao, 2001). NUE depends on several agronomic factors including tillage, time of sowing, appropriate crop variety, proper planting or seeding, sufficient irrigation, weed control, pest/disease management, and balanced and proper nutrient use (Srinivasarao, 2010). These factors largely influence NUE, either individually or collectively. For example, selection of proper planting material, population density, and balanced fertilization could collectively improve NUE by 25 to 50% (Srinivasarao *et al.*, 2006). Multi-site field experiments conducted in North and Northeast China also indicate that the yield responses of maize to medium K supply are greater in high-yield cultivation practices (HP) than in current cultivation practices (CP; Zhang *et al.*, 2011).

Soil degradation is occurring due to inadequate and imbalanced fertilization leading to nutrient mining and development of second generation problems in nutrient management. The estimated supply-demand gap will be about 1.8 million tonnes of N and 1.9 million tonnes of phosphorus (P) by 2011-12. The entire demand for K will continue to be met through imports. It is of concern that the partial factor productivity of fertilizers has been continuously declining. The efficiency of fertilizer N is only 30-40% in rice and 50-60% in other cereals. The efficiency of fertilizer P is 15-20% in most crops and that of K is 60-80%. Low nutrient recovery efficiency not only increases the cost of crop production but also causes environmental pollution.

The positive N-K interaction is also dependent on the form of nitrogen supplied. 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 behaviour 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). K activates plant enzyme 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 carbon (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). Optimal N and K application is essential for best nutrient management in agriculture. A N-K interaction generally exists in agricultural ecosystems (Gething, 1993; Johnston and Milford, 2009). In this paper we have reviewed the N-K interaction and its effect on NUE in cereals.

NUE is an aggregate efficiency index of contributions to crop yield derived from uptake of indigenous soil N, fertilizer N uptake efficiency and the efficiency with which N acquired by plants is converted to grain yield. Cereals use fertilizer N rather inefficiently. On the basis of a large number of experiments conducted on farmer's fields, Cassman *et al.*, 2002 observed that generally more than 50% of the applied N is not assimilated by plants (Table 1). Under favorable weather conditions the maximum recovery efficiency of nitrogen was nearly 50%. The global cereal N use efficiency was about 33%, and an increase in 1% NUE was calculated to be worth US$234 million (Magen and Nosov, 2008).

Role of K in enhancing NUE

Adequate and balanced application of fertilizer nutrients is one of the most common practices for improving the efficiency of N fertilizer and is equally effective in both developing and developed countries. In a recent review based on 241 site-years of experiments in China, India, and North America, balanced fertilization with N, P, and K increased first-year recoveries with an average of 54% compared to recoveries of only 21% where N was applied alone (Fixen and West, 2002). Much higher nutrient efficiencies could be achieved simply by sacrificing yield, but that would not be economically effective or viable for the farmer, or the environment (Srinivasarao and Subbarao, 1999).

K application and N uptake

Enhancement in uptake of N through K application ultimately helps in increasing the NUE. Yield response to K application 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 a moderate N fertilizer level was supplied to wheat (112.5 kg N ha^{-1}), yield increments of wheat after K application were higher than when N or K fertilizer was applied singly. Response to yield and the utilization of nitrogen by maize was

Table. 1. NUE in rice and wheat.

Crop	Region	Number of farms	Average N application	Recovery efficiency of N
			kg ha⁻¹	*%*
Rice	Asia - farmers practice	179	117 ± 39	31 ± 18
	Asia - field specific management	179	112 ± 28	40 ± 18
Wheat	India - unfavorable weather	23	145 ± 31	18 ± 11
	India - favorable weather	21	123 ± 20	49 ± 10

Source: Cassman *et al.*, 2002.

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found to be accentuated when K application was supplemented with farmyard manure (Nakashgir, 1992). However, over-application of N and K does not lead to further yield increments.

The impact of K application on N uptake was studied in three sorghum genotypes in K deficient sandy soils of Guntur district in Andhra Pradesh. In all three sorghum genotypes, K application improved the dry matter yields as well as N uptake (Fig. 2) (Pillai and Nookaraju, 1997). Optimum N:K ratios favor healthy plant growth and development whereas imbalance of N and K supply is detrimental to plant growth (Xie, 2000; Wells and Wood, 2007).

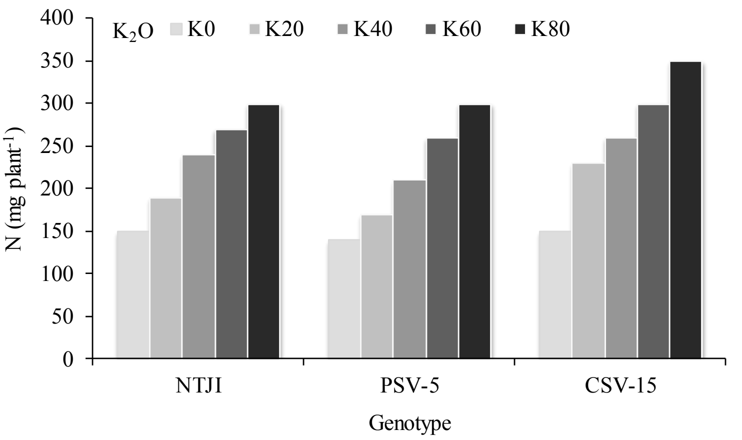

Fig. 2. Effect of K application on nitrogen uptake in three sorghum cultivars in Guntur district in Andhra Pradesh.

Source: Pillai and Nookaraju, 1997.

K application and protein content in plants

Application of K facilitates the uptake and transport of nitrate towards aerial parts of the plant, which in turn enhances the activities of nitrate assimilating enzymes (Anjana *et al.*, 2009). The parallel increase in activities of nitrogen assimilating enzymes with nitrate concentration indicates that these enzymes act in a coordinated manner in order to assimilate N in plants and thus improve the NUE.

In an experiment in which pearl millet was followed by wheat in rotation, the protein content of pearl millet and wheat grain increased due to K application (Table 2). The pearl millet grain protein content increased from 9.85 to 11.29% at 90 kg N ha^{-1}, and from 10.01 to 11.51% at 120 kg N ha^{-1} with the increase in K level from 0 to 60 kg K_2O ha^{-1} (Yadav *et al.*, 2007). Similarly, the wheat grain protein content increased from 10.62 to 11.74% at 120 kg N ha^{-1}, and from 10.86 to 11.87% at 150 kg N ha^{-1} due to the increase in residual K level from 0 to 60 kg K_2O ha^{-1}. Protein yield of grains was significantly increased as a result of K application regardless of the N level. These results show that K improves NUE by favouring protein formation.

Similarly, application of K in a pearl millet-mustard rotation also increased the grain protein content of pearl millet, which was significantly greater than the control at 40 kg K_2O ha^{-1} (Fig. 3). Protein yield (grain yield X % protein) was significantly increased due to K application, probably via the effect of K promoting photosynthate mobility to increase the utilization of N. Protein yield of pearl millet was increased from 252 to 340 kg ha^{-1}.

Application of K favours 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 protein content of grain 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).

Table. 2. Direct and residual effect of K on protein content in grain of pearl millet and wheat in alluvial soils of Haryana, India.

Nutrient application		Pearl millet		Wheat	
Pearl millet	Wheat	Protein content	Protein yield	Protein content	Protein yield
------------*kg ha^{-1}*------------		*%*	*kg ha^{-1}*	*%*	*kg ha^{-1}*
$N_{90}P_{60}K_0$	$N_{120}P_{60}K_0$	09.85	211	10.62	426
$N_{90}P_{60}K_{30}$	$N_{120}P_{60}K_0$	10.75	257	11.13	462
$N_{90}P_{60}K_{60}$	$N_{120}P_{60}K_0$	11.29	282	11.74	506
$N_{120}P_{60}K_0$	$N_{150}P_{60}K_0$	10.01	244	10.86	451
$N_{120}P_{60}K_{30}$	$N_{150}P_{60}K_0$	10.93	297	11.45	452
$N_{120}P_{60}K_{60}$	$N_{150}P_{60}K_0$	11.51	329	11.87	528
CD (5%)		0.79		0.81	

Source: Yadav *et al.*, 2007.

K application and N recovery efficiency (RE_N)

The large number of multi-location on-farm field experiments conducted in India shows the importance of balanced fertilization in increasing crop yield and improving NUE (Table 3). AE_N improved from 6 to 20% in predominant rainfed crops. Based on several balanced nutrition experiments, it was reported that AE_N improved with the application of P and K by 6.7 kg grain/kg N in sorghum, 10.3 in pearl millet,

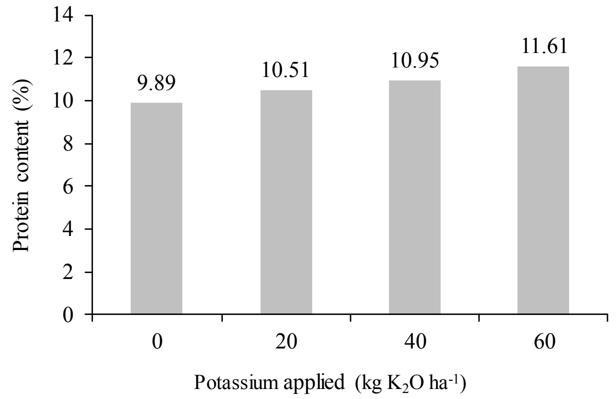

Fig. 3. Impact of K application on protein content of pearl millet in Alluvial soils of Haryana, India. (N and P_2O_5 applied were 120 and 60 kg ha^{-1}, respectively.)

Source: Yadav *et al.*, 2007.

Table. 3. Effect of balance fertilization on yield and AE_N.

Crop	Yield			Agronomic efficiency (AE_N)		
	Control	N alone	+PK	N	+PK	Increase
	---------*mt ha^{-1}*---------			---------*kg grain kg N^{-1}*---------		
Pearl millet	1.05	1.24	1.65	4.7	15.0	10.3
Maize	1.67	2.45	3.24	19.5	39.0	19.5
Sorghum	1.27	1.48	1.75	5.3	12.0	6.7

Source: Prasad, 2009.

Table. 4. RE_K and increase of NUE on maize.

Treatment*	RE_K (%)**		NUE increase (%)***	
	Range	Mean	Range	Mean
N_1K_0	-	-	-	-
N_1K_1	26.7-39.5	33.8	9.4-22.3	14.8
N_1K_2	38.3-42.7	40.5	20.7-25.1	22.2
N_1K_3	39.2-43.6	38.3	20.7-36.7	29.7
N_2K_0	-	-	-	-
N_2K_3	29.0~38.2	29.3	12.2~25.1	18.3

Source: Xie *et al.*, unpublished data; *In:* Zhang *et al.*, 2011.

* 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)/amount of K fertilizer] ×100.

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

and 19.5 kg grain/kg N in maize (Prasad, 2009).

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 spray), 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). The recovery efficiencies of K (RE_K) and N fertilizer in maize increased at 105-150 kg K_2O ha^{-1} and 195-240 kg N ha^{-1} (Table 4). Optimal N-K ratios favored crop growth and enhanced K and NUE. N-K interaction is not only positive for yields of rice and groundnut (Table 5) but it also improved the AE_N.

The interactions between N and K on crop growth and final yield seen at the agronomic level can be explained by their effects and interactions on the growth processes within the plant at the tissue and individual cell levels. Knowing how growth is controlled by these interactions within the plant makes it easier to understand why it is important to have sufficient exchangeable K in the soil. K has the property of high phloem mobility and, as a result, a high degree of re-utilization by re-translocation via the phloem (Marschner, 1995; Marschner *et al.*, 1997). K cycling and recycling play an important part in NO_3^- translocation from root to shoot as counter ion and assimilate loading in the phloem (Maathuis, 2007). The partitioning and the amount of phloem re-translocation 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). 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). 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). The effect of K in increasing agronomic efficiency may vary under different situations. With the application of 50 kg K_2O ha^{-1} the AE_N was much higher in sorghum fodder (f) as compared to wheat (Table 6).

Table 5. N-K interaction effect on yield and AE_N in rice and groundnut.

K rates	N rates (kg ha^{-1})				N rates (kg ha^{-1})			
	60	80	60	80	60	80	60	80
	Rice yield		AE_N		Groundnut pod yield		AE_N	
kg ha^{-1}	-------*mt ha^{-1}*-------		-------*kg kg^{-1}*-------		-------*mt ha^{-1}*-------		-------*kg kg^{-1}*-------	
0	3.10	3.02			1.68	1.70		
30	3.40	3.30	5.16	3.50	1.84	1.93	2.66	2.87
60	3.64	3.61	9.00	7.37	2.07	2.15	6.50	5.62
90	3.75	3.83	10.83	10.12	2.06	2.23	6.30	6.62
Mean	3.48	3.44			1.91	2.00		
LSD (0.05): N=NS, K=0.10, N×K=0.12					N=0.05, K=0.08, N×K=NS			

Source: Mitra *et al.*, 2001.

Table 6. Effect of N-K interaction on yield and AE_N in wheat and sorghum.

K rates	N rates (kg ha^{-1})		AE_N	N rates (kg ha^{-1})		AE_N
	0	120		0	80	
	Wheat yield			Sorghum (f) yield		
kg ha^{-1}	------*kg ha^{-1}*------		*kg kg^{-1}*	------*kg ha^{-1}*------		*kg kg^{-1}*
0	1.42	1.52	0.83	5.27	5.24	-
50	1.89	2.12	1.85	5.48	6.72	15.5
Mean	1.63	1.82		5.37	5.98	
LSD(0.05): N=0.16, K=NS, N×K=NS				N=0.42, K=NS, N×K=0.53		

Source: Golakiya *et al.*, 2001.

Table 7. Effect of K application on PFP_N in pearl millet at two levels of applied N.

K rates (kg K ha^{-1})	90 kg N ha^{-1}		120 kg N ha^{-1}	
	PFP_N	Increase	PFP_N	Increase
	kg kg^{-1}	*%*	*kg kg^{-1}*	*%*
20	23.8	-	20.3	-
40	26.6	11.7	22.6	11.3
60	27.8	16.8	23.8	17.3

N level 120 kg N ha^{-1}

Source: Yadav *et al.*, 2007.

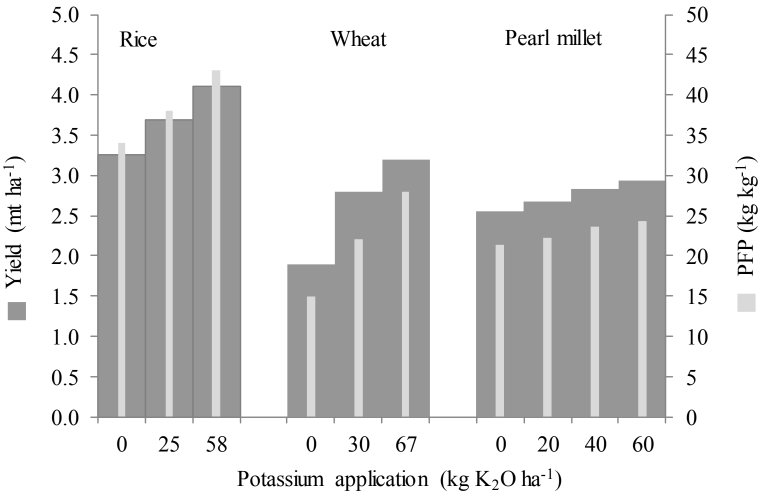

Fig. 4. Effect of applied K on PFP_N and yield of rice, wheat and pearl millet.

Adapted from: Magen and Nosov, 2008; Yadav *et al.*, 2007.

K application and partial factor productivity of N (PFP_N; kg yield per kg N applied)

In India, the PFP_N is decreasing over time. An initial decline in PFP_N is an expected consequence of the adoption of N fertilizers by farmers and is not necessarily a problem within the system contexts (Bijay-Singh and Yadvinder-Singh, 2008). However the low PFP_N during the last decade is due to low fertilizer NUE and is of particular concern. The application of K not only improved the yield of rice, wheat and pearl millet but also improved the partial factor productivity of applied N (Fig. 4). The study carried out by Yadav *et al.* (2007) further revealed that application of K increased the partial factor productivity of N irrespective of the level of applied N (Table 7). The PFP_N in pearl millet was increased at the application of 90 kg as well as 120 kg N ha^{-1} but the increase at the higher level of N was more the result of the combination with the high level of K.

Application of K greatly influenced PFP_N (kg grain/kg applied N) in maize. At different locations/years and with the application of K the PFP_N varied from 21.1 to 53.3 kg grain/kg applied N (Table 8). Averaged over years and sites the PFP_N was 32.7, 35.3, 38.0, and 39.0 kg grain/kg applied N at 0, 30, 60, and 90 kg of applied K_2O ha^{-1}. The graded levels of applied K increased PFP_N by 7.9, 16.2 and 19.3%, over K_0 application. Nitrogen recovery (kg N uptake/kg applied N) varied from 19 to 50% at different locations/years and on average increased from 32 to 41% in K_0 and K_{90} treated plots, indicating the favorable effect of applied K on N utilization. The practical implication of this will be the improved utilization and a lower loss of applied N under balanced fertilization.

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Table 8. Effect of K on PFP$_N$ (kg grain kg^{1} N) and apparent N recovery (%) in maize.

K level	2003	2004	2005	2006	2007	Average	Increase over K$_0$
kg K$_2$O ha^{-1}	----------------------------PFP$_N$ *(kg kg N^{-1})*----------------------------						*%*
0	21.1	32.0	26.8	38.2	45.4	32.7	-
30	24.2	37.9	27.3	39.5	47.6	35.3	7.9
60	27.0	41.8	27.4	41.3	53.3	38.0	16.2
90	26.4	40.9	30.9	48.2	48.8	39.0	19.3
	----------------------*Apparent N recovery (%)*----------------------						
0	19	32	30	41	40	32	-
30	22	39	31	41	44	35	9.3
60	24	44	30	41	42	36	12.5
90	23	46	37	50	47	41	28.1

Source: Brar *et al.*, unpublished data.

Table 9. Increase in grain yield and NUE achieved at IPI on-farm experiments in Asia and Europe.

Crop	Country	N rates	K rates	Yield increase	Increase in NUE
		------------------*kg ha^{-1}*------------------			*%*
Maize	India	125	30-90	200-1300	18 (6-29)
	China	150	75-180	200-1800	18 (5-29)
	Ukraine	30	30	720	15.5
Rice	Bangladesh	100	33-66	690-900	26.3 (23-30)
Wheat	China	90	60-120	230-610	10-23

Range in brackets.

Source: Magen and Nosov, 2008.

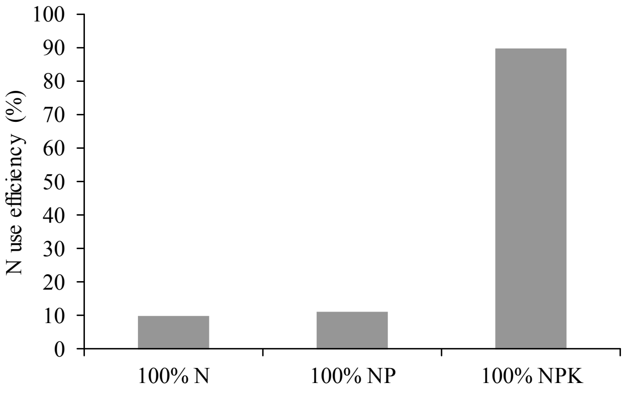

Fig. 5. NUE in finger millet with K application on K deficient Alfisols in Bangalore, India.

Source: Vasuki *et al.*, 2009.

K application and NUE

Fertilizer NUE is controlled by many factors such as crop demand for N, supply of N from the soil, fertilizer and manure application and losses of N from the soil-plant system. Imbalanced and inappropriate use of N and other nutrients such as K in agro-ecosystems can modify NUE. On-farm experiments carried out by IPI in Asia and Europe suggest that besides yield, the NUE, on average, can be increased from 15.5% in the Ukraine for maize to 26.3% for rice in Bangladesh with the application of appropriate amounts of K (Table 9).

The NUE normally depends on the extent of deficiency of K. On K deficient alfisols in Bangalore, India, there was a spectacular increase in NUE with the application of K. In the absence of applied K the application of both N and P failed to improve the NUE. NUE increased from 10% to 90% with the application of K on red laterite K deficient soils (Vasuki *et al.*, 2009, Srinivasarao 2010) (Fig. 5).

Conclusion

Balancing the fertilizer N application of different crops with fertilizer K is an urgent need to achieve higher NUE.

A gain of 20% in NUE can easily be achieved via balanced fertilization with K. A positive relationship between N and K exists for the uptake and utilization of N by plants to form protein and amino acids which ultimately affect the quality and yield of crops. Balanced use of N and K fertilizers in cereals and other crops will not only prove more profitable for farmers but also lead to reduced environmental degradation and climate change effects caused by dissipation of N originating from agricultural soils.

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Regional Activities/India and

N-K Interaction Center

Calculation of Carbon Footprint of Potash at Dead Sea Works, Israel

Weidberg, R.[(1)]

Introduction

Dead Sea Works Ltd. (DSW), a potash manufacturer in Israel, together with international consulting firms[(2)], have conducted an in-depth analyses of Carbon Footprint (CFP) calculations throughout its products, production facilities and supply chain, focusing on the competitive advantages that low-carbon performance brings to the company. Based on these analyses, we outline the CFP of two types of potash (fine and compacted grades) and compare these results to available industry benchmarks. The calculations made cover all of the direct components related to the production of potash (extraction, production, delivery etc.) in the production of "fine" and "compact" potash grades, which are used for direct application and granulation, and direct application and blending, respectively.

Overview of the DSW potash plant in Sdom. Photo by ICL.

Calculations of CFP

In order to accurately calculate the amount of carbon dioxide equivalent (CO_2e) used per tonne (or kg) of potash, DSW divided the production process of potash into four stages, and mapped all the greenhouse gas (GHG) emissions involved (Table 1). The process followed the standard method for assessing CFP as provided by the "Guide to PAS 2050; How to assess the carbon footprint of goods and services" (BSI, 2008). In 2011 it was modified according to Publicly Available Specification (PAS) 2050:2011 (BSI, 2011).

For each stage, we created a process map, and identified the activities that result in GHG emissions. The data was produced in 2008. For each emissions' source, we measured the annual activity figure (tonnes of raw material consumed or kWh of electricity used) using the following measurements (tCO_2e per tonne or kWh). The result was the tonne of CO_2e emitted by that source per year. The sum of the CO_2e emitted by all sources was then divided by the yearly production quantities, and the result was the tCO_2e per tonne of fine or compacted potash produced and delivered to the customer.

Table 1. Schematic stages and main processes producing GHG in the production of potash fertilizer.

Stage	Main GHG producing processes
Carnallite production	• Pumping Dead Sea water to evaporation ponds • Managing, harvesting and delivery of carnallite to the plant
From carnallite to potash	• Using water for the process • Energy used during the process
Compaction	• Energy used during the process
Delivery[(1)]	• Energy used in the delivery process (trucks, railway, ship) till the product is at an "average" port (in our calculations this port is in the UK).

[(1)]Delivery is an extra stage, outside the boundaries of "Cradle-to-Gate" as described in the PAS 2050:2011 (BSI, 2011).

The term "product carbon footprint" refers to the greenhouse gas (GHG) emissions of a product across its life cycle, from raw materials through production (or service provision), distribution, consumer use and disposal/recycling. It includes the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), together with families of gases including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and Sulphur hexafluoride (SF_6) (BSI, 2008; http://www.carbontrust.co.uk/solutions/CarbonFootprinting/what_is_a_carbon_footprint.htm).

"Cradle-to-Gate" describes the life cycle stages from the extraction or acquisition of raw materials to the point at which the product leaves the organization undertaking the assessment.

The work reported in this paper was undertaken by the GHG Center of Excellence at Israel Chemicals Ltd. (ICL), Tel Aviv, Israel.

[(1)] *Corresponding author: Roy-W@DSW.CO.IL.*

[(2)] *SKM Enviros (UK) has supported ICL through this process, and potash was among a group of products that have undergone a certification process by the Carbon Trust.*

Research Findings

Carnallite production

In the first production stage, water is pumped from the Dead Sea to the salt and carnallite ponds (about 10 km apart). The emissions are mostly related to electricity to power the pumps. The electricity is supplied by the Israeli grid, and the ICL Combined Heat & Power (CHP) plant at Sdom.

From carnallite to potash

This stage includes pumping of carnallite slurry for screening, thickening and filtering, flotation, crystallization, thickening, washing, drying and screening, warehouse and open storage (for delivery of "fine" grade); or feeding for compacting (for delivery of "compacted" grade).

Compaction

The following steps are conducted in the additional stage to produce compacted (granulated) potash: compacting, treating, screening and drying, warehouse and open storage.

Delivery (extra stage, values calculated but not presented in this paper)

Delivery includes electric conveyor belt, and transport by truck, rail and ship. Each stage has its own factor of emissions per tonne kilometer, allowing calculation of the total CFP of the delivery (tCO_2/t product). This stage is not a mandatory addition to the product CFP, according to the new version of PAS 2050 (issued in 2011), which recommends a "Cradle-to-Gate" approach.

GHG emission factors for raw materials used in the different processes were provided by ICL suppliers or evaluated from published data (such as life cycle analysis databases) and added to the total CFP.

The breakdown of the CFP by production stage is shown in Fig. 1.

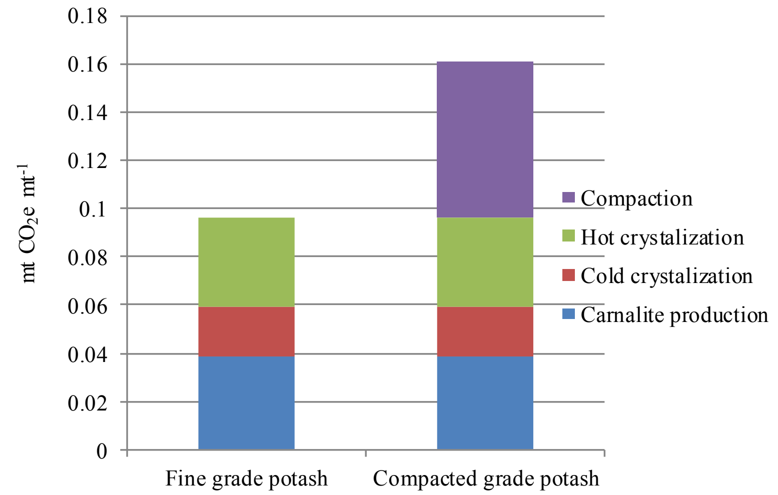

Fig. 1. CFP of fine and compacted (granulated) potash, by production stage (Cradle-to-Gate cycle).

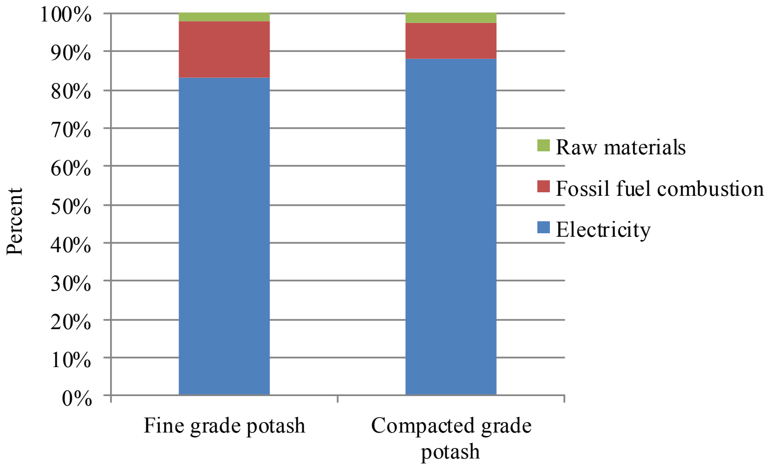

Fig. 2. Breakdown of the different emissions' sources share in the total Carbon Footprint of fine and compacted potash (Cradle-to-Gate).

Note: The emissions related to waste treatment and water consumption were negligible (under 0.1%) and hence not shown in Fig. 2. Raw materials used in the various stages (Table 1) are commonly used in the potash production process.

Results and conclusions

The calculated CFP for DSW Potash is 0.095 tCO_2e per tonne of fine potash and 0.161 tCO_2e per tonne of granulated potash, from cradle to the plant's gate(3).

Granulated potash has higher emissions due to the additional compaction stage, and slightly more carbon intensive transportation. The main source of emissions within the material extraction and manufacturing stages is the consumption of electricity. After 2008 (the year from which the data was used), the officially published GHG emission factor of the national electrical company in Israel has dropped by over 20%, due to a major transition to natural gas dependency. DSW has also started using natural gas in its Sdom CHP plant and other facilities. Therefore, the CFP

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(3) ICL has also calculated the CFP value at the port of the average customer, which also takes into account the delivery of the product. The results were 0.159 tCO_2e per tonne of fine potash and 0.243 tCO_2e per tonne of granulated potash. However, these figures are highly dependent on the actual location of the specific customer, and thus are not recommended by the new PAS 2050 standard, issued in 2011.

of potash produced by DSW is now expected to be lower. The ICL GHG Centre of Excellence has estimated that this transition could save about 20% of the energy-related emissions for potash, thus potentially reducing the CFP to about 0.076 tCO$_2$e per tonne of fine potash and 0.130 tCO$_2$e per tonne of granulated potash. A more precise re-calculation of the CFP is planned in 2012.

Kongshaug (1998) and later Jensenn and Kongshaug (2003) calculated the CFP of N, P and K fertilizer products. For these, they calculated a European average figure of 0.2 tCO$_2$e per tonne of potash, up to the manufacturer's gate. This figure is more than twice as high as the figure calculated for the ICL fine potash up to the same life cycle stage (0.095 tCO$_2$ per tonne). A possible explanation for this is the energy-efficient Carnallite extraction process employed at DSW. The factory uses the strong solar energy in the Dead Sea area by concentrating the brine in evaporation ponds. Moreover, potash has a much lower CFP than all forms of nitrogen-based fertilizers, due to the very energy intense process of nitrogen fixation (1.97 tCO$_2$e per tonne of nitrogen in modern ammonia plants; Kongshaug, 1998).

In conclusion, CFP calculation is an essential tool for product comparison, with regards to sustainability factors. Moreover, we assume that in the near future, industries will have to submit CFP calculations to the authorities (e.g. Poidevin, 2011). With agriculture accounting for approximately 30% of global GHG, the efficient use of energy is essential. The effective usage of solar energy at DSW significantly reduces the CFP of the company's potash.

Dredger used to harvest the carnallite from the pond's bed. Photo by ICL.

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The paper "Calculation of Carbon Footprint of Potash at Dead Sea Works" appears also at:

K Center Potassium and Environment

IPI Events

July 2012

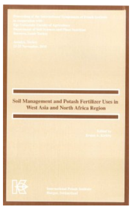
International Symposium on "Management of Potassium in Plant and Soil Systems in China", Chengdu, Sichuan, China, 24-27 July 2012. The symposium will be jointly organized by the International Potash Institute, Soil Science Institute, Nanjing, China, Chinese Academy of Sciences and the China Agriculture University. The 1st circular is available together with other details on the IPI website, or contact Mr. Eldad Sokolowski, IPI Coordinator China. ■

Other Events

May 2012

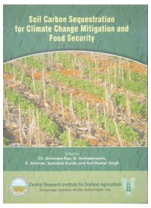
Agritech Israel 2012. The 18th International Agricultural Exhibition, Tel Aviv, Israel, 15-17 May 2012. Agritech Israel 2012 is one of the world's most important exhibitions in the field of agricultural technologies. The exhibition program will include the conference of the International Committee for Plastics in Agriculture (CIPA). See Agritech website. ■

Publications



Proceedings of the International Symposium on "Soil Management and Potash Fertilizer Uses in West Asia and North Africa Region". 22-25 November 2010, Antalya, Turkey. Invited Papers, 479 p. 2011. Edited by E.A. Kirkby. The symposium was organized by the International Potash Institute (IPI) in cooperation with Ege University, Faculty of Agriculture, Department of Soil Sciences and Plant Nutrition, Bornova, Izmir, Turkey. To order a hardcopy contact Prof. Dr. Dilek Anaç, Ege University, Faculty of Agriculture, Soil Sciences Department, 35100 Bornova, Izmir, Turkey, dilek.anac@ege.edu.tr. ■

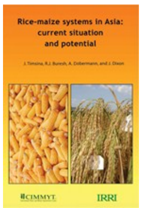
Other Publications



Soil Carbon Sequestration for Climate Change Mitigation and Food Security. 2011. Edited by Srinivasa Rao, Ch. B. Venkateswarlu, K. Srinivas, Sumanta Kundu and Anil Kumar Singh. Published by the Central Research Institute for Dryland Agriculture (CRIDA), Santoshnagar, Hyderabad, 500059, Andhra Pradesh, India.

This book contains 24 chapters dealing with various aspects of carbon sequestration in various agricultural systems. Chapter 4 entitled "Soil Carbon Sequestration in Rainfed Agriculture" by Ch. Srinivasa Rao *et al.*, describes also the long-term effect of various fertilizer treatments conducted in six different typical rainfed cropping systems on SOC. For a hardcopy contact Dr. Ch. Srinivasa Rao at cherukumalli2011@gmail.com. ■

Rice-Maize Systems in Asia: Current Situation and Potential. 2011. 232 p. Timsina, J., R.J. Buresh, A. Dobermann, and J. Dixon. Published by CIMMYT and IRRI. ISBN 978-971-22-0263-6. Also available on Google books.

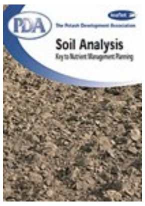


Rice-maize cropping systems have emerged in recent years on 3.5 million hectares in Asia in response to the increasing demand from a rapidly expanding human population for rice and livestock products. They are rapidly spreading in southern and northeastern India and Bangladesh, driven by the rising demand for maize by the poultry and fish sectors and the tightening world export-import markets. Read more on the IRRI website. ■

Publications by the PDA

The Potash Development Association (PDA) is an independent organisation formed in 1984 to provide technical information and advice in the UK on soil fertility, plant nutrition and fertilizer use with particular emphasis on potash. See also www.pda.org.uk/.

Note: Hardcopies of PDA's publications are available only in the UK and Ireland.



Soil Analysis: Key to Nutrient Management. Revised November 2011. Comprehensive guide to soil sampling and interpretation of soil results including indispensable reference material not found in any other single source. Download a pdf file from the PDA website. ■

Balanced Nutrition Shown by Nitrogen: Sulphur Ratios. November 2011. The majority of the N and S in crops (other than the Brassicae, such as oilseed rape, cabbage, kale etc) is in combination in proteins, and as with most animal proteins the ratio of N to S (N:S) in plants is fairly consistently around 12:1. Read more on the PDA website. ■

K in the Literature

Potassium Management during the Rotation from Alfalfa to Corn. Yost, M.A., M.P. Russelle, J.A. Coulter, C.C. Sheaffer, and D.E. Kaiser. Agron. J. 103(6):1785-1793. 2011.

Abstract:

High K fertilizer prices in recent years have made it imperative for growers to apply optimum K rates to alfalfa (*Medicago sativa* L.). Current university fertilizer guidelines in the Corn Belt do not change for the last production year, when alfalfa stand persistence is not a major concern. Furthermore, little is known about carryover of K applied to alfalfa on first-year corn (*Zea mays* L.) grain and silage yields. In 2008 to 2010, on-farm research was conducted on 10 fields with medium soil test potassium (STK) to determine response to K for alfalfa yield and quality in the last production year, and to estimate K carryover to first-year corn. Alfalfa yield and relative feed value (RFV) and quality (RFQ) did not improve with K fertilization. Herbage K concentration and K uptake increased with K fertilization across sites, indicating that applied K was available during the season of application. When corn relied on carryover K alone, each 100 kg ha^{-1} increase in the index of available K increased corn grain yield by 0.5 Mg ha^{-1}, decreased stover yield by 0.4 Mg ha^{-1}, and did not affect silage yields. Regardless of K rate applied to alfalfa, additional K applied to corn increased corn stover and silage yields by 10 and 8%, respectively. This suggests that carryover K was less available than K applied to corn. On medium STK soils going into the last year of alfalfa, applying fertilizer K to first-year corn rather than alfalfa may enhance economic return. ■

No-Till and Strip-Till Soybean Production with Surface and Subsurface Phosphorus and Potassium Fertilization. Farmaha, B.S., F.G. Fernández, and E.D. Nafziger. Agron. J. 103(6):1862-1869. 2011.

Abstract:

Compared to no-till, strip-till can offer improved seedbed conditions and deep banding of fertilizer. The objective of this study was to quantify the effect of rate and placement of P and K in no-till and strip-till systems on soybean [*Glycine max* (L.) Merr.] seed yield. A 3-yr field experiment was conducted near Urbana, IL, on Flanagan silt loam (fine, smectitic, mesic Aquic Argiudolls) and Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls) soils, with soybean planted following corn (*Zea mays* L.). Tillage/fertilizer placement was the main plot with no-till/broadcast (NTBC); no-till/deep band (NTDB); and strip-till/deep band (STDB); deep band placement was 15 cm beneath the planted row. Phosphorus-fertilizer rate (0, 12, 24, and 36 kg P ha^{-1} yr^{-1}) was the subplot, and K-fertilizer rate (0, 42, 84, and 168 kg K ha^{-1} yr^{-1}) was the sub-subplot. Soil water, soil and trifoliate P and K, and seed yield were measured. Overall, STDB produced 3.1 Mg seed ha^{-1}, 10, and 7% more yield than NTBC and NTDB, respectively. Seed yield, number of pods $plant^{-1}$, and trifoliate P concentration and accumulation increased with P fertilization uniformly across tillage/fertilizer placement indicating that fertilization cannot be reduced with deep band applications relative to broadcast applications without a reduction in seed yield, but deep banding increased subsurface soil test levels. Potassium fertilization decreased seed yield in both no-till systems but not in the STDB system. While P and K placement produced no differences, improved soybean yield and nutrient accumulation resulted from a tillage effect with STDB relative to the no-till systems. ■

Responses of Fruit Yield and Quality of Processing Tomato to Drip-Irrigation and Fertilizers Phosphorus and Potassium. Liu, K., T.Q. Zhang, C.S. Tan, and T. Astatkie. Agron. J. 103(5):1339-1345. 2011.

Abstract:

Water and nutrient management are essential to achieve high yield and desirable quality attributes in processing tomato (*Lycopersicon esculentum* Mill.). A 4-yr field study (2006–2009) was conducted to assess effects of contrasting water management (drip-irrigation vs. nonirrigation), fertilizer P (0, 30, 60, and 90 kg P ha^{-1}), and K (0, 200, 400, and 600 kg K ha^{-1}) on yields and quality of processing tomato when the optimum N rate of 270 kg N ha^{-1} was applied. Compared with nonirrigation, drip irrigation increased marketable fruit yield by 127%, total fruit yield by 66%, and fruit size by 32%, while it decreased soluble solids content (SSC) by 19% and lycopene content by 8%, with no effects on dry biomass of stems and leaves (DBSL). Phosphorus addition had no effects on marketable yield and SSC, but increased the DBSL and lycopene content to maximum values at 60 kg P ha^{-1}. Fertilize K rate affected all examined variables but the lycopene content. Increasing K rates from 0 to 200 kg K ha^{-1} increased marketable fruit yield by 10% and total fruit yield by 9%, but fruit size declined by 3%. Increasing K rates from 200 to 600 kg K ha^{-1}, however, had no effects on yield and fruit size. Fertilizer K rate had no effects on SSC with nonirrigation, but resulted in a linear increase in SSC with drip-irrigation. The results suggested that, with optimum N supply, K application is required to increase fruit yield and quality of drip irrigated processing tomato. ■

K in the Literature

Addition of Cover Crops Enhances No-Till Potential for Improving Soil Physical Properties. Blanco-Canqui, H., M.M. Mikha, D.A.R. Presley, and M.M. Claassen. Soil Sci. Soc. Am. J. 75(4):1471-1482. 2010.

Abstract:

Inclusion of cover crops (CCs) may be a potential strategy to boost no-till performance by improving soil physical properties. To assess this potential, we utilized a winter wheat (*Triticum aestivum* L.)-grain sorghum [*Sorghum bicolor* (L.) Moench] rotation, four N rates, and a hairy vetch (HV; *Vicia villosa* Roth) CC after wheat during the first rotation cycles, which was replaced in subsequent cycles with sunn hemp (SH; *Crotalaria juncea* L.) and late-maturing soybean [LMS; *Glycine max* (L.) Merr.] CCs in no-till on a silt loam. At the end of 15 yr, we studied the cumulative impacts of CCs on soil physical properties and assessed relationships between soil properties and soil organic C (SOC) concentration. Across N rates, SH reduced near-surface bulk density (ρ_b) by 4% and increased cumulative infiltration by three times relative to no-CC plots. Without N application, SH and LMS reduced Proctor maximum ρb, a parameter of soil compactibility, by 5%, indicating that soils under CCs may be less susceptible to compaction. Cover crops also increased mean weight diameter of aggregates (MWDA) by 80% in the 0- to 7.5 cm depth. The SOC concentration was 30% greater for SH and 20% greater for LMS than for no-CC plots in the 0- to 7.5 cm depth. The CC-induced increase in SOC concentration was negatively correlated with Proctor maximum ρb and positively with MWDA and cumulative infiltration. Overall, addition of CCs to no-till systems improved soil physical properties, and the CC-induced change in SOC concentration was correlated with soil physical properties. ■

Influences of Long-Term Fertilizer and Tillage Management on Soil Fertility of the North China Plain. Niu, L.A., J.M. Hao, B.Z. Zhang, and X.S. Niu. Pedosphere 21(6):813-820. 2011.

Abstract:

In the North China Plain, fertilizer management and tillage practices have been changing rapidly during the last three decades; however, the influences of long-term fertilizer applications and tillage systems on fertility of salt-affected soils have not been well understood under winter wheat (*Triticum aestivum* L.)-maize (*Zea mays* L.) annual double cropping system. A field study was established in 1985 on a Cambosol at the Quzhou Experimental Station, China Agricultural University, to investigate the responses of soil fertility to fertilizer and tillage practices. The experiment was established as an orthogonal design with nine treatments of different tillage methods and/or fertilizer applications. In October 2001, composite soil samples were collected from the 0-20 and 20-40 cm layers and analyzed for soil fertility indices. The results showed that after 17 years of nitrogen (N) and phosphorous (P) fertilizer and straw applications, soil organic matter (SOM) in the top layer was increased significantly from 7.00 to 9.3-13.14 g kg^{-1} in the 0-20 cm layer, and from 4.00 to 5.48-7.75 g kg^{-1} in the 20-40 cm layer. Soil total N (TN) was increased significantly from 0.37 and 0.22 to 0.79-1.11 and 0.61-0.73 g N kg^{-1} in the 0-20 cm and 20-40 cm layers, respectively, with N fertilizer application; however, there was no apparent effect of straw application on TN content. The amounts of soil total P (TP) and rapidly available P (RP) were increased significantly from 0.60 to 0.67-1.31 g kg^{-1} in the 0-20 cm layer, and from 0.52 to 0.60-0.73 g kg^{-1} in the 20-40 cm layer with P fertilizer application, but were decreased with combined N and P fertilizer applications. The applications of N and P fertilizers significantly increased the crop yields, but decreased the rapidly available potassium (RK) in the soil. Straw return could only meet part of the crop potassium requirements. Our results also suggested that though some soil fertility parameters were maintained or enhanced under the long-term fertilizer and straw applications, careful soil quality monitoring was necessary as other nutrients could be depleted. Spreading straw on soil surface before tillage and leaving straw at soil surface without tillage were two advantageous practices to increase SOM accumulation in the surface layer. Plowing the soil broke aggregates and increased aeration of the soil, which led to enhanced organic matter mineralization. ■

Impact of Long-Term Alfalfa Cropping on Soil Potassium Content and Clay Minerals in a Semi-Arid Loess Soil in China. Li, D.C., B. Velde, F.M. Li, G.L. Zhang, M.S. Zhao, and L.M. Huang. Pedosphere 21(4):522-531. 2011.

Abstract:

Alfalfa cropping has been considered an efficient method of increasing soil fertility. Usually nitrogen increase in root nodules is considered to be the major beneficial effect. A 21-year time series (five sampling periods) of alfalfa cultivation plots on a loess soil, initially containing illite and chlorite, in Lanzhou of northwestern China was selected to investigate the relationships among alfalfa cropping, soil potassium (K) content and soil clay minerals. The results indicated that soil K significantly accumulated after cropping, with a peak value at about 15 years, and decreased afterwards. The accumulated K was associated with the K increase in the well-crystallized illite mineral, which was not extracted by the traditional laboratory K extraction methods in assessing bioavailability. The steep decline in soil K content after 15-year cropping was in accord with the observed fertility loss in alfalfa soils.

in the Literature

Plant biomass productivity peaked at near 9 years of culture, whereas soil K and clay minerals continued to increase until copping for 15 years. This suggested that K increased in the topsoil came from the deep root zone. Thus alfalfa continued to store K in clays even after peak production occurred. Nitrogen did not follow these trends, showing a general decline compared with the native prairie soils that had not been cropped. Therefore, the traditional alfalfa cropping can increase K content in the topsoil. ■

Interactive Effect of Potassium and Phosphorus on Grain Quality and Profitability of Sunflower in Northwest Pakistan. Amanullah, and M.W. Khan. Pedosphere 21(4):532-538. 2011.

Abstract:

A field experiment was conducted using a split plot randomized complete block design with three replications to study the effects of potassium (K) and phosphorus (P) application on sunflower (*Helianthus annuus* L.) growth at the New Developmental Research Farm of Khyber Pakhtunkhwa Agricultural University in Peshawar, Pakistan. Six levels of K (0, 25, 50, 75, 100 and 125 kg K ha^{-1}) were main plots while four levels of P (0, 45, 90 and 135 kg P ha^{-1}) were subplots. Increase in both K and P levels enhanced grain oil concentration of sunflower. Increase in P level increased grain protein concentration, while increase in K level decreased grain protein concentration. Both oil and protein yields increased significantly with increase in K and P levels. The increase in oil and protein yields of sunflower was mainly attributed to the improvement in yield components (grains per head, grain weight and head size) and the significant increase in grain yield. The highest net returns of 297 and 368 US$ ha^{-1} based on grain and oil yields, respectively, were obtained from a combination of 100 kg K ha^{-1} + 45 kg P ha^{-1}. ■

Long-Term-Fertilization Effects on Soil Organic Carbon, Physical Properties, and Wheat Yield of a Loess Soil. Yang, X., P. Li, S. Zhang, B. Sun, and C. Xinping. J. Plant Nutr. Soil Sci. 174:775-784. 2011.

Abstract:

The large dryland area of the Loess Plateau (China) is subject of developing strategies for a sustainable crop production, *e.g.,* by modifications of nutrient management affecting soil quality and crop productivity. A 19 y long-term experiment was employed to evaluate the effects of fertilization regimes on soil organic C (SOC) dynamics, soil physical properties, and wheat yield. The SOC content in the top 20 cm soil layer remained unchanged over time under the unfertilized plot (CK), whereas it significantly increased under both inorganic N, P, and K fertilizers (NPK) and combined manure (M) with NPK (MNPK) treatments. After 18 y, the SOC in the MNPK and NPK treatments remained significantly higher than in the control in the top 20 cm and top 10 cm soil layers, respectively. The MNPK-treated soil retained significant more water than CK at tension ranges from 0 to 0.25 kPa and from 8 to 33 kPa for the 0-5 cm layer. The MNPK-treated soil also retained markedly more water than the NPK-treated and CK soils at tensions from 0 to 0.75 kPa and more water than CK from 100 to 300 kPa for the 10-15 cm layer. There were no significant differences of saturated hydraulic conductivity between three treatments both at 0-5 and 10-15 cm depths. In contrast, the unsaturated hydraulic conductivity in the MNPK plot was lower than in the CK plot at depths of 0-5 cm and 10-15 cm. On average, wheat yields were similar under MNPK and NPK treatments and significantly higher than under the CK treatment. Thus, considering soil-quality conservation and sustainable crop productivity, reasonably combined application of NPK and organic manure is a better nutrient-management option in this rainfed wheat-fallow cropping system. ■

Influence of Organic and Mineral Fertilizerson Nutrient Leaching. Spiess, E., V. Prasuhn, and W. Stauffer. Recherche Agronomique Suisse 2(9):376-381. 2011. French.

Abstract:

Between 2002 and 2009 the influence of fertilizer type on drainage water formation and nutrient leaching was investigated in one crop rotation at the Bern-Liebefeld lysimeter station. Slightly higher crop yields were obtained with purely organic fertilizer than with pure mineral or organic-mineral fertilizers. One of the reasons for this may be that optimum manure management is possible in a lysimeter trial. However the three fertilizer methods differed only slightly in amounts of drainage water, drainage water nitrate concentrations and leached nutrient loads. These were much more strongly influenced by climatic conditions and the crop cultivated. A greater differentiation between the treatments could presumably have been achieved with a longer trial period because of the long-term after-effects of organic nitrogen. On the one hand these after-effects produce slight yield increases over the years, but on the other hand an increase in leaching losses can be expected owing to greater humus mineralization. ■

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Read on:

Plants Use Alternative Strategies to Utilize Nonexchangeable Potassium in Minerals. Wang, H.Y., Q.H. Shen, J.M. Zhou, J. Wang, C.W. Du, and X.Q. Chen. 2011.

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Potassium Assessment of Grain Producing Soils in North China. Deshui Tan *et al.* 15 February 2012.

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Rate of Global Plant Carbon Uptake and Release Revised. Macaulay, C. 10 October 2011.

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Phosphorus Cycle: A Broken Biogeochemical Cycle. Elser, J., and E. Bennett. 6 October 2011.

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Microbial Activity, Community Structure and Potassium Dynamics in Rhizosphere Soil of Soybean Plants Treated with Glyphosate. Lane *et al.* 26 December 2011.

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