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Optimizing Crop Nutrition

Editorial

Dear readers,

With a global production of more than 740 million tonnes in 2016, rice is the staple food for nearly half of the world's population.

To produce high grain yield levels, modern rice cultivars require adequate amounts of essential nutrients. Of the 182 million tonnes of fertilizer ($N+P_2O_5+K_2O$) consumed globally during 2014-2015, 13.7% (25 Mt) was used in rice cultivation, and percentages of nitrogen (N), phosphorus (P), and potassium (K) were 15.2, 12.5, and 11%, respectively. To ensure higher rice productivity, appropriate nutrient management practices have also become an essential component of modern rice production.

A high potential exists for increasing rice yields, but inefficient nutrient use is one of the most significant limiting factors. In the major rice growing countries of China, India and across South-East Asia countries, there is overuse of N fertilizer, while K application is below recommended doses. This imbalanced use of fertilizers (extreme N:K ratio) not only leads to lower yields and quality of rice, but also proves to be uneconomic and environmentally unsafe.

Rice is usually produced in an intensive cropping system with wheat, or in double and triple rice-cropping systems. These intensive systems remove large quantities of nutrients from the soil. Having mined the soil of K, regular applications of K fertilizer have become necessary to produce optimum rice yields.

In this *e-ifc* edition, we feature two papers on rice K fertilization in China and Kenya, adding more scientific proof that K deficiency limits rice yields, and that N use efficiency in rice can be improved by proper K fertilization.

I wish you an enjoyable read.

Dr. Patricia Imas
IPI Scientific and Communications Coordinator

Photo cover page: Potash application in rice crop in Rajdhani, Vaishali, India. Photo courtesy of Potash for Life, India.

Research Findings

Alfalfa (*Medicago sativa*). Photo by A.C.C. Bernardi. 2017.

Polyhalite Compared to KCl and Gypsum in Alfalfa Fertilization

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Abstract

Poor acidic soils significantly challenge potassium (K) availability for crop production in Brazil. Therefore, huge amounts of K fertilizers, mostly KCl, are applied yearly. Nevertheless, KCl agronomic efficiency in those soil is often insufficient, hence alternative K donors are sought. In the present study, polyhalite, a natural mineral with potential as a multi-nutrient (11.7, 19, 3.6, and 12.1% of K, sulfur (S), magnesium (Mg), and calcium (Ca), respectively) fertilizer, was examined in a pot-grown (local topsoil) alfalfa (*Medicago sativa* L.) experiment vs. KCl together with gypsum. Four K application rates (equivalent to 0, 50, 100, and 200 kg K_2O ha^{-1}) were tested with seven fertilizer combinations: KCl; KCl + gypsum1; KCl + gypsum2; polyhalite + KCl (1:7); polyhalite + KCl (1:1); polyhalite + KCl (7:1); and polyhalite. The results of seven successive harvests indicated that K application was essential to obtain considerable plant biomass in a K-rate dependent pattern. Polyhalite application, in combination with KCl or exclusively, gave rise to significantly higher biomass yields than KCl application, with or without gypsum. Polyhalite significantly enhanced K, S, Ca, and Mg uptake, particularly when applied alone at the highest dose. Indications of K-Mg or Cl-S competition seen under KCl application diminished under polyhalite. In conclusion, under the terms of a pot-grown experiment, polyhalite appeared as a promising alternative among K fertilizers for alfalfa grown on Brazilian acidic soils. Polyhalite may be considered as a replacment to KCl as a K source, as well as a donor of Ca, Mg, and S. Broad scale field experiments are

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required, however, to further confirm this conclusion under practical terms.

Keywords: Acidic soil; calcium; magnesium; *Medicago sativa*; nutrient uptake; polyhalite; potassium; slow release; sulfur.

Introduction

Brazil is the fourth largest fertilizer consumer in the world (ANDA, 2016). In 2016, the estimated consumption of fertilizers was approximately 32.8 million tons, of which 28% was related to potassium (K) fertilizer (IPNI, 2017). The primary K source in the Brazilian fertilizer market is KCl (58-62% K_2O) (ANDA, 2016). Local KCl production comprises 5.3% of total consumption, and the rest is imported (IPNI, 2017).

The minerals commonly explored as K sources are sylvite (KCl), sylvinite (KCl + NaCl), and carnallite ($KMg_2Cl_3 \cdot 6H_2O$). However, there are other minerals composed of sulfates that may be considered of economic interest owing to their K content and easy solubilization, e.g. langbeinite, kainite, and polyhalite (Prud'homme and Krukowski, 2006; Vale and Sério, 2017). Polyhalite ($K_2MgCa_2(SO_4)_4 \cdot 2H_2O$) is a natural mineral occurring in large deposits, which has potential to be a multi-nutrient (ratio of 11.7% K, 19% sulfer (S), 3.6% magnesium (Mg), and 12.1% calcium (Ca)) fertilizer for forage crop production (Barbarick, 1991; Vale and Sério, 2017).

Supplying nutrients at balanced and adequate levels is a critical factor for alfalfa (*Medicago sativa*) production and is essential to maintain high quality and efficient yields. An alfalfa crop is extremely demanding on soil fertility (Moreira *et al.*, 2008; Bernardi *et al.*, 2013b). According to Werner *et al.* (1996) alfalfa nutrient uptake from soil could reach 20, 6.65, and 33.9 kg N, P_2O_5, and K_2O Mg^{-1} dry biomass.

Potassium fertilization is essential for alfalfa production and is the most common nutrient input for this crop, especially when grown on the highly weathered infertile acidic soils of Brazil (Moreira *et al.*, 2008). Therefore, imbalanced fertilization and ineffective soil management might lead to loss of alfalfa vigor and reduced longevity (Bernardi *et al.*, 2013a).

However, little information is available on the response of alfalfa to polyhalite. Acid, low-fertile, high-weathered soils are expected to benefit from the addition of K, Ca, Mg, and S nutrients. Therefore, polyhalite may provide an alternative to KCl, with the advantage of providing a slow-release source of these nutrients (Barbarick, 1991; Vale and Sério, 2017).

The objective of this study was to compare the effects of different K fertilizer doses on alfalfa dry matter yield and nutritional status.

Materials and methods

A greenhouse experiment was conducted at Embrapa Pecuária Sudeste, in São Carlos (22°01'S; 47°54'W, 856 m above sea level), State of São Paulo, Brazil. Alfalfa (cv. Crioula) plants were grown in 2-L pots filled with 3 kg topsoil (layer of 0-20 cm) of a Typic Hapludox (red yellow latosol), the properties of which are given in Table 1.

Pots were uniformly limed to raise soil base saturation (V%) to 80% with dolomitic lime (32% CaO, 19% MgO) 30 days before planting. At planting, all pots were applied with P (458 mg P_2O_5 kg^{-1}) as triple superphosphate (45% P_2O_5 and 15% Ca), and with 25 mg kg^{-1} micro-nutrient fertilizer FTE-BR12 (1.8% boron (B), 0.8% copper (Cu), 3% iron (Fe), 2% manganese (Mn), 0.1% molybdenum (Mo), and 9% zinc (Zn)). Four doses of K_2O, equivalent to field quantities of 0, 50, 100, and 200 kg ha^{-1}, were applied before planting and following each of the seven harvests during the season, using two K sources - polyhalite and KCl - in combination or alone. Additional treatments evaluated two gypsum doses (Table 2), as an alternative Ca and S donor, combined with KCl as the K donor. The gypsum doses were calculated to have equivalent levels of Ca and S of the treatments KCl+polyhalite (1:7), and KCl+polyhalite (1:1). A detailed description of the treatments is given in Table 2. Thus, the experiment consisted of 22 treatments (7x3+1) in a fractionated factorial design with four replications. The total quantities supplied at the crop cycle were equivalent to 0, 350, 700 and 1,400 kg K_2O ha^{-1}, respective to the dose asigned to each treatment.

Shoot dry matter yield was periodically determined when the crop reached 10% flowering and the 10 cm above-ground biomass was harvested. The samples were dried and dry matter yield was

Table 1. Texture and chemical properties of the local topsoil (depth of 0-20 cm) used as a growth medium in the alfalfa pot experiment.

Soil property	Quantity	Units
Sand	265	g kg^{-1}
Silt	198	g kg^{-1}
Clay	537	g kg^{-1}
pH ($CaCl_2$)	5.2	
Organic matter	24	g dm^{-3}
Cation exchange capacity (CEC)	52	$mmol_c$ dm^{-3}
Basic saturation	55	V%
Phosphorus, as P_{resin}	2	mg dm^{-3}
K	1.6	$mmol_c$ dm^{-3}
Ca	19	$mmol_c$ dm^{-3}
Mg	8	$mmol_c$ dm^{-3}
S, as SO_4	12	mg dm^{-3}
B	0.37	mg dm^{-3}
Cu	6.3	mg dm^{-3}
Fe	13	mg dm^{-3}
Mn	1.5	mg dm^{-3}
Zn	0.5	mg dm^{-3}

determined. Dry matter samples were used to determine total K, Ca, Mg and S concentrations.

Results and discussion

Alfalfa shoot biomass response to K application dose displayed an optimum curve, with a maximum of 67 g plant^{-1} at K_2O ranging from 145 to 165 kg ha^{-1} (Fig. 1A). However, the nature of the data do not allow to definite conclusion of whether plant biomass decreased beyond that rate, or actually obeyed a saturation curve. Alfalfa growth was severely restricted under no K application, obtaining less than 30 g dry matter (DM) plant^{-1}, while an application of 50 kg K_2O ha^{-1} gave rise to 80% biomass increase. These results are consistent with those observed by Smith (1975), Rassini and Freitas (1998), and Bernardi *et al.* (2013b), who found an alfalfa DM yield surge in response to increasing K application dose.

Nevertheless, yield response to K dose was significantly affected by K origin - KCl or polyhalite (Fig. 1B). As an exclusive K source, polyhalite was significantly more effective than KCl, obtaining higher biomass yields under all K doses, with an average peak of 82 g DM plant^{-1} under 200 kg K_2O ha^{-1}, 191% greater than in the no fertilizer control (Fig. 1B; Fig. 2). The KCl-polyhalite combinations also indicated a slight advantage to the higher polyhalite proportion, however, these differences were not always significant. Gypsum co-application with KCl did not result in any significant advantages.

Potassium concentration in shoots of the non-fertilized control was 6.5 g kg^{-1} DM, much lower than in all other treatments (Fig. 3). KCl application, with or without gypsum, significantly increased leaf K concentrations, however, in all treatments where polyhalite was involved, the higher K dose (200 kg ha^{-1}) gave rise

Table 2. A detailed description of the fertilization treatments and the rates of K, S, Ca, and Mg applied in each treatment per growth cycle (transformed into kg ha^{-1}).

Treatment	K_2O	S	CaO	MgO
	----------------*kg ha^{-1}*			----------------
Control (no K, S, Mg or Ca)	0	0	0	0
	50	0	0	0
100% KCl	100	0	0	0
	200	0	0	0
	50	9	6	0
100% KCl+gypsum1	100	18	13	0
	200	36	25	0
	50	34	24	0
100% KCl+gypsum2	100	68	48	0
	200	136	96	0
	50	9	5	2
87.5% KCl+12.5% polyhalite (1:7)	100	18	10	4
	200	36	20	8
	50	34	19	7
50% KCl+50% polyhalite (1:1)	100	68	38	13
	200	136	75	26
	50	60	38	11
12.5% KCl+87.5% polyhalite (7:1)	100	120	76	23
	200	240	151	46
	50	68	43	13
100% Polyhalite	100	136	86	26
	200	272	172	52

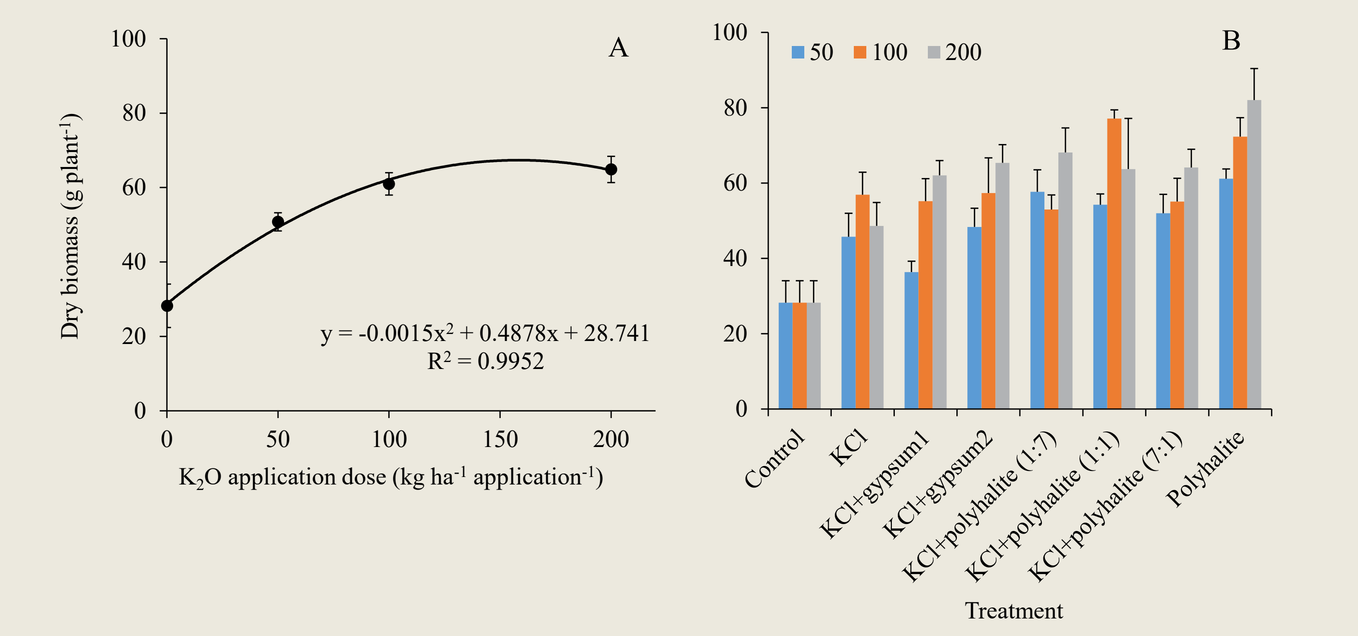

Fig. 1. Alfalfa dry biomass production in response to K application (rates of 50, 100, and 200 kg K_2O ha^{-1}) in a pot-grown experiment. Mean DM production in response to K dose (left); effects of K origin and dose on DM production (right). Bars indicate standard error (SE).

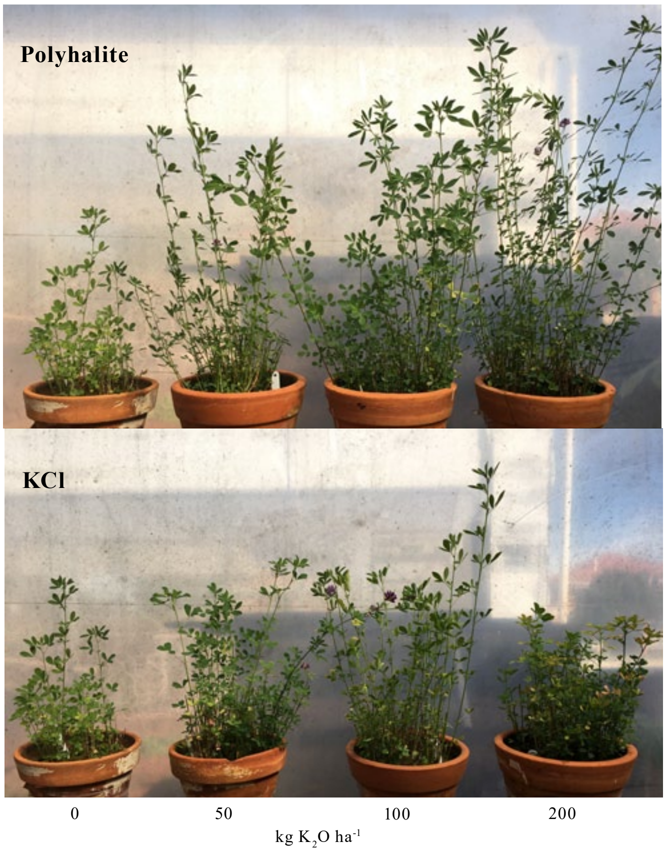

Fig. 2. Alfalfa plant performance under four K application levels using polyhalite or KCl. Photos by A.C.C. Bernardi.

to the highest leaf K concentrations, ranging from 18 to 22 g kg^{-1} (Fig. 3); three-fold greater than the control.

In Brazil, the ranges of K, Ca, Mg and S levels considered adequate for alfalfa shoots at early flowering are 20-35, 10-25, 3-8, and 2-4 g kg^{-1} for K, Ca, Mg and S, respectively (Werner *et al.*, 1996). Thus, the alfalfa shoots' K levels obtained in the present study were below the threshold and were lower than previous field results (Bernardi *et al.*, 2013b). On the other hand, Ca, Mg and S leaf concentrations were, in most cases, above the minimum thresholds (Fig. 3).

Nonetheless, a better insight into plant nutrition status may be provided by the nutrient uptake parameter, which integrates plant biomass with nutrient concentrations, resembling both soil nutrient availability and plant actual demands. The response of alfalfa K uptake to K application was dramatic, particularly where polyhalite at the highest K dose was involved (Fig. 4). The obvious advantage of polyhalite over KCl can be attributed to its stable, long-term pattern of K release, in contrast to the sudden but declining K availability that follows KCl application. Still, the mean K uptake curve suggests that K demands have not yet been fulfilled, even under the highest K dose employed in the present study (Fig. 4). Altogether, considering the low leaf K concentrations and the unsatisfied plant K demand, these results may point to another factor limiting plant performance, even under favorable K supply.

In Brazil, nitrogen (N) fertilization throughout alfalfa crop cycles is rare, since N supply relies on biological fixation performed by seed-inoculated with *Sinorhizobium meliloti* bacteria (Oliveira *et al.*, 2004). Nevertheless, balanced nutrition is essential to the maintenance of N_2 fixation activity. In plants experiencing K defficiency, this process might be negatively affected due to the decline of photosynthate's export rates from source leaves to roots (Mengel and Kirkby, 2001). The declining sugar supply to root nodules might lead to a considerable reduction in N_2 fixation and to an export of bound N (Collins and Duke, 1981). On the other hand, N supply from the biological process might not meet plant requirements under favorable K supply. The metabolic interactions between N and K are not limited to N fixation, having a broad scale of impacts on plant physiology and productivity (Fageria, 2001). Therefore, consequent to the entrance of new and more efficient K fertilizers, such as polyhalite, the need of N fertilization should be revisited.

Sulfur is another macronutrient essential to alfalfa metabolism and growth, and in combination with N, it participates in the synthesis of amino acids (methionine and cysteine) and proteins (DeBoer and Duke, 1982). Vale and Sério (2017) have pointed out that one of the advantages of polyhalite is in S delivery. Alfalfa S requirements and the positive effect of this nutrient in increasing DM production have already been demonstrated (Scherer and Lange, 1996; Moreira *et al.*, 1997). Moreira *et al.* (2008) recommended an annual application of 4 kg S Mg^{-1} DM. Considering an alfalfa yield of 20 Mg ha^{-1}, an amount of 420 kg S ha^{-1} yr^{-1} should be enough to meet this need. Sulfur concentration in alfalfa shoots remained quite constant under the macronutrient supply through either polyhalite or gypsum (Fig. 3). Under KCl as the sole K source, leaf S concentration displayed a reduction, which was further pronounced under the higher K dose. Mean S uptake increased with K dose, reflecting mainly the biomass rise (Fig. 4). Sulfur uptake was significantly greater under the higher polyhalite doses, confirming the considerable potential of the new fertilizer as an S source for alfalfa.

Leaf Ca concentrations were quite stable under the different K fertilizers, however, values showed a clear tendency to decrease in response to the allevating K dose (Fig. 3). This tendency was more significant with leaf Mg concentrations that were very low under KCl, exclusively or with gypsum application (Fig. 3). Mean Ca uptake surged from 600 to 1,200 mg $plant^{-1}$ in response to the lower K application dose of 50 kg ha^{-1}, but remained stable or even decreased under higher K doses (Fig. 5). While Ca uptake significantly declined under the highest KCl dose, polyhalite application maintained it at a high level in most of the combinations, and in particular when applied exclusively (Fig. 5).

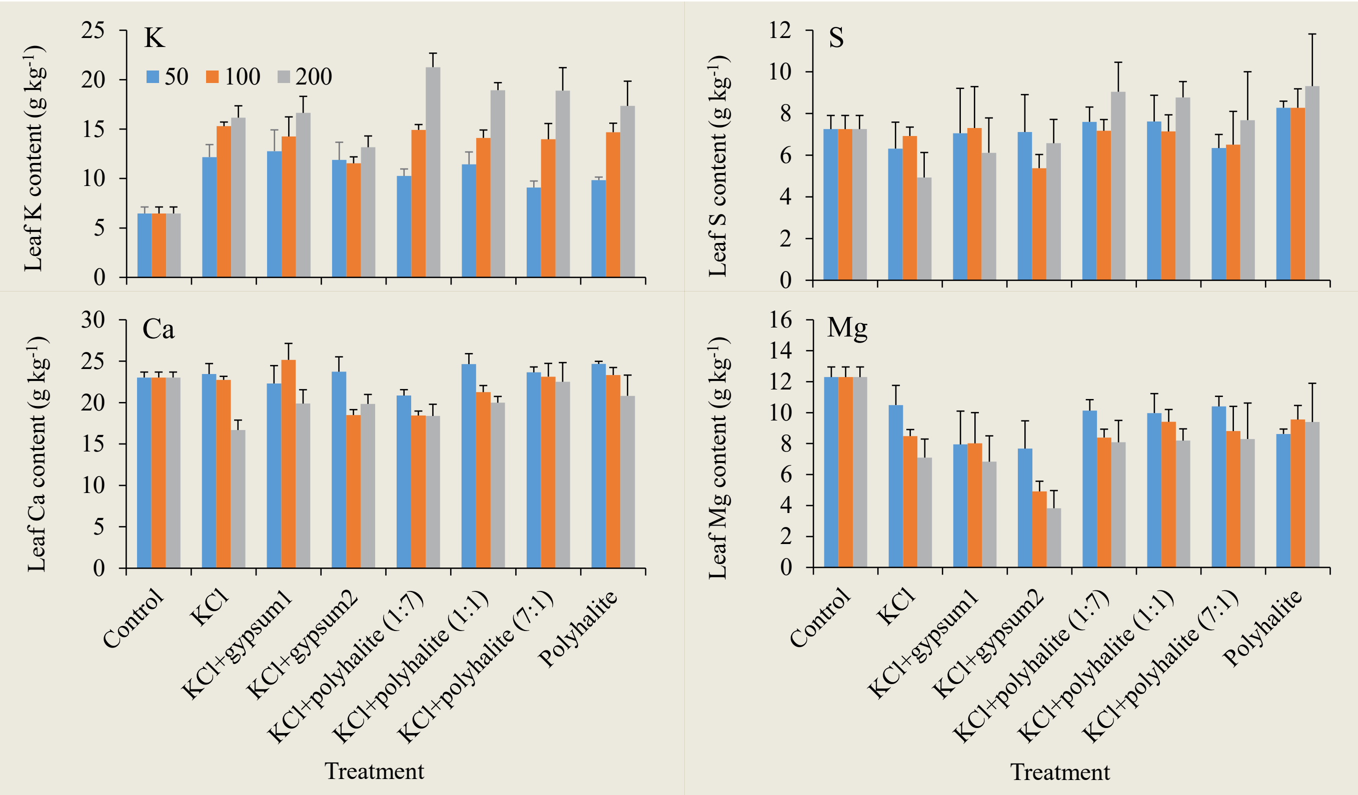

Fig. 3. Alfalfa leaf nutrient (K, S, Ca, and Mg) concentration in response to different K fertilization practices (rates of 50, 100, and 200 kg K_2O ha^{-1}) using several combinations of KCl, polyhalite, and gypsum in a pot-grown experiment. Bars indicate SE.

The response of the mean Mg uptake to increased K dose was quite moderate, compared to Ca uptake, but it displayed a similar pattern, with a clear reduction under the highest K rate (Fig. 5). While significantly lower under KCl + gypsum, Mg uptake was considerably higher under polyhalite application than the control, in most cases (Fig. 5). The phenomenon of reduced leaf Ca and Mg in response to allevated K fertilization had already been reported by Smith (1975), Lanyon and Smith (1985) and Lloveras *et al.* (2001).

KCl is the most common K fertilizer in use. Due to its high water solubility, K is immediately available for plant roots. Nevertheless, this might be a serious disadvantage in acidic soils with poor CEC. In many cases, the soil solution is K^+-saturated soon after KCl application, leading to transient stresses such as competition between K^+ and other cations (Ca, Mg, etc.) as well as between Cl^- and other anionic nutrients (NO_3^-, SO_4^{-2}), and high osmotic tension. Furthermore, due to poor soil CEC, K^+ is extremely mobile in the soil profile and might be leached away during successive irrigation (in pot experiments) or rainfall events (field conditions). Thus, the agronomic efficiency of KCl in such soils might be reduced considerably.

Some indications for competition between Cl and S or between K and Ca and Mg under exclusive KCl application, are highlighted in Figs. 4 and 5, respectively. Soil amelioration using gypsum ($CaSO_4{\cdot}2H_2O$) partially reduced the competition with Ca or S, but not with Mg. Using polyhalite fertilizer, in combination with KCl or exclusively, reduced or diminished these difficulties. As a relatively slow-release fertilizer, polyhalite brought about increased K uptake and biomass production, probably due to the consistent soil K availability it had provided. Most of the indications of competition among nutrients disappeared and nutrient uptake rates rose, including that of Mg, in a polyhalite rate-dependent pattern (Figs. 4 and 5).

In conclusion, in the present pot-grown experiment, polyhalite appeared as a promising K fertilizer alternative for alfalfa grown on Brazilian acidic soils. Polyhalite may be considered to replace KCl as a K source, as well as an important donor of Ca, Mg, and S. Broad scale field experiments are required, however, to further confirm this conclusion under practical terms.

Acknowledgement

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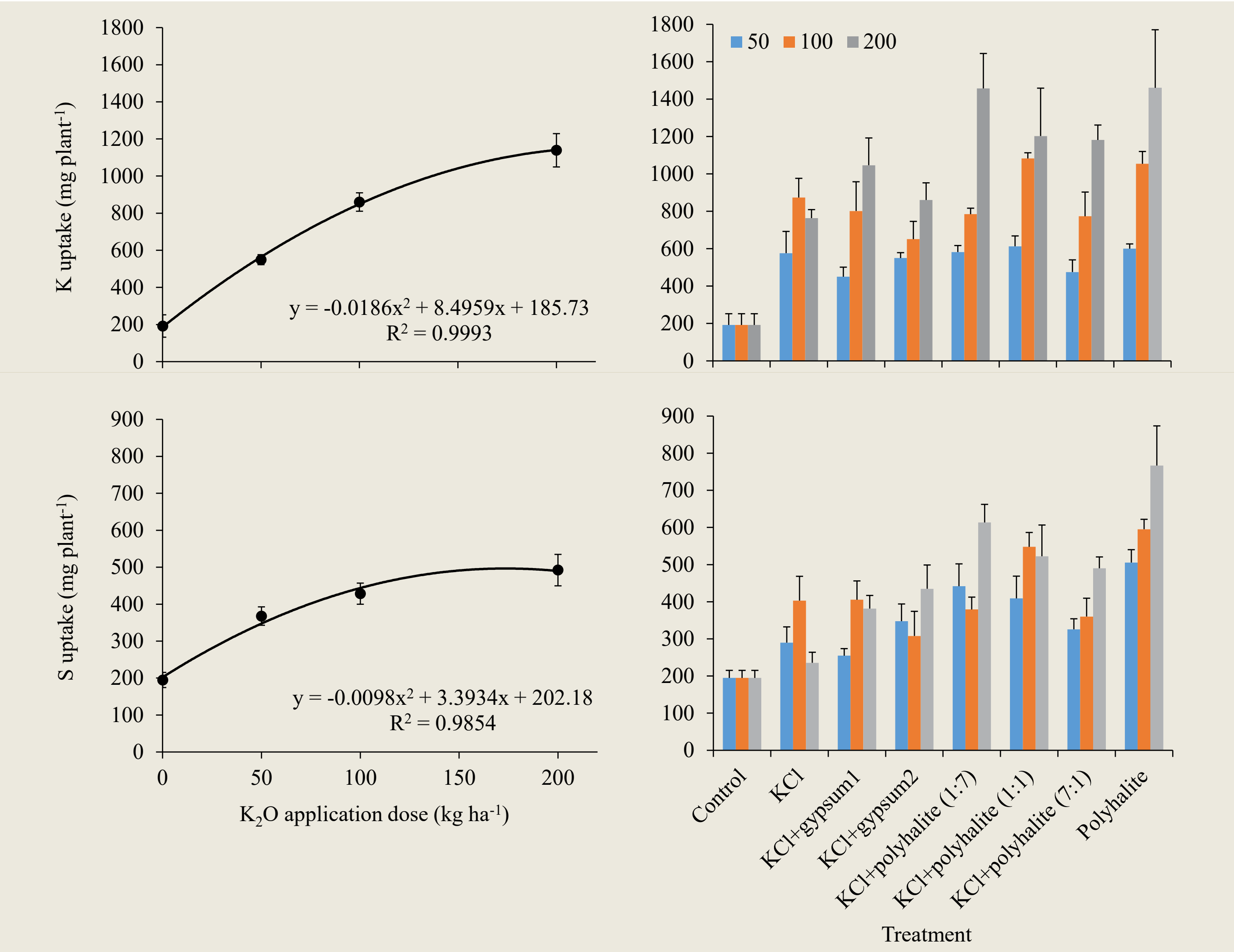

Fig. 4. Alfalfa K and S uptake in response to K application (rates of 50, 100, and 200 kg K_2O ha^{-1}) in a pot-grown experiment. Mean K or S uptake in response to K dose (left); effects of K origin and dose on K or S uptake (right). Bars indicate SE.

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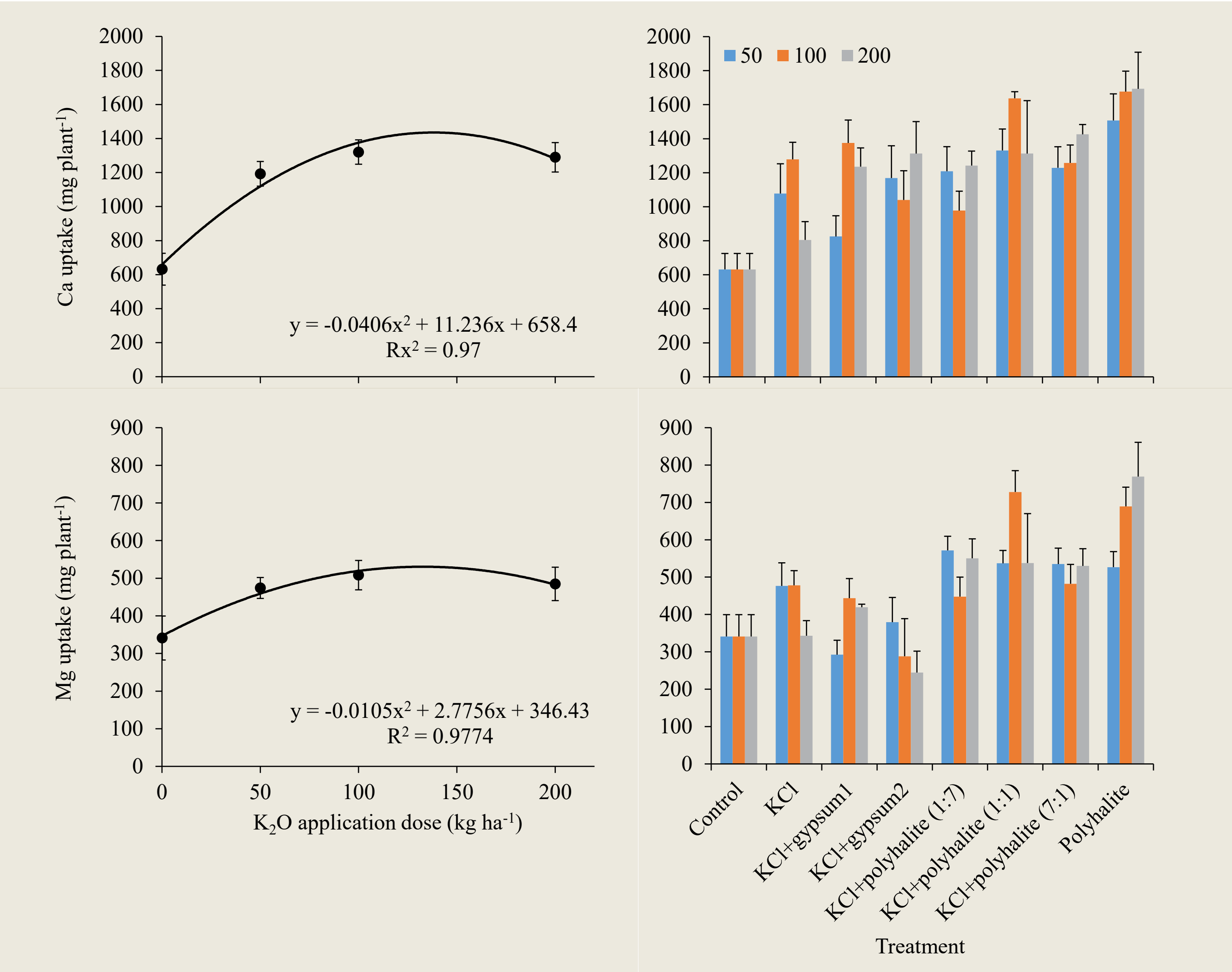

Fig. 5. Alfalfa Ca and Mg uptake in response to K application (rates of 50, 100, and 200 kg K_2O ha^{-1}) in a pot-grown experiment. Mean Ca or Mg uptake in response to K dose (left); effects of K origin and dose on Ca or Mg uptake (right). Bars indicate SE.

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The paper "Polyhalite Compared to KCl and Gypsum in Alfalfa Fertilization" also appears on the IPI website at:

Regional activities/Latin America

Research Findings

Photo 1. Field experiment exploring the effects of potassium applied through either mineral fertilizer or rice straw. Photo by the authors.

Effects of Long-Term Application of K Fertilizer and Rice Straw on Yields, Crop K Uptake, and Soil K Supply Capacity in Double Rice Cropping Systems on Reddish Paddy Soils

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Abstract

The effect of potassium (K) application through mineral fertilizer or rice straw (RS) on rice yield, crop K uptake, and soil K supply capacity were studied in a long-term fertilization experiment (1981-2012) under an intensive double rice cropping system. The application of combined mineral K and soil-embedded RS significantly increased rice grain and straw yields. Potassium uptake significantly increased following consistent application of mineral K, RS, or both. The average annual amount of crop K uptake was in the order of: mineral NPK+RS > NPK > NP+RS > CK > NP. Long-term absence of K application led to a deficit in available, slowly-available, and total topsoil K. Long-term K application through mineral fertilizer and RS not only increased topsoil illite content, but also transformed poor-crystallized illite into well-crystallized illite. In-vitro K saturation treatments

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demonstrated the increased X-ray diffraction peak area of illite versus the declining vermiculite/chlorite peak. Soil K quantity/intensity (Q/I) parameters indicate an improved soil K capacity following long-term K application. It appears that two contradictory processes occurred in the reddish paddy soil, when applied with K releasing materials. The first is the enrichment of the soil solution with K^+ ions and its positive consequences on the clay composition and on K saturation of clay minerals, mostly illite. While mineral K application boosts the soil solution with K at the beginning of the crop cycle, the degrading RS provides a consistent K supply thereafter. The conflicting process is the declining soil pH, with its negative effect on clay mineral structure and its affinity to K and other cations. So far, the positive effects dominate, demonstrating significant influences on crop performance as well as soil fertility. However, the mechanisms involved in the long-term K status in paddy soils are very complex, with many interactive factors, most of which are still obscure. Apparently, RS can successfully replace much of the mineral fertilizer, however, the particular sensitivity of the paddy soil system to soil pH must be taken into account.

Keywords: Illite; long-term K application; potassium quantity/intensity; *Oryza sativa* L.; reddish paddy soil; rice straw.

Introduction

Potassium (K) is an essential nutrient for plants' metabolism and growth, and it has an irreplaceable role in agricultural production (Huang *et al.*, 1998; Liao *et al.*, 2008; Liao *et al.*, 2010). The shortage of K resources in China, and insufficient soil K supply, have severely restricted the development of agricultural production. Therefore, evaluating soil capacity for K supply and the effects of enduring fertilization is critical.

Soil K occurs in different forms: water soluble - free K^+ in the soil solution; exchangeable form - K^+ adhered to the surface of soil particles; non-exchangeable form - K adsorbed to the inner fractions of soil particles; and, mineral form - where K is intrinsic to the chemical structure of the soil minerals. Soil K supply capacity is attributed mostly to the former available forms - water soluble K and exchangeable K, nevertheless, on the long-term, the other two forms may also contribute to the soil K supply. The available K forms are the main source for the current crop's K requirements; therefore, they are considered as an important index characterizing the actual or immediate soil K status. The non-exchangeable K, including mineral lattice K (e.g., biotite) or fixed mineral K (such as in vermiculite and other 2:1 layered silicate minerals), may be converted under certain conditions into exchangeable K or even into soluble K. Different K pools are transformable, and the direction, extent, and rate are affected by various factors (Scherer and Zhang, 2002; Liao *et al.*, 2013a; Liao *et al.*, 2013b), among which mineral composition and quantity have important roles (Zheng *et al.*, 1989; Jin, 1994; Fan and Xie, 2005; Liao *et al.*, 2013b).

Plant response to K availability is often influenced by other soluble nutrients in a given soil. Therefore, methods of physical chemistry must be employed. Thus, thermodynamic parameters, such as relative K activity, K intensity, K-specific site, K strength, K capacity, and potential K-buffering capacity have been widely applied in the efforts to assess soil K supply capacity (Woodruff, 1955; Salmon, 1960; van Schouwenburg and Schuffelen, 1963; Beckett, 1964; le Roux and Sumner, 1968; Molina, 2016).

In earlier studies, basic mechanisms related to the variation and transformation of soil K forms, the interaction between crop root and soil K transformation, and to the interaction between organic and inorganic K fertilizer sources with soils under redox effects remained unclear, particularly under conditions of

Photos 2. Plots with different nutrients omitted (left); plots with and without K application (right) (at tillering stage). Photos by the authors.

continuous cropping systems. Therefore, it is important to further investigate the transformation characteristics of soil K in general, and especially of clay mineral K under long-term continuous cropping rice systems that are very common in China. Understanding these mechanisms will enable the design of improved fertilization management, which will consider the inherent soil K balance and its interactions with applied organic and inorganic K fertilizers, all together meeting crop K demands (Xie *et al.*, 2000; Chen *et al.*, 2000; Liao *et al.*, 2009).

The objectives of the present study were to determine the influence of long-term application of K fertilizer and straw on rice yield and crop K uptake, and to evaluate and quantify the dynamics of soil K forms, including K-bearing clay minerals and K adsorption and desorption under continuous application of K fertilizer and straw. The study provides a theoretical basis for optimal K management of double-rice cropping systems on red soils.

Materials and methods

Site description

Field experiments were conducted from 1981 until 2012 in Huangjin town, Wangcheng county, Hunan Province of China at the Scientific Observing and Experimental Station of Arable Land Conservation, Ministry of Agriculture, 28°37'N, 112°80'E, 100 m above sea level. The average annual rainfall was 1,393 mm, the annual mean temperature was 18°C, and the annual mean frost-free period was 300 days. Soil characteristics are given in Table 1.

Table 1. Experimental soil properties.

Soil type	Quaternary red soil
Soil texture	Silty light-clay
pH	6.6
Organic matter	34.7 g kg^{-1}
Total nitrogen (N)	2.05 g N kg^{-1}
Alkali-hydrolysable N	151.0 mg kg^{-1}
Total phosphorus (P)	0.66 g P_2O_5 kg^{-1}
Available P	10.2 mg kg^{-1}
Total potassium (K)	14.2 g K_2O kg^{-1}
Immediately available K	62.3 mg kg^{-1}
Slowly available K	173.8 mg kg^{-1}

Experimental design

The field experiment was laid out with five treatments (Table 2) in three replicates. Each plot area was 66.7 m^2, with 30 cm wide cement bunds between plots in order to avoid cross contamination. There were two rice crops each year, early (late April to mid July) and late (late July to late October), using regular and hybrid rice cultivars, respectively. Nitrogen (N), P and K mineral fertilizers used were urea, superphosphate and KCl, respectively.

Five treatments were: CK (no fertilizer); NP (mineral N and P fertilizer); NPK (mineral N, P, and K fertilizer); NP+RS (mineral N and P fertilizer, and rice straw); NPK+RS (mineral N, P, and K fertilizer, and rice straw). During the period from 1981 to 2012, N fertilizer was applied at 150 and 180 kg N ha^{-1} for early and late rice, respectively. Phosphate fertilizer was applied at a rate of 38.7 kg P_2O_5 ha^{-1} for the early as well as late crops. Potassium fertilizer rates were 99.6 kg K_2O ha^{-1} in early and late rice. Rice straw was incorporated into the soil at a rate of 2.1 Mg ha^{-1} (containing 21.4, 2.8, and 54.6 kg ha^{-1} of N, P_2O_5, and K_2O, respectively) in the early as well as in the late rice seasons. Phosphorus (P) and K fertilizer and straw were applied to the soil before transplanting, while N fertilizer was applied twice: 50% before transplanting, and the rest at tillering. The regular rice cultivar was planted for the early crop, and a hybrid rice for the late one. The early crop was planted in late April and harvested in mid-July. The late crop was planted in late July and harvested in late October. Seedlings at 30-35 days of age were transplanted into each plot; 4-5 per hole in the early rice, and 1-2 in the late rice. Plant spacing was 20 x 20 cm. Pest management and other routines were applied using local farmers' practices.

Sampling, measurements, and data analysis

Grain yield was determined from the whole plot of each replicate. Plant samples were collected from multiple points and mixed evenly. Plant K content was determined using a flame photometer (Lu, 2000).

Soil samples were collected from 0-15 cm topsoil (one week after the late crop harvest, 2 November 2012), using a tubular soil sampler. Soil was air dried, sieved and stored in a sealed jar. Soil K extraction and determination followed the methods described by Lu (2000), using a flame photometer. Total soil K was extracted with NaOH, slowly-available K was extracted with hot HNO_3 (1 mol L^{-1}), and available K was extracted with NH_4OAc (1 mol L^{-1}). Basic physical and chemical

Table 2. Detailed fertilization plan of the treatments.

Treatment	Mineral N		Mineral P_2O_5		Mineral K_2O		Straw N		Straw P		Straw K	
	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late
	kg ha^{-1}											
CK - no fertilizer	-	-	-	-	-	-	-	-	-	-	-	-
NP	150	180	38.7	38.7	-	-	-	-	-	-	-	-
NPK	150	180	38.7	38.7	99.6	99.6	-	-	-	-	-	-
NP+RS	150	180	38.7	38.7	-	-	21.4	21.4	2.8	2.8	54.6	54.6
NPK+RS	150	180	38.7	38.7	99.6	99.6	21.4	21.4	2.8	2.8	54.6	54.6

properties of the samples were conventionally determined according to Lu (2000). Clay mineral composition was determined using X-ray diffraction method (Moore and Reynolds, 1997), followed by numerical-graphic methods (Lanson, 1997), and the mineral diffraction peak areas were calculated using NEWMOD program (Reynolds, 1985). Potassium quantity/intensity (Q/I) parameters in soil samples were determined following Beckette (1964). Data analyses employed Microsoft Excel 2003 and 7.5 DPS data processing system.

Results

Rice grain and straw yields increased significantly in response to long-term application of K, either through mineral K fertilizer, embedding of RS or both (Fig. 1). The order of grain yield in early and late rice was: NPK+RS > NPK > NP+RS > NP > CK. Compared with the non-fertilized control (CK), the application of NP fertilizer gave rise to 69.5% and 39.9% increase in early and late grain yields, respectively. Potassium supply, either through mineral NPK, organic K source (rice straw), or both, provided additional significant rise in grain yields, of 88-111% and 60-75% over CK, in the early and the late crop, respectively. When compared to the NP yield, K supply brought about 10.9%, 15.9%, and 24.7%, and 14.4%, 17.5%, and 25.2% increase in the grain yield of RS, NPK, and NPK+RS, of the early and late rice crops, respectively. Straw biomass tended to increase in response to application of NP fertilizer. However, this response was significant only following K supply, resulting in 41-58% and 38-62% increases in straw biomass of early and late rice crops, compared to CK (Fig. 1). No significant differences occurred between the K contributing treatments; however, when compared to NP, straw biomass increased by 9-21%, and 14-34%, in the early and late crops, respectively (Fig. 1).

Responding to application of NP fertilizer, K uptake by the grain yield increased significantly, by 99% and 56% in the early and late crop, respectively, compared to CK (Fig. 2). Mineral NPK

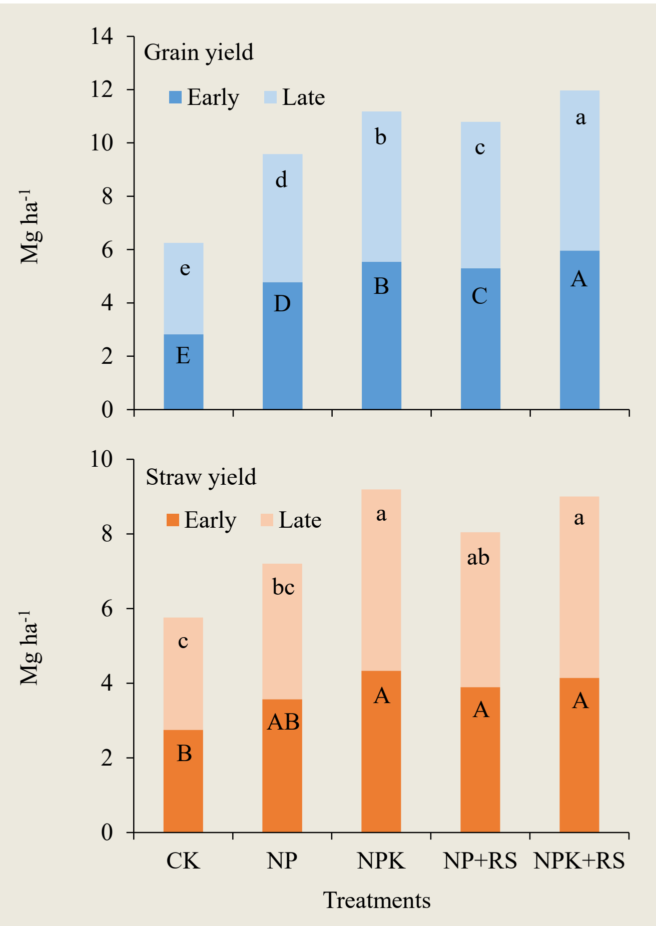

Fig. 1. Effects of K fertilization and rice straw (RS) application on grain yield and straw biomass of two successive rice crops, early and late, in 2017, following 32 years of the experiment. Similar lowercase and uppercase letters indicate no statistical differences at P = 0.01 within the early and the late crop, respectively.

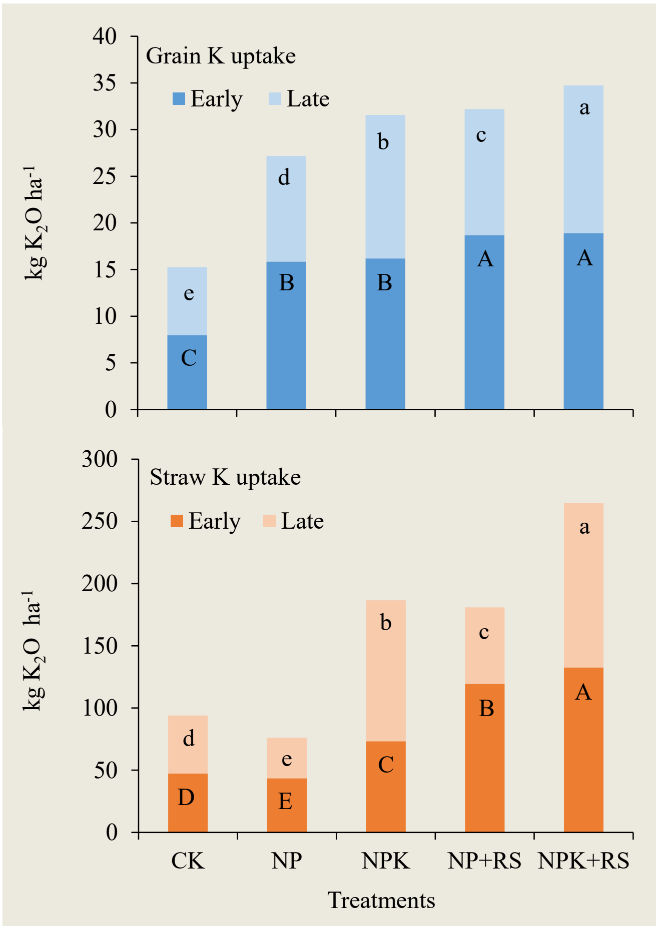

Fig. 2. Effects of K fertilization and RS application on K uptake by grain and straw biomass of two successive rice crops, early and late, in 2017. Similar lowercase and uppercase letters indicate no statistical differences at P = 0.01 within the early and the late crop, respectively.

application brought about a significant increase in grain K uptake, 36% more than NP but only in the late crop, whereas no impact was observed for the early crop. Embedded RS, on the other hand, resulted in a significant rise in grain K uptake of both early and late crops, 18-20% more than NP. The combination of mineral NPK and RS application gave rise to the greatest grain K uptake, particularly in the late crop, 40% more than NP (Fig. 2). Nevertheless, K uptake by the straw biomass was far greater than that of the grains (Fig. 2). Under no fertilization (CK), K uptake by each crop was about 47 kg K_2O ha^{-1} and 7-8 kg K_2O ha^{-1}, in the straw and grains, respectively. Contrary to grain K uptake, straw K uptake declined significantly in response to NP fertilizer, especially in the late crop. Application of mineral NPK resulted in significant increases in straw K uptake, 70% and 250% more than NP, in the early and late crop, respectively. On the other hand, RS supported significant straw K uptake during the early crop, but a modest one in the late crop (174% and 88% more than NP, respectively). Yet, the most pronounced K uptake by straw biomass was in response to the combined treatment (NPK+RS), 180% more than CK in both crops, and 3- and 4-fold K uptake by NP straw in the early and late crop, respectively (Fig. 2).

The overall yearly K uptake of CK was 109 kg K_2O ha^{-1}, an amount which slightly decreased under mineral NP application to 103 kg K_2O ha^{-1}. Obviously, the origin of the K taken up in those two cases was the native soil (Fig. 3). Once mineral K was applied (NPK), crop K uptake surged to about 220 kg K_2O ha^{-1}, of which the soil K contribution was about 10%. Under application of mineral NP+RS (but no mineral K), crop K uptake was about 200 kg K_2O ha^{-1}, with an equal K contribution by RS and soil K. However, under combined application of mineral NPK+RS crop, K uptake increased to 300 kg K_2O ha^{-1}, 67% of which was supplied by the mineral fertilizer, and 33% by the embedded RS.

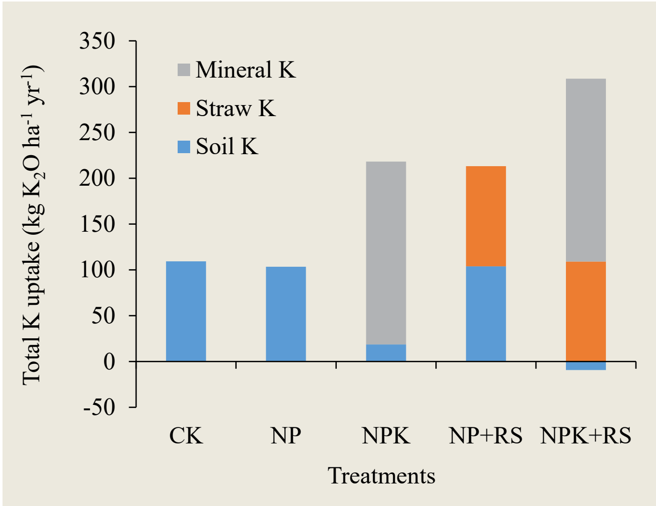

Fig. 3. The contribution of mineral fertilizer, RS, and soil K to total yearly K uptake by two rice crops following 32 years of experiment.

Theoretically, under this practice, an excess yearly amount of about 9 kg K_2O ha^{-1} enriches the soil-K reserves (Fig. 3).

Compared to the initial soil properties, fertilization treatments - not including mineral K - brought about an obvious degradation in the soil exchangeable K content, which embedded RS alone did not prevent (Fig. 4). Application of mineral K fertilizer, alone or with RS, gave rise to significant increases of about 50% and 100% in exchangeable K content, respectively. A more or less similar pattern was observed with the non-exchangeable component of soil K; however, both degradation and repair rates were much smaller than in the exchangeable K fraction. During 32 years of the double rice cycle, total soil K content declined considerably in all fertilization treatments (Fig. 4). Total K loss from CK topsoil

Photos 3. Plots with different nutrients omitted (left) (mature stage); plots with and without K application (right) (just before mature stage). Photos by the authors.

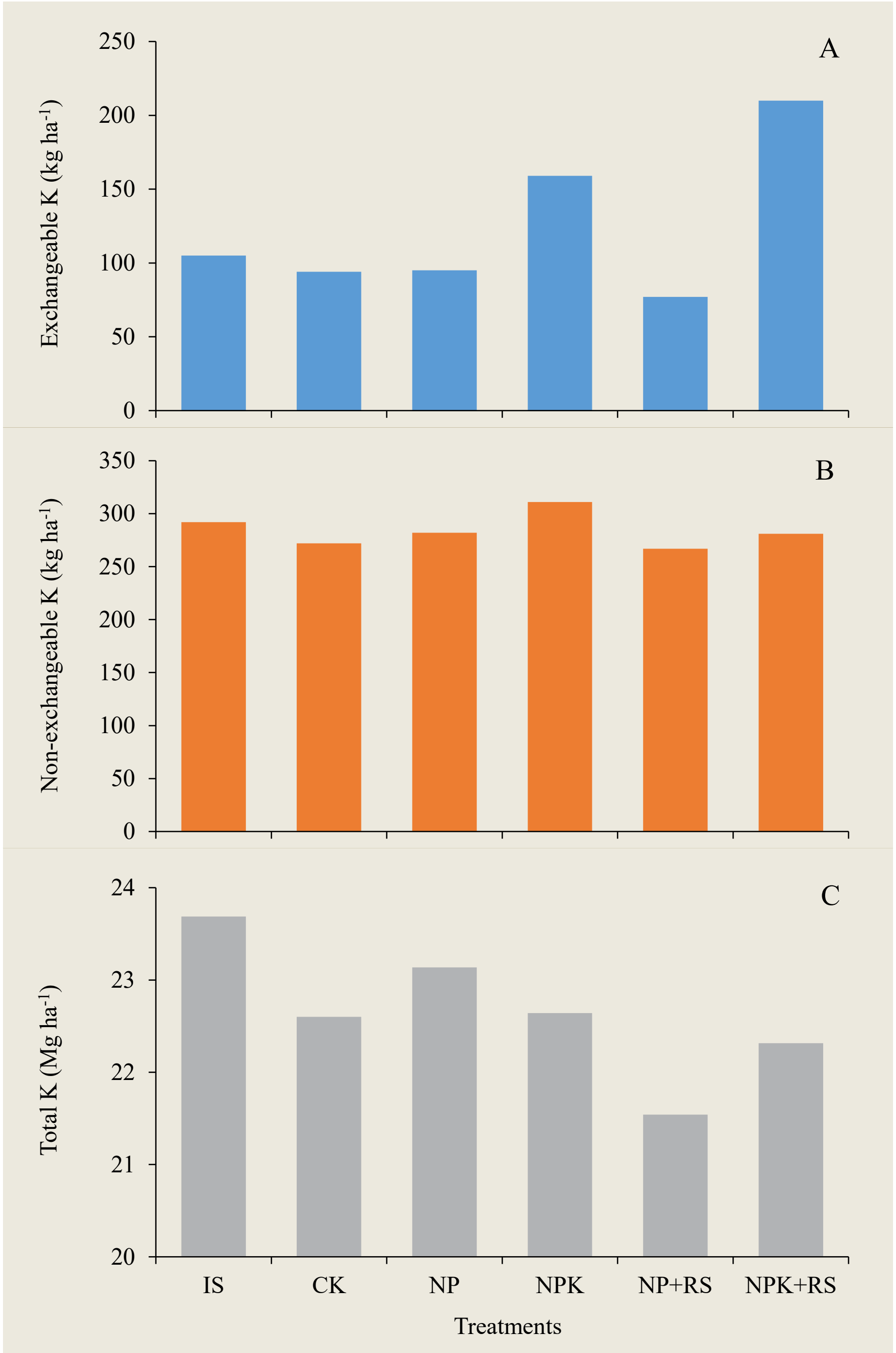

Fig. 4. Effects of long-term (32 years) treatments on the exchangeable (A), non-exchangeable (B), and total K (C) topsoil (depth 0-15 cm) contents. (IS: initial soil).

was about 1.1 Mg ha^{-1}, similar to that of NPK, and twice as high as NP treatments. Interestingly, the greatest total K loss, 2.15 Mg ha^{-1}, was recorded in NP+RS treatment, compared to about 1.37 Mg ha^{-1} in NPK+RS (Fig. 4).

X-ray diffraction patterns of the clay fraction (soil particles < 5 µm) treated with magnesium-saturated glycerin, ethylene-glycol, K^+ saturation, and 300°C or 550°C heat treatments, were used to determine the nature and distribution of the dominant clay minerals in the soil and to evaluate the influences of the different long-term fertilization treatments on clay mineral composition (Table 3).

Vermiculite/chlorite, the dominant clay fraction (36-40%), slightly increased from 38% (IS) to almost 40% under the absence of K fertilization, and decreased down to 36% under consistent K supply of mineral, as well as organic origin. Kaolinite proportion, 27.6% of the clay fraction, also increased in the absence of K supply, and declined to 25% where K was supplied. The mixed-layer mineral (comprising vermiculite/chlorite and illite) was stable at 18% under no K application, and dropped to 14-16% when K was supplied. An opposite response pattern was observed for illite and its two components - well- and poorly-crystalized illite; their portion decreased in the absence of K supply, and rose by 40-50% (from 16 to 24%) of the clay minerals in response to K application. All these changes were much more pronounced where mineral K was involved; however, the response to RS alone was obvious (Table 3).

Further in-depth X-ray diffraction analyses of the major K-responsive clay minerals (illite, vermiculite/chlorite, and the mixed-layered mineral of the two), before and after K^+ saturation, revealed the significance of illite fractions in the K^+ exchange processes. The profile of K-saturated illite in the X-ray diffraction tests was doubled, compared to the natural free illite (Fig. 5). In contrast, the vermiculite/chlorite profile tended to decrease in response to K-saturation treatments. As indicated from the various mixtures of clay minerals examined (data not shown), the greater the illite fraction in the clay mineral composition, the higher the soil K exchange capacity.

Years of different fertilization regimes had only a slight influence on the topsoil organic matter content, which gradually increased from 33.14 g kg^{-1} to 38.55 g kg^{-1},

Table 3. Clay mineral distribution (%) in paddy soils after 32 years of consistent fertilization treatments compared to that of the initial soil (IS).

Treatment	V/CH	ML	KL	IL	WCI	PCI
IS	38.09	18.21	27.60	16.10	4.20	11.90
CK	39.23	17.32	28.75	14.70	3.08	11.62
NP	39.61	18.45	27.57	14.37	2.82	11.55
NPK	36.17	15.57	25.12	23.14	6.64	16.50
NP+RS	37.30	15.26	25.98	21.46	6.62	14.84
NPK+RS	35.99	14.41	25.31	24.29	6.88	17.41

Note: V/CH: vermiculite-chlorite; IL: illite; ML: a mixed-layer mineral of V/CH and IL; KL: kaolinite; WCI: well-crystallized IL; PCI: poorly-crystallized IL.

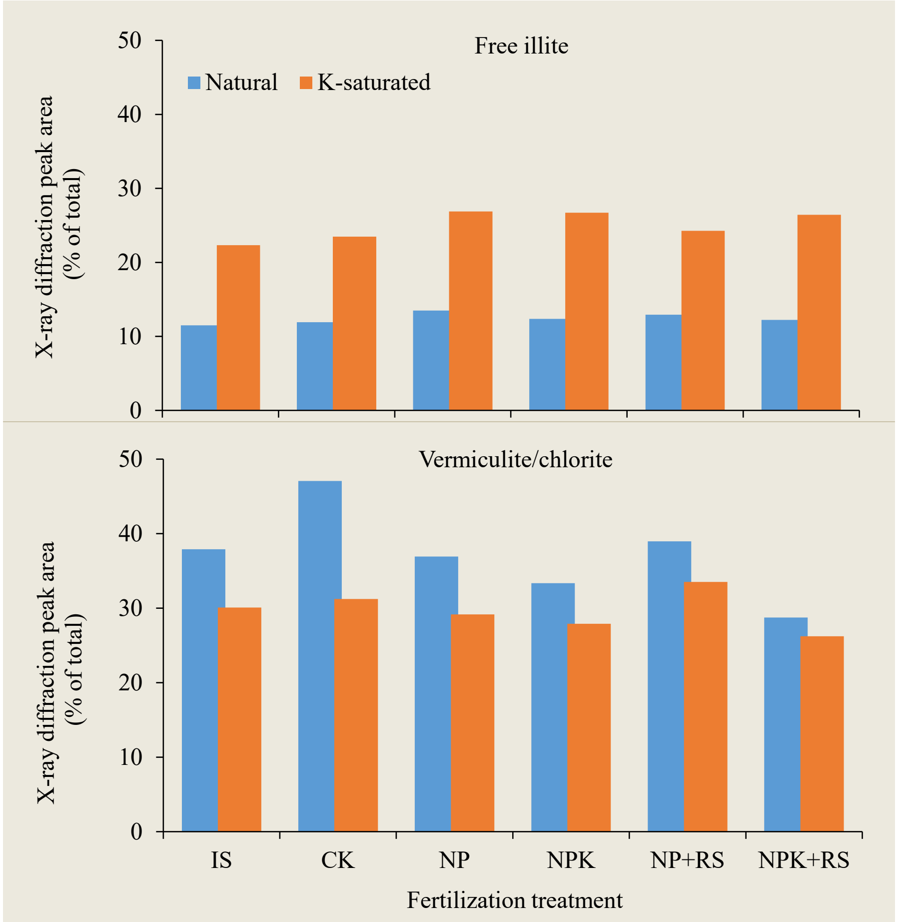

Fig. 5. Effects of long-term K fertilization regimes on the relative X-ray diffraction peak area of free illite and vermiculite/chlorite in the natural or K-saturated states.

from CK to NPK+RS (Table 4). This was in spite of the considerably large straw biomass quantities added to the RS treatments. Exchangeable K, measured using the NH_4OAc method, increased slightly at NP+RS, was higher at NPK, and much higher at NPK+RS.

Cation exchange capacity (CEC), also measured using the NH_4OAc method, was somewhat higher at NP+RS only, displaying no significant changes in the other treatments. Soil pH declined from 5.8 at CK, to 5.2-4.4 in the fertilized treatments (Table 4).

The long-term impact of the different fertilization treatments was further examined evaluating several K quantity/intensity (Q/I) parameters in the reddish paddy soil. Soil content of labile K ($-\Delta K^o$) in CK and NP was low, indicating poor levels of soluble K. While embedded straw (NP+RS) brought about a slight increase of labile K, mineral K application (NPK) caused a more considerable rise of this parameter (about 50%). Nevertheless, the most significant increase, about 100%, occurred in the combined NPK+RS treatment (Table 5).

Quite similar response patterns to the fertilization treatments were displayed by the K-specific adsorption sites parameter (K_X). Here, NPK and NP+RS had an equal impact, increasing K_X by about 30%, but NPK+RS yielded a 50% rise, compared to CK (Table 5). AR_e^k is another indicator of the intensity of easily released K. AR_e^k values in non-fertilized (CK) and NP treatments were significantly lower than those obtained by NPK and NPK+RS treatments, although NP+RS did not lag far behind (Table 5). PBC^K is a measure of soil potential K-buffering capacity - the ability to maintain K strength in the soil solution. High PBC^K values, such as displayed by CK and NP, indicate that large K^+ quantities are required to obtain a given soluble K concentration in the soil solution. In other words, the soil particles absorb most of the added K from the soil solution. The lower values observed in the K fertilized treatments indicate the smaller K amount required for the same purpose in those soils (Table 5). Gibbs free energy ($-\Delta G$) measures the energy required to exchange adsorbed K with an equivalent amount of Ca and Mg ions, and is an additional indicator of soil K availability. The high values observed for CK and NP indicate the considerably high energy needed to release K from the soil particles and a higher risk of crop K deficiency. $-\Delta G$ values slightly decrease in the NP+RS soil, but significantly drop in the NPK, and decrease even further in the NPK+RS soils (Table 5).

Table 4. Soil organic matter, pH, and cation exchange capacity (CEC) of reddish paddy soil samples representing long-term application of fertilizers and rice straw.

Treatment	Organic matter	Exchangeable K	CEC	pH
	g kg⁻¹	-----------------*cmol kg⁻¹*-----------------		*H_2O*
CK	33.14	0.17	12.9	5.8
NP	33.96	0.14	13.2	5.2
NPK	36.02	0.28	13.2	5.3
NP+RS	37.03	0.20	15.0	5.4
NPK+RS	38.55	0.37	13.5	5.4

Discussion

In the recent decades, Chinese agriculture has undergone tremendous changes in order to increase efficiency and productivity. Nevertheless, traditional farming is still the livelihood source for millions of farmers. Double-rice cropping on paddy soils is the basis of traditional farming in many regions. Improving the productivity as well as securing the sustainability of this system is essential. The maintenance of long-term soil fertility is pivotal; while N and P application is commonly practiced by most farmers, dissemination of the need to restore and maintain an appropriate soil K status requires further approval and demonstration. Rice crops produce significant straw biomass, which must be taken care of between cycles. Rice straw is commonly used as a biofuel; however, significant amounts of nutrition elements, including K, are withdrawn from the field that way. Another practice is on-field straw burning, so the ash returns to the soil. Nevertheless, this practice impedes the opportunity to enrich the soil with organic matter, which might affect soil structure and texture. The contribution of embedded RS to soil fertility, structure, and K status can be evaluated in the long-term - over many years - as the processes involved are very slow. The present study, ending 32 years and 64 cycles of rice crops, provides a comprehensive as well as an in-depth insight into the long-term impact of mineral NPK, with and without embedded RS application, on the system productivity, soil clay composition, and K status, compared to the necessary controls.

Unequivocally, mineral NP application brought about a significant primary boost in grain and straw biomass, about 40% more than the non-fertilized (CK) treatment (Fig. 1). NP application drew the limited K available from straw to grains (Fig. 2), and consequently significantly increased the harvest index from 52% to 57% (Fig. 6). The addition of K to the mineral NP application significantly increased crop K uptake (Fig. 2) and released the pressure from soil K (Fig. 3). It also increased crop biomass, especially that of straw (Fig. 1), thus reducing the harvest index (Fig. 6). Nevertheless, mineral NPK gave rise to a further significant increase in grain yields (Fig. 1). Interestingly, crop K uptake - where K supply was solely through RS (NP+RS) - was similar to that of mineral NPK (Fig. 2). Embedded RS contributed 50% of K uptake (Fig. 3). Grain and straw biomass were slightly (though statistically significant) lower than those of mineral NPK treatment (Fig. 1). The highest grain yields were obtained by the NPK+RS treatment which, together with the mineral NPK treatment, also had the highest straw biomass (Fig. 1). NPK+RS also displayed the highest K uptake, which was especially pronounced in the straw (Fig. 2). Noteworthy is the full dependency of the crop on supplied K and, moreover, the considerable support to soil K status in this treatment (Fig. 3). In both NP+RS and NPK+RS, the high harvest index of 57% was restored and maintained (Fig. 6). These results may suggest that mineral K has more impact on the vegetative biomass, while embedded RS supports the grains. An explanation may also be provided by the different nature of the two K origins. Mineral K is soluble and mobile in the soil, and its impact is therefore short-term and may be limited to the earlier crop phase, closer to its application. On the other hand, K release from organic matter, such as embedded RS, is much slower but consistent, and hence available during the grain-filling period.

As shown in Figs. 1-3, relying solely on soil K resources (CK and NP) certainly restricts crop performance and, furthermore, it might significantly

Table 5. Effect of long-term application of K fertilizer and rice straw on Q/I parameters in reddish paddy soil.

Treatment	Labile K; $-\Delta K°$	K-specific sites; Kx	Labile K intensity; AR_e^K	Potential K buffering capacity; PBC^K	Gibbs free energy; $-\Delta G$
	---------------------*cmol kg⁻¹*---------------------		*$cmol\ kg^{-1\ 0.5}$*	*$cmol\ kg^{-1}/cmol\ kg^{-1\ 0.5}$*	*$kJ\ mol^{-1}$*
CK	0.1498	0.1532	0.0078	19.67	15.34
NP	0.1608	0.1624	0.0082	19.85	14.87
NPK	0.2181	0.2194	0.0145	15.11	10.50
NP+RS	0.1868	0.2099	0.0136	15.48	13.80
NPK+RS	0.2970	0.2400	0.0168	14.29	9.79

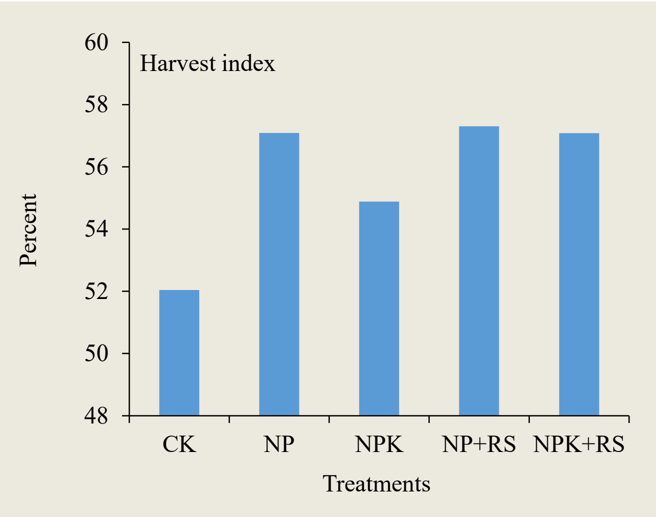

Fig. 6. Effect of long-term fertilization treatments on the harvest index of double rice crop in 2012, following 32 years of experiment.

degrade soil fertility. In fact, after 32 years of rice crops, the total topsoil K content declined in all treatments (Fig. 4). It was particularly reduced in the NP+RS treatment, where the enhancement of crop performance relied on the organic K from RS. Any expectation for higher yields must be accompanied by sufficient external K supply. Accounting for NP+RS, the amounts of RS should be increased in order to meet crop performance under mineral NPK. The NPK+RS combination, at the doses tested in the present study, seem to meet crop K requirements and provide the desired yield.

In intensive agricultural systems, K application is also essential for the maintenance of soil fertility. The type and rate of K application affect the exchangeable and non-exchangeable fractions of soil K. Excluding the NPK treatment, the non-exchangeable K declined in all treatments. Topsoil exchangeable K, however, increased significantly in the NPK and NPK+RS treatments, but decreased in the others (Fig. 4).

A long-term fertilization regime, 32 years, has significant influences on the composition of soil clay minerals (Table 3). While decreasing under regimes with no K application (CK and NP), illite fraction substantially increased under consistent K supply. These results support earlier evidence of gradual transformation of one clay mineral to the other as a result of long-term fertilization regime (Tributh *et al.*, 1987). The increasing fractions of poor- and well-crystallized illite under K fertilization, relative to the total illite fraction, clearly indicate an active development of new illite minerals at the expense of vermiculite/chlorite. This dynamic is absent, or even opposite where no K was applied (Table 3). Results of K-saturation treatments applied on the different clay minerals may demonstrate the process through which long-term K application can transform vermiculite to illite (Fig. 5).

Soil organic matter content is known to have a direct effect on soil CEC (Thomas and Hargrove, 1983). Nevertheless, the differences in soil organic matter content between treatments were very small in the present study, although substantial quantities of RS were applied to two of them. Possibly, the degradation rates of organic matter were very rapid under the typically high moisture and temperature conditions of the region. Fermenting organic matter might have contributed to the pH decline (Table 4) which might, in turn, negatively affect CEC (Helling *et al.*, 1964; Blum and Bride, 1979; Thomas and Hargrove, 1983).

It appears that two contradictory processes occurred in the reddish paddy soil when applied with K releasing materials. The first is the enrichment of the soil solution with K^+ ions and its positive consequences on the clay composition and on the penetration and saturation of clay mineral, mostly illite, with K, as reflected in the changes in Q/I parameters of soil K status (Table 5). While mineral K application boosts the soil solution with K at the beginning of the crop cycle, close to the application time, the degrading RS provides a consistent K supply thereafter. The higher affinity of soil particles vs. organic matter (Salmon, 1960) derive K from RS to illite. Thus, $-\Delta G$ values in CK and NP treatments were far below the K deficiency threshold (Woodruff, 1955), equal to this threshold in NP+RS, and considerably higher, with sufficient K in the NPK and NPK+RS treatments, although calcium (Ca) deficiency might be induced (Woodruff, 1955). The conflicting process is the negative effect of too lowered pH on clay minerals and their affinity to K and other cations (Prett *et al.*, 1962).

So far, the positive effects seem to dominate, demonstrating significant influences on crop performance as well as soil fertility. However, the mechanisms involved in long-term K availability in paddy soils are very complex, with many interactive factors, the full understanding of which still requires further substantial research efforts. The paddy soil system is extremely sensitive to many factors, including soil pH which must be taken into account.

Acknowledgement

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Regional activities/China

Research Findings

Basmati rice harvesting at Wamumu site, Kenya. Photo by the authors. 2017.

Rice Response to Potassium Fertilization in Mwea, Kenya

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Abstract

In Kenya, the importance of potassium (K) fertilization to enhance crop yields for food security and income generation cannot be disregarded. The present study aimed to evaluate rice responses to different rates of Muriate of Potash (MOP) fertilizer, thus establishing the fertilizer recommendation for maximum rice yields and further identifying the best K fertilizer resource for maximum rice yields. The two most popular rice varieties, Basmati 370 and BW 196, were used. Five different K rates were examined: 0, 40, 80, 120 and 160 kg K_2O ha^{-1}. In addition, three K fertilizers were tested: MOP, Sulphate of Potash (SOP), and NPK-17-17-17 (SSS), all applied at 80 kg K_2O ha^{-1}. Experimental design was a split plot design with fertilizer rates as main plots and rice varieties as the sub-plots in experiment 1, while in experiment 2 fertilizer types were the main plots and varieties were the sub-plots. These experiments were conducted in parallel in four locations in the Mwea Irrigation Scheme: Karaba, Tebere, Thiba, and Wamumu.

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Results revealed significant differences in plant height, tillering, total biomass, grain yield, and harvest index in most instances. These differences were associated with location, cultivar, and K application rates. Generally, grain yields were modest, ranging from 2.0 to 5.5 Mg ha^{-1} for Basmati 370, and from 2.0 to 10.0 Mg ha^{-1} for BW 196. Crop response to K application rate was quite small and limited, in most cases, to 40-80 kg K_2O ha^{-1}. No significant effect was observed for the K fertilizer type. Soil tests indicated severe soil acidity and K shortage at most locations. The restrained yields and relatively poor response to K rates points to fundamental challenges requiring solutions (e.g. soil acidity and water availability) before K fertilization is taken care of. However, splitting K dose during the season may improve K availability when required and crop K uptake, thus supporting better rice yields and income.

Keywords: Basmati 370; BW 196; *Oryza sativa*; soil acidity; paddy soil; potassium.

Introduction

The global population is expanding rapidly and will hit 9.4 billion by 2050 (United Nations Census Bureau, 2012). It is therefore of vital importance to improve crop yield to meet the food demands of future generations, while preserving the environment. However, agricultural production continues to be constrained by a variety of abiotic factors that significantly reduce the quantity and quality of crop production.

In Kenya, rice is the third most important cereal food crop after maize and wheat. Annual consumption is increasing at a rate of 12%, compared to 4% for wheat and 1% for maize, which is the main staple food (Emong'or *et al.*, 2009; Republic of Kenya, 2013). This is attributed to progressive changes in food consumption habits. The current demand for rice in Kenya is estimated at 325,000 Mg per year against the national production of 110,000 Mg per year (Republic of Kenya, 2013). The deficit, about two-thirds of consumption, is met through imports which were valued at KSh 7 billion in 2008. Promotion of rice production will therefore improve food security, increase smallholder farmers' income, contribute to employment creation in rural areas, and reduce the rice import bill.

The productivity of rice is not keeping up with growing demand in Kenya, posing a major threat to national food security. Practices of intensive continuous cropping with no, limited, or imbalanced fertilization has resulted in significant soil nutrient depletion. While efforts have been made to fertilize soils with nitrogen (N) and phosphorus (P), there has been very limited attention to potassium (K).

Potassium is one of the 17 essential nutrients required for plant growth and reproduction (Oborn *et al.*, 2005). It is essential for many physiological processes such as carbon assimilation, photosynthesis, protein synthesis, enzyme activation, stomatal movement, and translocation of organic and inorganic nutrients from soil to plant (Marschner, 2012). Management of K and other essential nutrients is therefore key to achieving a balanced fertility program (Orbon *et al.*, 2005; Zörb *et al.*, 2014). Potassium has a direct influence on the quality of seeds, fruits and vegetables by enhancing size, color, taste, and storage quality (Marschner, 2012; Zörb *et al.*, 2014). Furthermore, plants grown with K fertilizers have also been shown to have increased tolerance to stress factors like drought and frost, and have improved resistance to pests and diseases.

A lack of awareness in Kenya of the importance of K fertilization can be attributed to the general belief that Kenyan soils are well supplied with K (Hinga and Foum, 1972; Muchena, 1974). Nevertheless, evidence has indicated that outflows of major nutrients, including N, P, and K, is greater than inputs, therefore resulting in mining of these nutrients and associated decline in crop yields over time (Kanyanjua *et al.*, 2005). A study conducted several years ago in Mwea Irrigation scheme, revealed a severe K deficiency in 47 sites spread across the five major paddy rice growing sections in the scheme (Gikonyo *et al.*, 2012). Thus, there is growing evidence of increasing K deficiency as a result of: i) sub-optimal or no application of K fertilizers, and; ii) imbalanced use of N and P (Kanyanjua and Buresh, 1999; Gikonyo, 2002; Kanyanjua *et al.*, 2006). Despite these studies, K has not been included in fertilizer recommendations for major food crops in Kenya and its use remains low and limited to high value cash crops like tea, coffee, and some horticultural crops (Kanyanjua *et al.*, 2005). This fact is further confirmed in the recent economic review of agriculture in Kenya (Oseko and Dienya, 2015), showing that fertilizer utilization is still dominated by N and P.

Mwea Irrigation Scheme is a long-term project aimed at providing irrigation water to smallholder farmers in central Kenya (National Irrigation Board, 2017). Rice is the dominant crop in Mwea, and therefore the region has become a target for testing and adoption of the system of rice intensification (SRI), the goals of which are increasing rice yields substantially, saving water, and getting better grain quality (Mati *et al.*, 2015). Mwea Irrigation Scheme is situated between longitudes 37°13'E and 37°30'E and latitudes 0°32'S and 0°46'S. It is in Kirinyaga County, Mwea East and Mwea West sub-Counties (Map 1). The scheme is located at the foothills of Mt. Kenya about 100 km to the northeast of Nairobi. Although only 6,000 ha are under irrigation, the entire scheme covers 12,000 ha and supports a population of more than 50,000 people organized in about 3,242 farm families living in 36 villages. Mwea is the largest scheme in Kenya and is divided into five sections: Tebere, Mwea, Thiba, Wamumu and Karaba, with 820, 770, 750, 710, and 660 ha under irrigation, respectively. The region is classified as tropical, with a semi-arid climate, having an annual mean air temperature of 23-25°C, with about 10°C difference between the minimum (June/July) and the maximum temperatures (October and March). Annual rainfall ranges from 356 to 1,626 mm (average 950 mm), with 2,485 hours of sunshine. The soils in Mwea are classified as Vertisols (Sombroek *et al.*, 1982).

Currently, Mwea Irrigation Scheme accounts for 80% of the country's rice production. Two rice crops are grown annually, the main season occurring between August and December during the short rains, with a long rains crop grown between January and June. Three major rice varieties are grown in the scheme (Basmati 217/370, BW 196, and IR 2793-80-1). Mwea producers suffer from water shortages during the main growing season and often from blast attack during the long rains season, factors that lead to reduced rice yields in both seasons. Other benefits of rice beside income generation for farmers include employment both on farms and in the market. Rice is therefore very important to the livelihoods of Mwea people, with wider economic and food security implications for Kenyans.

In order to promote rice production in Mwea Irrigation scheme and support farmers' livelihood, determining a novel and suitable fertilization policy for rice is focal. Thus, appropriate fertilizer rates must be determined according to soil fertility and crop requirements at each location. Also, there is a need to look at crop performance and costs when identifying suitable fertilizer types. Consequently, the current study aims to sustainably increase rice production through K application. The specific objectives are:

1) To evaluate the response of the two most popular rice varieties in Mwea to different rates of K fertilizer in prospect of establishing a location-suitable K rate required to maximize yields.
2) To test the agronomic efficiency of three K fertilizer types in order to identify the most suitable one.

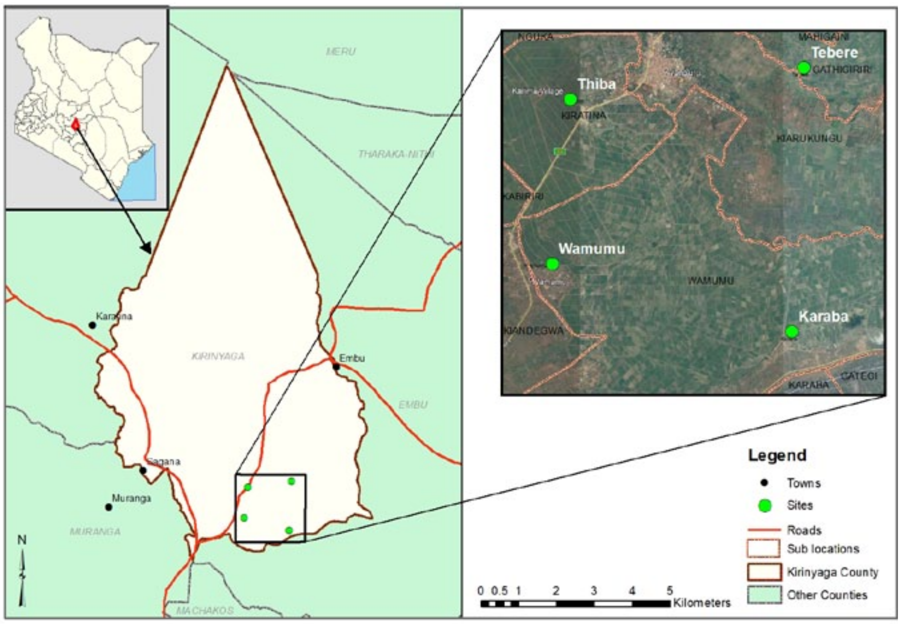
Materials and methods

The trials were conducted in four project sites representing the major rice systems covering the whole scheme. Selected sites were: a) *Thiba*, unit H19 of Ndungi (0º41'26.688 S; 37º20'8.874 E); b) *Wamumu*, unit W7 of Purity Wanjiru (0º43'45.556 S; 37º23'18.54 E); c) *Karaba*, unit K4 of John Ndambiri (0º44'47.176 S; 37º19'53.628 E); d) *Tebere*, unit T18 of James Kiarie (0º40'59.58 S; 37º23'28.638 E) (Map 1).

Composite soil samples were collected in a zig-zag fashion from each trial site. At least 10 samples from each site were combined to make one sample, put in a paper bag and labelled. Collected soil samples, pooled into one sample, were sent to KALRO-Kabete for complete soil fertility analysis. The soils exhibited different characteristics from site to site (Table 1) but generally:

- soils from all the sites were K deficient (K < 0.24 meq %) except Tebere top soil;
- all sites were P deficient (Mehlich 1 extractable P < 35 ppm) except Wamumu sub-soil;
- all soils had low soil pH (1:1 soil: water ratio), ranging from very strongly acid to strongly acid, except the sub-soils of Wamumu and Tebere;
- N and organic carbon (OC) were at sufficient levels except at Wamumu, where they were deficient;
- calcium and magnesium (not shown) were sufficient in all soils;
- iron (Fe) was very high, particularly in Karaba and Tebere, but was not very high in Wamumu;
- zinc (Zn) levels were adequate in all sites (Zn > 3.0 ppm); and
- sodium (Na) was generally high, particularly in Tebere and Wamumu.

Two experiments were carried out. The first, experiment 1, tested rice response to different K rates applied as Muriate of Potash (MOP, KCl). Nitrogen and P were applied according to crop nutrient removal, assuming crop yields of 7 Mg ha^{-1}. Thus, N and P were applied at 150 kg N ha^{-1} and 100 kg P_2O_5 ha^{-1}, respectively.



Map. 1. The locations of the experiment sites in Kirinyaga County, Kenya.
Source: Kenya Soil Survey (KSS).

Table 1. Soil characteristics of the four experiment sites. Bold figures indicate values below critical thresholds.

Location	Thiba		Karaba		Tebere		Wamumu	
Soil depth (cm)	0-20	20-50	0-20	20-50	0-20	20-50	0-20	20-50
Soil pH (soil:water, 1:1)	**4.51**	**4.53**	**5.14**	**4.50**	**5.44**	6.02	**5.12**	6.50
Exch. acidity (meq %)	0.4	0.4	0.3	0.4	0.1	n/a	0.2	n/a
Total nitrogen (%)	0.24	0.28	0.24	0.24	0.40	0.28	0.24	0.19
Total organic C (%)	2.29	2.58	2.26	2.31	3.86	2.72	2.32	1.95
Mehlich P (ppm)	**15**	**25**	**30**	**25**	**30**	**25**	**10**	40
Potassium (meq %)	**0.14**	**0.06**	**0.18**	**0.10**	0.26	**0.14**	**0.14**	**0.06**
Calcium (meq %)	15.0	14.8	15.0	13.8	28.0	25.8	17.8	19.8
Iron (ppm)	70.3	69.4	150	219	234	108	42.4	44.2
Zinc (ppm)	6.60	5.14	4.30	5.00	3.88	3.61	4.85	4.19
Sodium (meq %)	0.34	0.34	0.52	0.36	0.94	0.64	0.70	0.76

Phosphate was applied at planting, while N was applied in three splits: 30, 60, and 60 kg N ha^{-1} (sulphate of ammonia, SA) at transplanting, 24 days after transplanting (DAT), and 45 DAT, respectively. Potassium was applied at 0, 40, 80, 120 and 160 K_2O kg ha^{-1} at planting (Table 2). Two varieties of rice, basmati 370 and BW196, were used as test crops.

In experiment 2 (Table 3), rice cultivars Basmati 370 and BW 196 were tested for their response to three K sources: Muriate of Potash (MOP), Sulphate of Potash (SOP), and NPK 17-17-17 (SSS) (a complex commercial fertilizer blend comprising N, P_2O_5, and K_2O at 17% each), all of which were applied at a rate of 80 kg K_2O ha^{-1}. Blanket fertilizer rates of N and P similar to those used in experiment 1 were adjusted and applied.

Experiments 1 and 2 were conducted using a split-plot design replicated three times where the main plots were the fertilizer rates (experiment 1) and fertilizer type (experiment 2), and rice varieties were the sub-plots. The main plots were separated by polythene sheets inserted to about 0.2 m below the soil surface to prevent fertilizer seepage from one main plot to the other (Photos 1).

The four farms were planted from 25 July to 2 August 2016. Seedlings were planted at 21-25 days old in all farms except in Tebere, where 14-day rice seedlings were planted. Planting spaces were 25 cm between rows, and 15 cm between plants. Two seedlings were planted per hole. A starter fertilizer of 30 kg N ha^{-1} (SA), triple superphosphate fertilizer, and potash fertilizer (corresponding to the treatment) were applied before planting. No irrigation was applied for the first week to allow the seedlings to establish. Weeding was carried out as deemed necessary.

Data were taken from each plot using 10 plants that were tagged soon after transplanting. Plant height measurements were started two weeks after transplanting and continued at bi-weekly intervals. Basmati 370 was harvested in November, whilst BW 196 was harvested three weeks later, in December.

During harvesting, final tillering was determined. Towards harvest, the two outer rows and two outer seedlings of each plot were removed, leaving the inner area of 4.94 m^2 for harvesting. Harvesting was done manually using sickles, and rice was cut at about 15 cm above the ground. Total biomass weight was determined immediately, and later, after threshing, the grain yield was weighed. The stover and rice paddy were sampled for moisture determination by weighing before and after drying. Data were statistically analyzed using ANOVA. The significance of differences between mean values was evaluated by Duncan's Multiple Range Test. Treatments were declared significantly different if $p \leq 5\%$.

Table 2. Treatments of the K application rates, experiment 1.

Rice variety	K application rates through MOP (kg K_2O ha^{-1})
Basmati 307	0
	40
	80
	120
	160
BW 196	0
	40
	80
	120
	160

Table 3. Treatments of experiment 2, testing different fertilizers as K source for two rice cultivars. All treatments were adjusted at 80 kg K_2O ha^{-1}.

Rice variety	Fertilizer type
Basmati 370	MOP
	SOP
	SSS
BW 196	MOP
	SOP
	SSS

Plant height is often used as an indicator of nutrient influence on plant performance, especially at early developmental stages. For both cultivars and in most of the locations, plant height at 28 DAT was greater as K rates increased up to 80 kg

Photos 1. Demarcating sub-plots and main plots receiving different fertilizer rates. Inserting the plastic sheets (left); planting the demarcated plots (right). Photos by the authors.

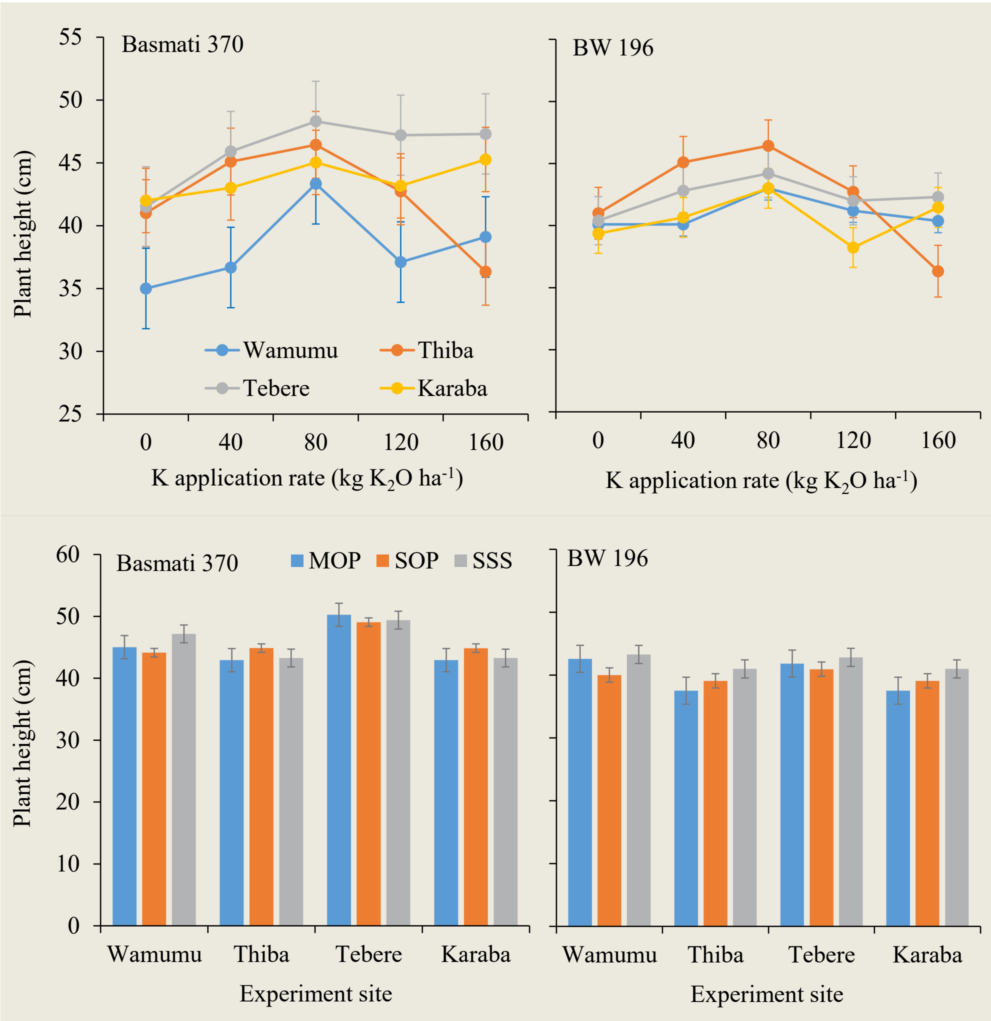


Fig. 1. Effects of K application rate (upper pair), and different K fertilizers at 80 kg K_2O ha^{-1} (lower pair), on plant height of two rice cultivars (Basmati 370 and BW 196) at 28 DAT.

K_2O ha^{-1}. Beyond this K rate, and excluding Basmati 370 at Tebere and Karaba, plant height declined (Fig. 1). Plant height of Basmati 370 differed significantly between experiment sites, with especially low values at Wamumu. The differences in plant height between sites were much less pronounced for cultivar BW 196. In the second experiment, where different K fertilizers were tested at a uniform rate (80 kg K_2O ha^{-1}), no significant differences were observed in plant height at 28 DAT (Fig. 1). There was a slight tendency of Basmati 370 to grow higher, in comparison to BW 196. Also, Basmati 370 was a bit higher at Tebere than the other sites.

The number of tillers per plant can be a good yield predictor. The tillering response to K rates differed substantially between cultivars and sites (Fig. 2). In Tebere, Basmati 370 displayed a consistent rise from 16 to 24 tillers per plant, while being quite constant in Thiba and Karaba (about 20 tillers plant^{-1}), and low in Wamumu (15-17 tillers plant^{-1}). Also BW 196 in Tebere displayed significantly greater tillering capacity, above 25 tillers plant^{-1}, with a clear response to K rate up to 80 kg K_2O ha^{-1}. This response pattern was visible also for BW 196 at Wamumu and Thiba at a lower tillering range. In Thiba, tillering of BW 196 was reduced above 80 kg K_2O ha^{-1}. In Karaba, tillering response was positive at the low and at the high K application rates, but it usually remained at 15-20 tillers plant^{-1} (Fig. 2). The influence of K fertilizer type on rice tillering was minor and inconsistent (Fig. 2). In Wamumu and Thiba, both cultivars tended to grow more tillers under SOP and SSS fertilizers, while this trend disappeared in Tebere and Karaba.

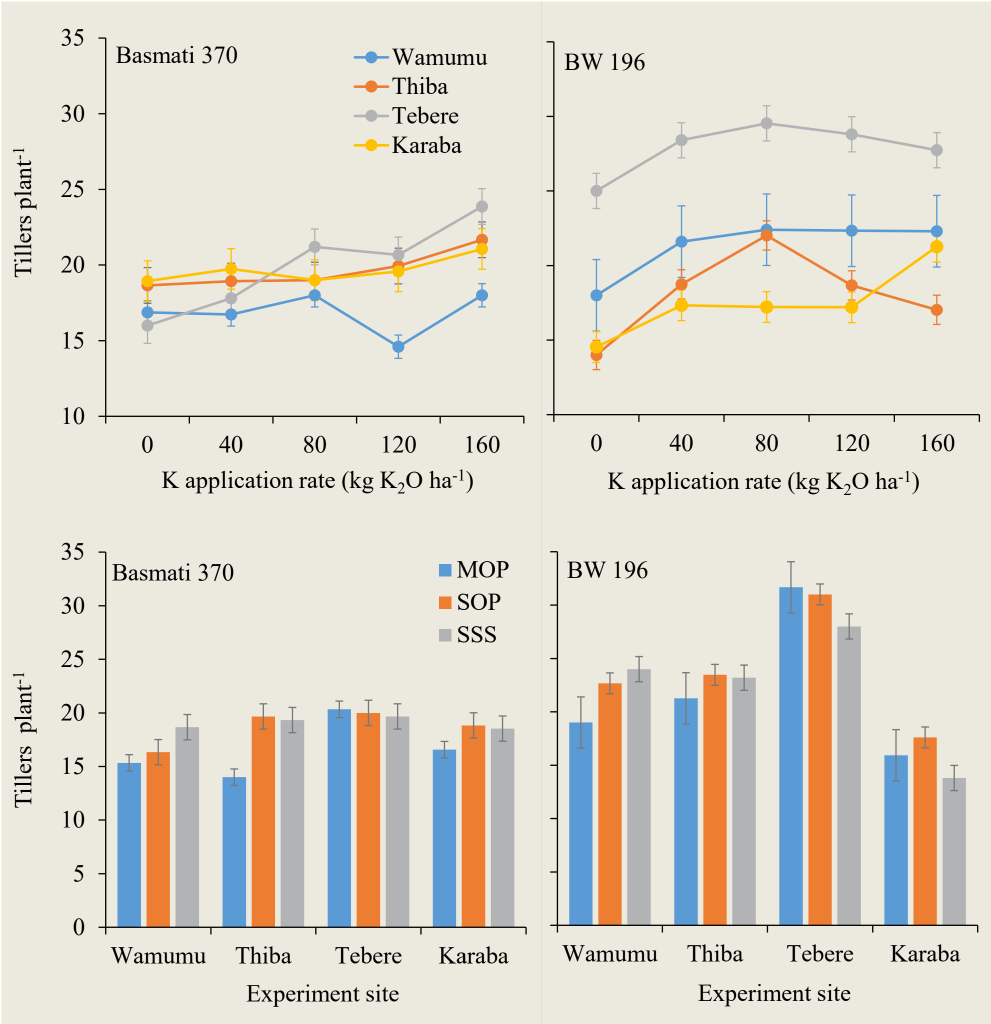


Fig. 2. Effects of K application rate (upper pair), and different K fertilizers at 80 kg K_2O ha^{-1} (lower pair), on the final tillering of two rice cultivars (Basmati 370 and BW 196).

Generally, rice total above-ground biomass at harvest displayed significant response to K application rates (Fig. 3). However, the response patterns were subject to cultivar and site. The greater biomass was produced at Thiba, for both cultivars, where the biomass increased with the rising K rate up to 120 kg K_2O ha^{-1}, and then declined. The smallest biomass was produced at Karaba, where Basmati 370 displayed a significant positive response up to K rate of 80 kg K_2O ha^{-1} but then declined, while BW 196 hardly responded. Similar patterns were observed at Wamumu, although here BW 196 had a more positive response. The two cultivars were significantly different in the biomass response to K rates at Tebere. While Basmati 370 displayed a consistent though small biomass increase with rising K rate, the biomass of BW 196 seemed to decline or remain constant in response to K application. Apart from some local differences, no consistent influence of the K fertilizer type could be observed (Fig. 3).

Paddy grain yield response to K application rates was specific to cultivar and location (Fig. 4). At Wamumu, both cultivars displayed the same pattern of yield response - a significant increase up to 80 kg K_2O ha^{-1}, and a decrease at higher K rates. Also at Karaba, both cultivars shared a similar response pattern, however, yield rise was limited to the first step of K rates from 0 to 40 kg K_2O ha^{-1}, with no further response at higher levels. At Thiba, Basmati 370 grain yield showed no response to K rate, remaining constant at a range of 4.0-4.4 Mg ha^{-1}. On the other hand, BW 196 grain yield increased from 4.3 under no K application, to 6-7 Mg ha^{-1} above 120 kg K_2O ha^{-1}. Interestingly, the grain yields of the two cultivars differed significantly at Tebere, although both cultivars obtained their maximum yields there (Fig. 4). BW 196 yield increased by 100%, from 5 to 10 Mg ha^{-1}, in response to increased K rates from zero to 80 kg K_2O ha^{-1} respectively. The corresponding increase in Basmati 370 yield however stopped at a K rate of 40 kg K_2O ha^{-1} and did not rise further above 5 Mg ha^{-1}. Excluding Tebere, where BW 196 grain yield was significantly low under SOP, K fertilizer type did not affect the grain yields of the two cultivars in both experiment sites (Fig. 4).

With a few exclusions, the harvest index (HI) - the ratio between grain and total aboveground biomass yields - was considerably influenced by the K application rate only at the first step, from 0 to 40 kg K_2O ha^{-1} (Fig. 5). Beyond this range, HI remained constant or even slightly declined. The basal HI was low and subject to

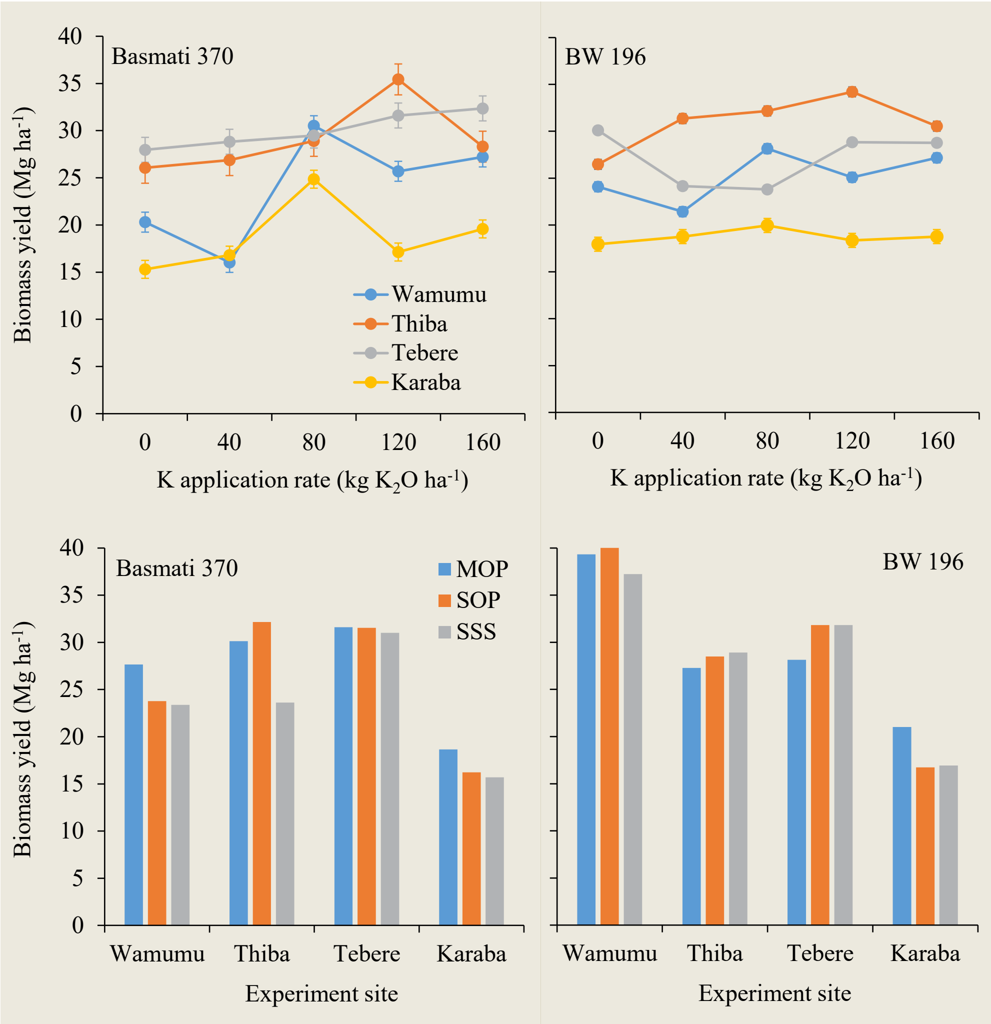


Fig. 3. Effects of K application rate (upper pair), and different K fertilizers at 80 kg K_2O ha^{-1} (lower pair), on the dry aboveground plant biomass of two rice cultivars (Basmati 370 and BW 196).

Photos 2. Data Collection; BW 196 height measurement (left), and BW tillers counting (right). Photos by the authors.

cultivar and location. Basmati 370's HI at Wamumu and Tebere doubled from 9 to 18% in response to K application rate of 40 kg K_2O ha^{-1}, and then declined steadily to 15% with increasing K rates. At Thiba, the initial Basmati 370 HI was the highest, 15%, however, it did not increase, and in one case even declined, in response to elevated K rates. Basmati 370 HI at Karaba displayed a remarkable increase, from 13 to 24%, in response to the K application rate of 40 kg K_2O ha^{-1}, but it fluctuated with the further rise in K application rates. BW 196 HI was a bit more responsive to increasing K application rates (Fig. 5). In Wamumu, it rose from 12 to 21% under 120 kg K_2O ha^{-1}, and then dropped under 160 kg K_2O ha^{-1}. In Thiba it displayed a slight but consistent rise from 17 to 20% along the whole range of K application rates. In Karaba, BW 196's HI pattern was quite similar to that of Basmati 370, but more stable. The most exceptional response was observed at Tebere, where the HI increased from 17% under no K application, to levels greater than 31% under 40 kg K_2O ha^{-1} and above. No considerable differences were observed concerning HI response to K fertilizer types (Fig. 5).

Discussion

In spite of the relative proximity of the four experiment locations (Map 1), large differences occurred between them in the performance of the two rice cultivars and the response of their yield parameters to K application. Significant differences between locations occurred in some critical soil properties (Table 1). Although soil pH was low in all samples, soil acidity in Thiba and Karaba was critically high (pH 4.5-5), while it was less serious in Tebere and Wamumu (pH 5-6). High soil acidity might significantly reduce the cation exchange rate of the soil particles surface, and thus negatively affect soil fertility. Under extreme soil acidity, Fe toxicity might occur in addition to soil structure and texture deterioration, as the mineral composition of the soil particles gradually collapses. In such soils, soil amendment means should be seriously considered in order to raise soil pH and halt processes of soil degradation.

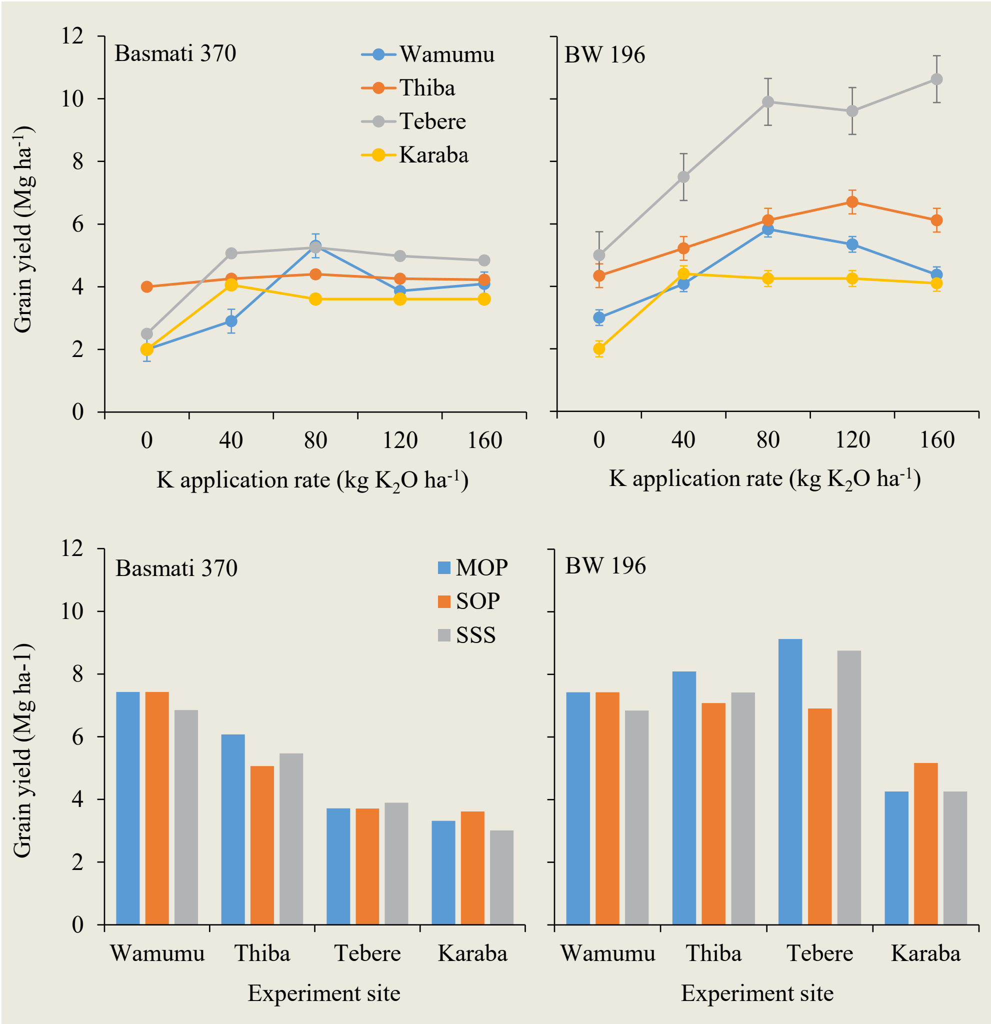


Fig. 4. Effects of K application rate (upper pair), and different K fertilizers at 80 kg K_2O ha^{-1} (lower pair), on the grain yield of two rice cultivars (Basmati 370 and BW 196).

Soils from most locations were poor in P and K (Table 1). Excluding Tebere, where K levels in the upper soil layer seemed on the safe side, soil K concentrations of all other locations were below the minimum threshold considered sufficient for cropping - 0.24 meq% (Gikonyo *et al.*, 2002). Also, differences between locations occurred in respect of water availability during the season, a problem which was especially serious in Karaba. Thus, cultivars' performance and the response to K application should be evaluated in light of these facts.

The two cultivars chosen for the study differ significantly. Basmati 370 is a classic tall (about 165 cm), low tillering cultivar, which tends to lodge under high fertility conditions and lose grains. It matures in about 120-130 days with a low average yield (about 4.8 Mg ha^{-1}) but is highly appreciated due to its aromatic flavor and desired cooking qualities (Ashfaq *et al.*, 2014; Ndiiri *et al.*, 2017). In contrast, BW 196 is a long-duration variety (about 160 days) and is considered high tillering, with a relatively high grain yield (7 Mg ha^{-1}). Nevertheless, both cultivars often fail to obtain considerable yields in the Mwea Irrigation Scheme (Ndiiri *et al.*, 2017). Undoubtedly, K deficiency is a major problem restricting rice yields in the region.

Plant height is a good and early indicator of rice K requirements (Wakeel *et al.*, 2017). This is the most direct parameter of rice response to K application, as it is not involved with the complex reproductive process. Thus, four weeks after transplanting, both cultivars in most locations displayed increased plant height, which peaked at the application rate of 80 kg K ha^{-1}, and then decreased or remained stable at higher K rates (Fig. 1). Tillering also takes place quite early in a plant's life, however, this parameter seems much more restricted to the cultivars genetic traits. Possessing a low tillering capacity, Basmati 370 hardly responded to K application, excluding in Tebere where the initial soil K was above the deficiency threshold (Table 1). In BW 196, on the other hand, the number of tillers increased with the rising K rates up to a certain limit, and again, tillering was higher in Tebere (Fig. 2). These results of plant height and tillering suggest that K application has significant advantages if applied at the early stages of crop development.

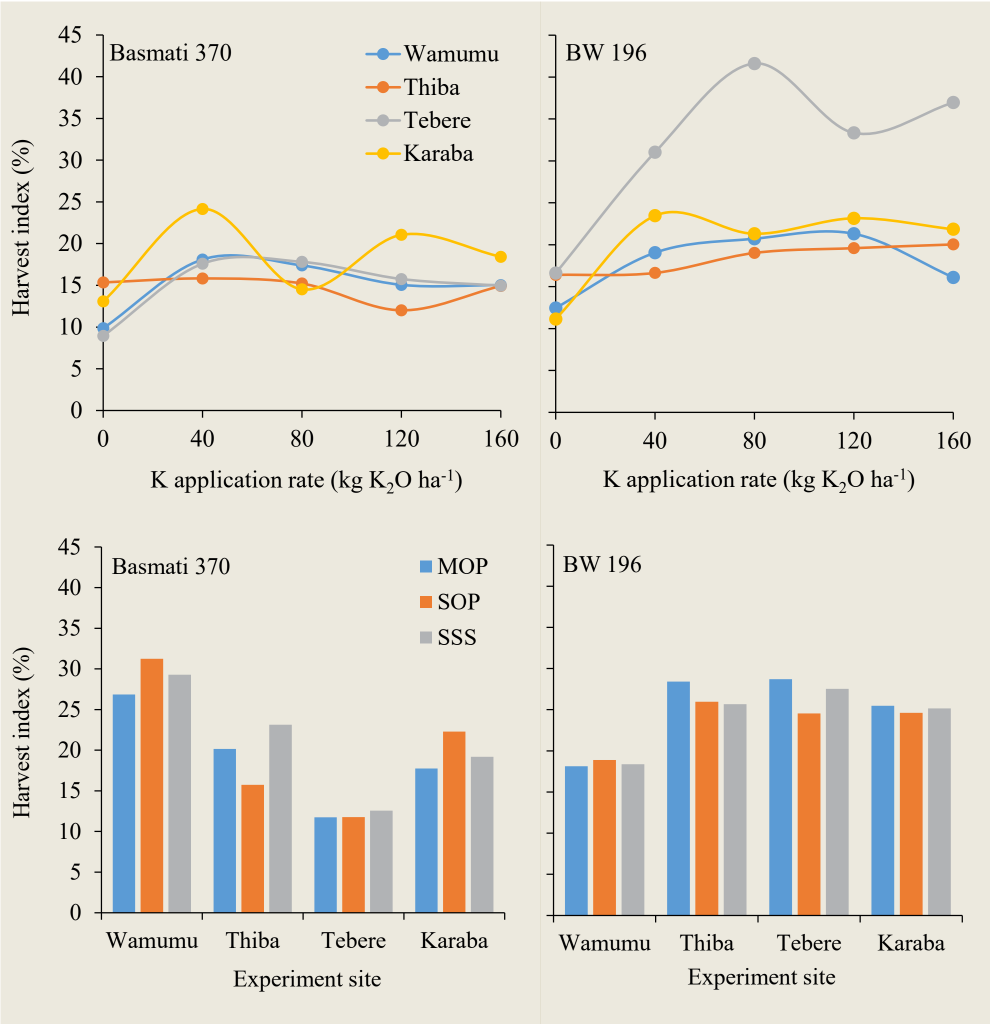


Fig. 5. Effects of K application rate (upper pair), and different K fertilizers at 80 kg K_2O ha^{-1} (lower pair), on the harvest index of two rice cultivars (Basmati 370 and BW 196).

Total rice biomass is expected to increase in response to rising K rates (Pandavuthi, 1977; Dwivedi *et al.*, 2000; Samejima *et al.*, 2005; Wakeel *et al.*, 2017). Nevertheless, in the present study, biomass response was mostly week and not always consistent (Fig. 3). Excluding Thiba, where biomass of both cultivars steadily increased by 25-30% up to a K rate of 120 kg ha^{-1}, and inexplicable fluctuations of Basmati 370 in Wamumu and Karaba, biomass change was very small. This disappointing pattern also occurred with grain yields which were generally quite modest (Fig. 4), when compared to values mentioned in the literature for other countries (FAO, 2016).

The reproductive phase is always complex and more sensitive to nutrient deficiency and abiotic stresses. Potassium is a key nutrient in this process, as it facilitates carbon reallocation and translocation during the grain filling stage (Yang *et al.*, 2004). Thus, K is required quite late, at about 90 to 120 days after transplanting, depending on the cultivar. However, in the practice employed in the present study, K application takes place just once, and early - the whole dose at transplantation. Under these circumstances, rice response to K application would be rate-dependent solely at the very beginning of crop development, but later on, it might correspond to K availability in the rhizosphere. Potassium, especially when applied in the rapidly soluble form of KCl, is highly mobile in wet soils and might be easily leached below the root zone. Furthermore, clay minerals that are extremely poor with K might permanently adsorb the soluble K while the soil dries, thus exhausting any reserve of available K when the soil gets wet again.

When related to unfertilized rice, K application did provide significant increases in grain yields, sometimes by 150% and more (Fig. 4). Yet, even though the range of K application rates that the rice was responsive to was in agreement with earlier studies, 40-120 kg K_2O ha^{-1} (Padmavathi, 1997; Dwivedi *et al.*, 2000; Dong *et al.*, 2010; Kaushik *et al.*, 2012), it would be premature to jump to any conclusions with respect to Mwea, since the absolute yields can be much higher. The improvement in HI, obtained mainly at the lower K rates (Fig. 5), together with the response patterns of plant height and tillering to K, altogether indicate substantially inefficient K fertilization, which requires careful attention.

Several important conclusions arise from the present study. Before any attempts are made to establish K fertilizer recommendations in the region, significant efforts must be made to reduce soil acidity. Severe soil acidity exposes plants to aluminum and Fe toxicity, inhibits root development, and diminishes the availability of most nutrients, leading to extremely poor crop yields (Fageria and Nascente, 2014). Liming should be examined as a suitable solution (Zimdahl, 2015), with soil enrichment using rice straw (Wang *et al.*, 2015). Second, water availability is required to secure normal rice growth and development. In order to evaluate fertilization practices, a stable and continuous water supply should be guaranteed. Unfortunately, water shortages have significantly worsened recently (Kamau, 2017).


Photos 3. Planting Basmati seedlings. Photos by the authors.

Beyond the elementary hurdles of soil acidity and water availability stands the challenge of K fertilization. The soils are depleted of K (Table 1), so the application of this nutrient is essential. However, the inadequate response of the rice yields to substantial K rates (Fig. 4) indicate inefficient application methods. So far, replacing MOP with other K fertilizers did not bring about significant change (Figs. 1-5). Alternatively, it may be postulated that when the K dose is fully applied at transplanting, most of it is diminished before being available at the critical stages of plant development. It is therefore suggested to conduct experiments, in which K doses are split, at least into two applications - at transplanting, and toward bloom. We hypothesize that this way, crop K uptake will significantly improve, K availability will better coincide with crop requirements, and rice yields will rise considerably, even with moderate K rates.

Acknowledgements

The KALRO-IPI potash project team greatly acknowledges the financial support from the International Potash Institute to conduct the current study. The Director of KALRO is acknowledged for the management of the funds and provision of logistics. The cooperation of the farmers where the trials were conducted was greatly appreciated.

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Regional activities/sub-Saharan Africa/Eastern Africa

Events

International Symposia and Conferences

July 2018

10th Symposium of the International Society of Root Research (ISRR10), 8-12 July 2018, Yearim Hotel, Israel.

The symposium, titled: “Exposing the Hidden Half - Root Research at the Forefront of Science”, will assemble multiple disciplines in order to facilitate exploration of novel approaches and investigation of complex processes and mechanisms.

For more information visit the ISSR10 website.

Publications

Publications by the PDA

Nitrogen and Potassium Interactions

POTASH News, April 2018.

Justus von Liebig’s Law of the Minimum states that yield is proportional to the amount of the most limiting nutrient, whichever nutrient it may be (Figure 1).

Nitrogen is the nutrient that most frequently provides the largest response, suggesting that this is usually most limiting. However, the plant available potassium status of a soil has a considerable influence on the uptake of nitrogen by crops, as shown through field experiments. Yield response to applied fertilizer nitrogen is decreased when the exchangeable K content of a soil is below a critical target level, index 2-. Read more on the PDA website.

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.

Scientific Abstracts

K in the Literature

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Potassium Behavior and Clay Mineral Composition in the Soil with Low Effectiveness of Potassium Application

Kubo, T., T. Hirayama, S. Fujimura, T. Eguchi, N. Nihei, S. Hamamoto, M. Takeuchi, T. Saito, T. Ota, and T. Shinano. 2017. J. Soil Sci. Plant Nutr. 64(2):265-271. DOI: https://doi.org/10.1080/00380768.2017.1419830.

Abstract: Increasing exchangeable potassium (ExK) content in soil to an appropriate level is important to mitigate the transfer of radioactive cesium to crops. We focused on a buckwheat (*Fagopyrum esculentum* Moench) field with a low ExK content, despite the application of K, in Fukushima Prefecture, Japan (Field A), following the Tokyo Electric Power Company Fukushima Dai-ichi (No. 1) Nuclear Power Plant accident in March 2011. We examined the relationship between K concentration and clay mineral composition in the soil of Field A and compared the findings with another field in Fukushima Prefecture (Field B) to clarify whether K applied to the soil was leached or remaining fixed. Pot experiments showed that K concentration in water seepage from pots following irrigation was significantly lower in pots from Field A than in those from Field B. Soil ExK content after soybean cultivation was lower in soils of Field A than those of Field B. These results indicate that K applied to Field A was fixed in the soil. Analysis of clay mineral composition confirmed the distinctive vermiculitic nature of Field A soils. This clay mineralogy would be associated with the higher K fixation ability of Field A than Field B soils. This study demonstrated that K fixation in vermiculite was a factor preventing the increase in ExK content from K application to Field A.

Driving the Expression of *RAA1* with a Drought-Responsive Promoter Enhances Root Growth in Rice, its Accumulation of Potassium and its Tolerance to Moisture Stress

Guang Chen, Chaolei Liu, Zhenyu Gao, Yu Zhang, Li Zhu, Jiang Hu, Deyong Ren, Guohua Xu, and Qian Qian. 2018. Environmental and Experimental Botany 147:147-156. DOI: https://doi.org/10.1016/j.envexpbot.2017.12.008.

Abstract: Drought impedes the acquisition of potassium (K) by restricting root growth, in turn causing a reduction in the plant’s K nutritional status, thereby further depressing its tolerance of the stress. The product of *RAA1 (Root Architecture Associated 1)*

is involved in the auxin-mediated development of the rice root system. Here, the introduction of a transgene comprising *RAA1* driven by the promoter of *HAK1*, a gene which encodes a drought-enhanced K transporter, was shown to exert a positive effect on the size of the root system and the number of adventitious roots formed. Transgenic seedlings demonstrated a higher level of tolerance to moisture stress than wild type (WT) ones, accumulated more K, proline and abscisic acid and suffered a lower level of lipid peroxidation. The genes *AKT1*, *HAK1* and *HAK5* were all up-regulated in the roots of transgenic drought-stressed hydroponics-grown seedlings, as were several known stress-responsive genes in the leaves of soil-grown, moisture-stressed transgenic plants. Under moisture deficient conditions, the transgenic plants developed more effective tillers than did WT plants, showed an enhanced level of spikelet fertility and produced larger grains. While under moisture sufficient conditions there was no significant difference in the grain yield of the transgenic and WT lines, under water limiting conditions, the transgenics recorded a 20-40% grain yield advantage over the WT. The implication was that the promotion of root growth and development achieved by enhancing the expression of *RAA1* in the root could represent a viable approach for enhancing the productivity of cereal crops exposed to moisture stress.

Rhizobium Inoculation Reduces P and K Fertilization Requirement in Corn-Soybean Intercropping

Nyoki, D., and P.A. Ndakidemi. 2018. Rhizosphere 5:51-56. DOI: https://doi.org/10.1016/j.rhisph.2017.12.002.

Abstract: The field experiment was carried out at Tanzania Coffee Research Institute (TaCRI) for two consecutive years to assess the effects of *Rhizobium* inoculation, supplemented with phosphorus and potassium on nutrient uptake in soybean intercropped with maize. The experiment was laid out in split-split plot design with 2×4×7 factorial arrangement replicated thrice. The main plots had two rhizobial inoculation treatments, while the sub plots were comprised of four cropping systems: Maize (sole-crop), Soybean (sole-crop) and two intercropping at different soybean spacing (75 × 20 and 75 × 40 cm). The sub-subplots were assigned to fertilizer levels (kg ha^{-1}): control; 20K; 40K; 26P; 52P; 26P + 20K; 52P + 40K. The statistical analysis was performed using ANOVA. The fisher's L.S.D. was used to compare treatment means at p=0.05 level of significance. The results indicated that soybean pure-stand significantly improved the uptake of Mg over the soybean under intercropping systems for the two cropping seasons. The uptake of Fe increased in intercropped soybean for the first cropping season relative to soybean pure stand. *Rhizobium* inoculation significantly improved the uptake of all other macro nutrients (N, K, P, and Mg) and micronutrients (Fe, Cu, Zn, Mn) in soybean shoots over un-inoculated soybean. Fertilization of soybean with P and K significantly increased the uptake of N, P and K for both cropping seasons. However, the uptake of macro nutrients such as calcium (Ca) and Magnesium (Mg) and micro nutrients such as Fe and Cu decreased with the increase of P and K fertilizers. P and K fertilization did not significantly affect the uptake of Mg and Mn for the two cropping seasons. Based on the findings of this study, *Rhizobium* inoculation and P and K fertilization at lower rates are recommended for improved uptake of macro and micro nutrients in legumes such as soybean.

Over-Fertilization Does Not Build Soil Test Phosphorus and Potassium in Ohio

Fulford, A.M., and S.W. Culman. 2017. Agron. J. 110(1):56-65. DOI: 10.2134/agronj2016.12.0701.

Abstract: Appropriate P and K fertilizer recommendations for corn (*Zea mays* L.) and soybean [(*Glycine max* (L.) Merr.] in Ohio are essential, as water quality and nutrient management issues in the region have intensified over the last several years. The objectives of this study were to: (i) evaluate corn and soybean grain yield response to P and K fertilization, (ii) examine soil test phosphorus (STP) and potassium (STK) and corn Leaf P and Leaf K trends, and (iii) compare the ability of soil and leaf tissue testing to reflect corn and soybean response to fertilization. We evaluated three P and K fertilizer rates, no fertilizer (0×), an estimated nutrient removal rate (1×), and twice the estimated nutrient removal rate (2×), in corn-soybean rotations at three sites over 9 yr. Grain yield was generally non-responsive to P and K fertilization, with only 9 of 42 site-years yielding significantly positive responses. Soil test P and K started in the maintenance range, but significantly declined with the 1× rate at two of three sites for P and at all sites for K. Furthermore, the 2× rate of P and K failed to build STP and STK at any site, with significant declines at one site. The results revealed an inability to maintain initial STP and STK levels with the 1× rate and call into question the suitability of current fertilizer P and K recommendations aimed at maintaining STP and STK. These recommendations require updating to better reflect fertilizer needs of modern corn and soybean.

Correlation and Calibration of Soil-Test Potassium from Different Soil Depths for Full-Season Soybean on Coarse-Textured Soils

Williams, A.S., Md. R. Parvej, D.L. Holshouser, W.H. Frame, and M.S. Reiter. 2017. Agron. J. 110(1):369-379. DOI: 10.2134/agronj2017.06.0344.

Abstract: Quantifying soil-K availabilities at deeper depths may be necessary to determine optimum fertilizer-K rate for soybean [*Glycine max* (L.) Merr.] grown on low cation exchange capacity (CEC) soils that are prone to K leaching. We characterized full-season soybean response to fertilizer-K across 19 coarse-textured low-CEC sites during 2013 and 2014. Mehlich-1 soil-K concentrations at 0 to 15 and 0 to 30 cm depths better correlated with relative yield and explained 90% of relative yield variation compared to 77% for 0 to 60 cm depth. Critical soil-K concentrations were similar for relative yield, V5 plant-K concentration, and R2 leaf-K concentration, ranging from 48 to 73 mg K kg^{-1} for 0 to 15 cm and 41 to 63 mg K kg^{-1} for 0 to 30 cm depths. Soil-K concentrations less than this critical range accurately predicted positive yield responses to fertilizer-K 89% of the time for 0 to 15 cm and 80% for 0 to 30 cm depths. Plant- and leaf-K concentrations were equally good in predicting relative yield with critical concentrations of 19 to 22 g plant K kg^{-1} and 18 to 21 g leaf K kg^{-1}. Plant-K concentration was better than leaf-K concentration in diagnosing K-deficient sites. Calibration model confirmed that soybean requires no fertilizer-K to maximize yield for soil-K concentrations above the critical ranges at both depths. However, for K-deficient soils, soil-K concentrations at 0 to 30 cm depth resulted in 7 to 32% less fertilizer-K requirements than 0 to 15 cm depth, indicating the value of deeper sample in recommending fertilizer-K for soybean grown on coarse-textured low-CEC soils.

Correlation of Field-Moist, Oven-Dry, and Air-Dry Soil Potassium for Mid-Atlantic USA Soybean

Williams, A.S., Md. R. Parvej, D.L. Holshouser, W.H. Frame, and M.S. Reiter. 2017. Soil Sci. Soc. Am. J. 81(6):1586-1594. DOI:10.2136/sssaj2016.10.0324.

Abstract: The extractable soil-K concentration, used for fertilizer-K recommendations, may be affected by soil drying. Although air or oven drying are the most common soil processing methods, K from field-moist soil has been documented to be a better predictor of soil-K availabilities and fertilizer-K needs for soybean [*Glycine max* (L.) Merr.] grown on fertile silt loam to clayey soils. We evaluated the effect of four soil processing methods (field-moist [FM], air-dry [AD], air-dry followed by oven-dry [ADOD], and oven-dry [OD]) in predicting extractable soil-K availability for soybean production on less fertile Mid-Atlantic sandy-textured soils. Twelve soybean field trials were conducted in 2014 on Coastal Plain and Piedmont soils in Virginia and North Carolina. Soil K was extracted by Mehlich-1 with each soil processing method and correlated with soybean relative yield. Soil-K concentrations from each method were statistically similar and strongly correlated (r^2 = 0.94-0.98) with each other having intercept and slope coefficients that were not different from zero and one, respectively. Extractable soil-K concentrations from each method were also strongly correlated with soybean relative yield and explained 93 to 95% of the relative yield variation for FM soil, 95 to 96% for AD soil, 83 to 86% for ADOD soil, and 94 to 95% for OD soil. Results suggest that soil-K concentrations from FM, AD, and OD samples are similar in predicting K availability for soybean. Soil drying should not be an issue of concern in extracting soil K and recommending fertilizer-K rate for soybean production on Mid-Atlantic coarse-textured Coastal Plain and Piedmont soils.

Potassium, Sulfur, and Liming Value of Ash Co-Product from Corn Stover Processing for Ethanol Production

Groenenboom, S.J., and A.P. Mallarino. 2018. Agron. J. 110(1):115-126. DOI: 10.2134/agronj2017.06.0337.

Abstract: Ash results from the processing of corn (*Zea mays* L.) stover for ethanol production and subsequent combustion to produce electricity. However, the potential value of this ash as a soil amendment has not been fully evaluated. Preliminary chemical analyses of the ash obtained for this study showed potential to raise soil pH and supply K and S. This potential was evaluated at two Iowa fields comparing ash with KCl fertilizer, gypsum, and $CaCO_3$. Three 2-yr separate K, S, and lime trials were established at each site, where several rates of each material were applied only the first year. Corn was planted in 2014 and soybean [*Glycine max* (L.) Merr.] in 2015. Soil samples (15 cm depth) were taken at the V6 growth stage of each crop and after crop harvest for analyses of pH, soil-test K, and extractable SO_4^{-2}. Leaf samples were taken at the corn R1 growth stage and soybean R3 growth stage for analyses of total K and S. There were large K effects on grain yield, soil-test K, and leaf K concentration but no differences between the K sources. First-year soil SO_4^{-2} at the V6 corn growth stage and leaf S at the corn R1 stage showed that S supplied by the ash was less than for gypsum, but other measurements were inconclusive as of differences between the S sources. The ash had liming value comparable to pure $CaCO_3$.

Double-Crop Soybean Response to Potassium on Mid-Atlantic Coastal Plain and Piedmont Soils

Parvej, Md. R., A.S. Williams, D.L. Holshouser, W.H. Frame, and M.S. Reiter. 2017. Agron. J. 110(1):399-410. DOI: 10.2134/agronj2017.07.0397.

Abstract: Potassium fertilization research on soybean [*Glycine max* (L.) Merr.] double cropped with winter wheat (*Triticum aestivum* L.) is lacking. We characterized double-crop soybean response to fertilizer K across 22 Coastal Plain and Piedmont sites with and/or without wheat straw removal during 2013 to 2015. Mehlich-1 soil-K concentrations at 0 to 15 and 0 to 30 cm depths were better in explaining relative yield variability (r^2 = 0.80), defining critical soil-K concentrations that ranged from 40 to 75 mg K kg^{-1} for 0 to 15 cm and 36 to 66 mg K kg^{-1} for 0 to 30 cm depths, and identifying K-deficient sites (100% accurate) than soil-K concentration at 0 to 60 cm depth (r^2 = 0.48; 56% accurate). Critical soil-K concentration at 0 to 30 cm depth did

not change with wheat straw management, but slightly increased at 0 to 15 cm depth when straw was removed. The R2 leaf-K concentration with a critical range of 20 to 23 g K kg^{-1} was better (75% accurate) in diagnosing K deficiency than V5 plant-K concentration (50% accurate) with a critical range of 17 to 23 g K kg^{-1}. Double-crop soybean required 33 to 119% more fertilizer K than Virginia Cooperative Extension recommendations for ≤50 mg soil-K kg^{-1} at 0 to 15 cm depth, but 6 to 55% less fertilizer K for similar soil K concentration at 0 to 30 cm depth. Wheat straw management should not be an issue of concern for fertilizer-K recommendations based on soil-K concentration at 0 to 30 cm depth for double-crop soybean production on Coastal Plain and Piedmont soils.

Simulating the Effects of Different Potassium and Water Supply Regimes on Soil Water Content and Water Table Depth over a Rotation of a Tropical *Eucalyptus grandis* Plantation

Christina, M., G. le Maire, Y. Nouvellon, R. Vezy, B. Bordon, P. Battie-Laclau, J.L.M. Gonçalves, J.S. Delgado-Rojas, J.-P. Bouillet, and J.-P. Laclau. 2018. Forest Ecology and Management 418:4-14. DOI: https://doi.org/10.1016/j.foreco.2017.12.048.

Abstract: Although large amounts of potassium (K) are applied in tropical crops and planted forests, little is known about the interaction between K nutrition and water supply regimes on water resources in tropical regions. This interaction is a major issue because climate change is expected to increase the length of drought periods in many tropical regions and soil water availability in deep soil layers is likely to have a major influence on tree growth during dry periods in tropical planted forests. A process-based model (MAESPA) was parameterized in a throughfall exclusion experiment in Brazil to gain insight into the combined effects of K deficiency and rainfall reduction (37% throughfall exclusion) on the water used by the trees, soil water storage and water table fluctuations over the first 4.5 years after planting *Eucalyptus grandis* trees. A comparison of canopy transpiration in each plot with the values predicted for the same soil with the water content maintained at field capacity, made it possible to calculate a soil-driven tree water stress index for each treatment. Compared to K-fertilized trees with undisturbed rainfall (+K+W), canopy transpiration was 40% lower for K deficiency (−K+W), 20% lower for W deficit (+K−W) and 36% lower for combined K deficiency and W deficit (−K−W) on average. Water was withdrawn in deeper soil layers for −W than for +W, particularly over dry seasons. Under contrasted K availability, water withdrawal was more superficial for −K than for +K. Mean soil water content down to 18 m below surface (mbs) was 24% higher for −K+W than for +K+W from 2 years after planting (after canopy closure), while it was 24% lower for +K−W and 12% lower for −K−W than for +K+W. The soil-driven tree water stress index was 166% higher over the first 4.5 years after planting for −W than for +W, 76% lower for −K than for +K, and 14% lower for −K−W than for +K+W. Over the study period, deep seepage was higher by 371 mm yr^{-1} (+122%) for −K than for +K and lower by 200 mm yr^{-1} (−66%) for −W than for +W. Deep seepage was lower by 44% for −K−W than for +K+W. At the end of the study period, the model predicted a higher water table for −K (10 mbs for −K+W and 16 mbs for −K−W) than for +K (16 mbs for +K+W and 18 mbs for +K−W). Our study suggests that flexible fertilization regimes could contribute to adjusting the local trade-off between wood production and demand for soil water resources in planted forests.

Different Characteristics of Nutrient Absorption and Utilization between Inbred *Japonica* Super Rice and Inter-Sub-Specific Hybrid Super Rice

Haiyan Wie, Lei Hu, Ying Zhu, Dong Xu, Leiming Zheng, Zhifeng Chen, Yajie Hu, Peiyuan Cui, Baowei Guo, Qigen Dai, and Hongcheng Zhang. 2018. Field Crops Research 218:88-96. DOI: https://doi.org/10.1016/j.fcr.2018.01.012.

Abstract: Although previous researchers have revealed that inter-sub-specific hybrid rice between *indica* and *japonica* has super-high yield potential, the mechanisms underlying nutrient absorption and utilization remain limited. The present study assessed nutrient accumulation and utilization, root morphology, and physiology of inter-sub-specific hybrid super rice cultivars (IHSRC) Yongyou 12 and Yongyou 15, using inbred *japonica* super rice cultivars (IJSRC) Nanjing 44 and Ningjing 3 as control. Total nitrogen (N), phosphorus (P), and potassium (K) accumulations in IHSRC were 12.53%, 20.81%, and 17.30% higher than those in IJSRC respectively. The larger amounts of accumulated nutrients in IHSRC were mainly attributable to the high rates of nutrients accumulation before elongating and the long growth duration without premature senescence after elongating. The apparent recovery efficiency of N fertilizers, agronomic N use efficiency, and the partial factor productivity of applied N in IHSRC were all higher than those in IJSRC, whereas the physiological N use efficiency and internal N, P, and K use efficiencies of IHSRC were similar to or lower than those of IJSRC. Compared with IJSRC, the root weights of IHSRC were heavier with greater length and bigger volume, the total and active absorption areas were also larger. In conclusion, with strong and active root systems, IHSRC are more efficient in nutrient absorption than utilization.

Shifts in Soybean Yield, Nutrient Uptake, and Nutrient Stoichiometry: A Historical Synthesis-Analysis

Balboa, G.R., V.O. Sadras, and I.A. Ciampitti. 2018. Crop Science 58(1):43-54. DOI: 10.2135/cropsci2017.06.0349

Abstract: Few studies have investigated changes over time in nutrient uptake and yield, in addition to the study of nutrient stoichiometry as a metric of nutrient limitations in soybean [*Glycine max* (L.) Merr.]. A comprehensive synthesis-analysis was performed by compiling a global historical soybean database of yield, total biomass, and nutrient (N, P, and K) content and concentration in studies published from 1922 to 2015. This period was divided in three eras based on genetically modified soybean events: Era I (1922–1996), Era II (1997–2006), and Era III (2007–2015). The main findings of this review are: (i) seed yield improved from 1.3 Mg ha^{-1} in the 1930s to 3.2 Mg ha^{-1} in the 2010s; (ii) yield increase was primarily driven by increase in biomass rather than harvest index (HI); (iii) both N and P HIs increased over time; (iv) seed nutrient concentration remained stable for N and declined for both P (18%) and K (13%); (v) stover nutrient concentration remained stable for N, diminished for P, and increased for K; (vi) nutrient ratios portray different trends for N/P (Era I and III > II), N/K (Era I > II and III), and K/P (Era II and III > I); (vii) yield per unit of nutrient uptake (internal efficiency) increased for N (33%) and P (44%) and decreased for K (11%); and (viii) variations in nutrient internal efficiency were primarily explained by increase in nutrient HI for N and K, but equally explained by both HI for P and seed P concentration. These findings have implications for soybean production and integrated nutrient management to improve yield, nutrient use efficiency, and seed nutrient composition.

Comparing Extractants for Calibrating Potassium Rates for Tomato Grown on a Calcareous Soil

Zhu, Q., M. Ozores-Hampton, Y.C. Li, and R.S. Mylavarapu. 2017. Soil Sci. Soc. Am. J. 81(6):1621-1628. DOI: 10.2136/sssaj2017.04.0134.

Abstract: Potassium application rates based on a reliable soil testing method are critical for maximizing crop yields and minimizing fertilizer costs. Vegetables grown on calcareous soils, however, have no soil test potassium (STK) interpretations in Florida. Therefore, the objectives of this study were to compare Mehlich-3, ammonium bicarbonate-DTPA (AB-DTPA), and water to estimate K availability and calibrate K rates for tomato (*Solanum lycopersicum* L.) grown on a calcareous soil. The experiment was conducted during the winter seasons of 2014 and 2015. Potassium fertilizers were applied through preplant dry fertilizer and drip fertigation at total rate of 0, 56, 93, 149, 186, and 223 kg K ha^{-1}. Regression models were performed to calibrate K rates by tomato relative yield with total K input (initial STK plus full-season K rate). Concentrations of STK were significantly correlated among the three extractants and the highest correlation occurred between Mehlich-3 and AB-DTPA. Due to the high variability, water was ineffective to estimate K availability. Significantly linear relationships were found between total K uptake (TKU) and total K inputs using both Mehlich-3 extracted K (Mehlich-3-K) and AB-DTPA-K. The low STK levels were predicted from 85 to 150 and 70 to 120 mg K kg^{-1} and the corresponding required K rates ranged from 307 to 151 and 271 to 151 kg K ha^{-1} using Mehlich-3-K and AB-DTPA-K, respectively. Thus, both Mehlich-3 and AB-DTPA can be used to predict K availability and K rates needed to produce optimal marketable yield for tomato grown on calcareous soils in Florida.

A Stepwise Change of Frayed Edge Site Content in Biotite in Response to the Gradual Release of Potassium from the Interlayers

Ogasawara, S., A. Nakao, and J. Yanai2017. Soil Science and Plant Nutrition 63(6):529-535. DOI: https://doi.org/10.1080/00380768.2017.1402660.

Abstract: Radiocesium (RCs) is selectively adsorbed on weathered micaceous minerals (mica) in soils. Although it is clear that weathered mica has selective adsorption sites for RCs, which have been called 'frayed edge sites (FES)', the relationship between the degree of mica weathering and the FES content has not been fully investigated. To evaluate the effect of mica weathering on its FES content, we investigated the changes in the FES content with the release of K^+ from biotite samples by using sodium tetraphenylborate solution. The FES content was estimated from radiocesium interception potential. The vermiculitic layer charge (Vt charge) was also determined as an indicator of the degree of mica weathering. The amount of K extracted from biotite increased from 154 to 803 mmol kg^{-1} as the condition of the K extraction was more intensive (i.e., longer time, lower solid/liquid ratio, and higher temperature). As K^+ was removed to a greater extent, the FES content increased from 3.96 to 11.5 mmol kg^{-1}, whereas the Vt charge value increased from 17.1 to 329 mmol kg^{-1}. At the earlier stage of mica weathering, the formation of FES was proportional to the increasing amount of K^+ released and to the Vt charges. However, at the later stage of mica weathering, when vermiculite was detected by an X-ray diffraction analysis, FES was not necessarily increased in proportion to the increase in K^+ released and the amount of Vt charge. These findings indicated that although mica weathering largely increased the FES, the increase was not continuous throughout the weathering stage but evident at the earlier stage of weathering.

KIN7 Kinase Regulates the Vacuolar TPK1 K^+ Channel during Stomatal Closure

Isner, J.C., A. Begum, T. Nuehse, A.M. Hetherington, and F.J.M. Maathuis. 2018. Current Biology 28(3):466-472. DOI: https://doi.org/10.1016/j.cub.2017.12.046.

Abstract: Stomata are leaf pores that regulate CO_2 uptake and evapotranspirational water loss. By controlling CO_2 uptake, stomata impact on photosynthesis and dry matter accumulation.

The regulation of evapotranspiration is equally important because it impacts on nutrient accumulation and leaf cooling and enables the plant to limit water loss during drought [1]. Our work centers on stomatal closure [2-6]. This involves loss of potassium from the guard cell by a two-step process. Salt is released across the plasma membrane via anion channels such as SLAC1 [7-9] and depolarization-activated channels such as GORK [10, 11], with the net result that cations and anions exit guard cells. However, this critically depends on K^+ release from the vacuole; with ~160 and 100 mM K^+ in cytoplasm and vacuole of open guard cells [12], vacuolar K^+ efflux is driven by the negative tonoplast potential, and this expels K^+ from the vacuole via tonoplast K^+ channels like TPK1. In all, guard cell salt release leads to a loss of turgor that brings about stomatal closure. First, we show that the TPK1 vacuolar K^+ channel is important for abscisic acid (ABA)- and CO_2-mediated stomatal closure. Second, we reveal that, during ABA- and CO_2-mediated closure, TPK1 is phosphorylated and activated by the KIN7 receptor-like protein kinase (RLK), which co-expresses in the tonoplast and plasma membrane. The net result is K^+ release from the vacuole. Taken together, our work reveals new components involved in guard cell signaling and describes a new mechanism potentially involved in fine-tuning ABA- and CO_2-induced stomatal closure.

Phosphorus and Potassium Availability from Cattle Manure Ash in Relation to their Extractability and Grass Tetany Hazard

Thinh Tran, Q., M. Maeda, K. Oshita, M. Takaoka, and K. Saito. 2018. J. Soil Sci. Plant Nutr. DOI: https://doi.org/10.1080/00380768.2018.1433958.

Abstract: Due to a decrease in phosphorus (P) and potassium (K) mining, manure is incinerated to concentrate P and K in ash. To understand the alternative use of manure-derived ash as P and K sources, laboratory and greenhouse experiments were conducted to determine the relationship between extractability and P and K uptake in cattle manure ash (CMA) and that between CMA application and a grass tetany hazard. The results showed that more P was extracted with 2% citric acid (90% of the total P) than with 2% formic acid (72-84% of the total P). Ninety-one percent of the total K was soluble in water. A greenhouse pot experiment was conducted to test P and K availability to Guinea grass (*Megathyrsus maximus*). Cattle manure ash or calcium dihydrogen phosphate (CF) was incorporated into sandy soil at 10, 20, and 50 g P_2O_5 m^{-2}. Two combinations of CMA and CF were tested at 20 g P_2O_5 m^{-2}. Potassium rates followed K content in CMA applied at different rates of P equivalent to 19, 38, or 96 g K_2O m^{-2}. In four harvests, there was no significant difference in the total yields between CMA and CF treatments. The total P uptake was significantly lower in the CMA treatment than in the CF treatment, while it was not in the combined CMA and CF treatments. The P uptake in response to different extraction methods indicated that the extraction of P by 2% formic acid without sonication is recommended to predict P availability in CMA. The potassium uptake from CMA application was comparable to that from the KCl application, and excessive K occurred at 38 and 96 g K_2O m^{-2}. The grass tetany hazard ratio higher than 2.2 was observed at the beginning period at the lowest application rates of CMA and CF. In conclusion, the combination use of CMA and CF was better than the single use of CMA. Moreover, CMA would be an available K source, but the grass tetany hazard still needs to be considered in application rates and pretreatments.

Plant Tissue Analysis to Assess Phosphorus and Potassium Nutritional Status of Corn and Soybean

Stammer, A.J., and A.P. Mallarino. 2018. Soil Sci. Soc. Am. J. 82(1):260-270. DOI: 10.2136/sssaj2017.06.0179.

Abstract: There is a need for reevaluating the value of tissue testing in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] for current yield levels and genotypes. The objective of this research was to determine tissue critical P and K concentrations for these crops at vegetative and reproductive growth stages. Response trials were conducted in Iowa at 30 sites for P (32 site-years with corn and 34 with soybean) and at 53 sites for K (67 site-years with corn and 52 with soybean). We sampled whole plants at the V5-V6 stage, corn ear-leaf blades at the R1 stage, and trifoliate soybean leaves at the R2-R3 stage. Critical concentration ranges (CCRs) were defined using linear-plateau and quadratic-plateau models. All models fit significantly ($P \leq 0.01$). Model R^2 values were the lowest (0.31-0.45) for corn plant P, soybean plant and leaf P, and soybean plant K; intermediate (0.51-0.53) for corn plant and leaf K and soybean leaf K; and the highest (0.62-0.64) for corn leaf P. For corn plants and leaves, CCRs were 4.8 to 5.5 and 2.5 to 3.1 g P kg^{-1} and 18.8 to 25.4 and 10.6 to 14.2 g K kg^{-1}, respectively. For soybean plants and leaves, CCRs were 3.3 to 4.1 and 3.5 to 4.7 g P kg^{-1} and 18.9 to 22.7 and 15.6 to 19.9 g K kg^{-1}, respectively. Testing of corn ear-leaves for P was more accurate than for plants but either tissue provided similar K assessments. Testing soybean plants for P was more accurate than for leaves, but for K testing of leaves was more accurate than for plants.

Soil Processes and Wheat Cropping Under Emerging Climate Change Scenarios in South Asia

Jat, M.L., Bijay-Singh, C.M. Stirling, H.S. Jat, J.P. Tetarwal, R.K. Jat, R. Singh, S. Lopez-Ridaura, and P.B. Shirsath. 2018. Advances in Agronomy 148:111-171. DOI: https://doi.org/10.1016/bs.agron.2017.11.006.

Abstract: Wheat is one of the most important staple foods as it provides 55% of the carbohydrates and 20% of the food calories

and protein consumed worldwide. Demand for wheat is projected to continue to grow over the coming decades, particularly in the developing world, to feed an increasing population. More than 22% of global area under wheat is located in South Asia which is home to about 25% of the world's population. The Intergovernmental Panel on Climate Change has projected that in the 21st century South Asia is going to be hit hard by climate change. Changes in mean annual temperature will exceed 2°C above the late-20th-century baseline and there can be declines in the absolute amount of precipitation during December to February, when wheat is grown in the region. Temperature, precipitation, and enhanced CO_2 level in the atmosphere, the three climate change drivers can affect wheat cropping both directly at plant level and indirectly through changes in properties and processes in the soil, shifts in nutrient cycling, insect pest occurrence, and plant diseases. Studies pertaining to the effects of climate change on soil processes and properties are now becoming available and it is becoming increasingly clear that climate change will impact soil organic matter dynamics, including soil organisms and the multiple soil properties that are tied to organic matter, soil water, and soil erosion. Warmer conditions will stimulate soil N availability through higher rates of mineralization so that fertilizer management in wheat is also going to be governed by emerging climate change scenarios. Similarly, higher temperatures and altered precipitation regimes will determine the net irrigation water requirements of wheat. Several simulation models have projected reduced wheat yields in the emerging climate change scenarios, but occurrence of an extreme heat event around senescence can lead to crop models to underestimate the effects of heat on senescence by as much as 50% for late sowing dates for 2°C rise in mean temperature. So as to project productivity of wheat in South Asia in the emerging climate change scenarios with increased certainty, integrated holistic modeling studies will be needed which also take into account effect of extreme heat events as well as the contribution of altered soil processes and properties.

The *Arabidopsis* GORK K^+-Channel is Phosphorylated by Calcium-Dependent Protein Kinase 21 (CPK21), which in turn is Activated by 14-3-3 Proteins

Van Kleeff, P.J.M., J. Gao, S. Mol, N. Zwart, H. Zhang, K.W. Li, and A.H. de Boer. 2018: Plant Physiology and Biochemistry. 125:219-231. DOI: https://doi.org/10.1016/j.plaphy.2018.02.013.

Abstract: Potassium (K^+) is a vital ion for many processes in the plant and fine-tuned ion channels control the K^+-fluxes across the plasma membrane. GORK is an outward-rectifying K^+-channel with important functions in stomatal closure and in root K^+-homeostasis. In this study, post-translational modification of the *Arabidopsis* GORK ion channel and its regulation by 14-3-3 proteins was investigated. To investigate the possible interaction between GORK and 14-3-3s an *in vivo* pull-down from an *Arabidopsis* protein extract with recombinant GORK C-terminus (GORK-C) indeed identified endogenous 14-3-3s (LAMBDA, CHI, NU) as binding partners in a phosphorylation dependent manner. However, a direct interaction between 14-3-3's and GORK-C could not be demonstrated. Since the pull-down of 14-3-3s was phosphorylation dependent, we determined GORK-C as substrate for CPK21 phosphorylation and identified three CPK21 phospho-sites in the GORK protein (T^{344}, S^{518} and S^{649}). Moreover, interaction of 14-3-3 to CPK21 strongly stimulates its kinase activity; an effect that can result in increased GORK phosphorylation and change in activity. Using the non-invasive vibrating probe technique, we measured the predominantly GORK mediated salt induced K^+-efflux from wild-type, *gork*, *cpk21*, *aha2* and 14-3-3 mutant roots. The mutants *cpk21* and *aha2* did not show statistical significant differences compared to WT. However, two (out of six) 14-3-3 isoforms, CHI and PHI, have a clear function in the salt induced K^+-efflux. In conclusion, our results show that GORK can be phosphorylated by CPK21 and suggest that 14-3-3 proteins control GORK activity through binding with and activation of CPK21.

Comparison of Crop Productivity and Soil Microbial Activity among Different Fertilization Patterns in Red Upland and Paddy Soils

Kai-lou, L., L. Ya-zhen, Z. Li-jun, C. Yan, H. Qing-hai, Y. Xi-chu, and L. Da-ming. 2018. Acta Ecologica Sinica. DOI: https://doi.org/10.1016/j.chnaes.2017.08.003.

Abstract: Soil enzyme activity and microorganism community can be changed through different long-term fertilization patterns. However, the effect of different fertilization practices on soil microorganisms might differ among crop systems. The objective of the study was to reveal the change of soil enzyme activity and soil microorganism community in different fertilizations both in upland and paddy soils. Therefore, based on long-term fertilization experiments in upland soil started in 1986 and adjacent paddy soil experiment commenced in 1981, with both consisting of four treatments: Control (no fertilization), N (only nitrogen fertilizer), NPK (nitrogen, phosphate and potassium fertilizers) and NPKM (nitrogen, phosphate and potassium fertilizers plus organic manure), grain yield, soil fertility, activities of soil urease, catalase, acid phosphatase, microorganism community (the number of bacteria, fungus and actinomycete) were analyzed. The result showed that: the highest grain yield was attained under the application of chemical fertilizers plus manure, as compared with Control, NPKM significantly increased the grain yield by 908.63% in corn and 118.80% in rice ($p < 0.05$). Meanwhile, NPKM treatment increased significantly soil organic matter and nutrient contents in upland and paddy soils. Interestingly, there was no significant difference in soil pH among all the treatments

of paddy soil, but in upland, NPKM increased pH in comparison to Control by 23.06% (1.15 units of pH). Compared with Control, soil urease, catalase activities, bacteria and actinomycete numbers of NPKM were increased by 321.39%, 129.64%, 229.79%, 85.81% in upland soil, and 25.11%, 251.12%, 292.83%, 196.34% in paddy soil. However, in paddy soil, the soil acid phosphatase activity of Control, NPK and NPKM treatments were higher than upland soil by 34.87%, 44.81%, 52.73% and 30.11%. Then, the soil fungus and actinomycete numbers of paddy soil were lower than upland soil by 20.20% and 88.29%. Therefore, it indicated that long-term application of chemical and organic fertilizers delivered highest productivity in both experiment but the effect of fertilizer practices differed between land uses.

Silver Vase Bromeliad: Plant Growth and Mineral Nutrition under Macronutrients Omission

Young, J.L.M., S. Kanashiro, T. Jocys, A.R. Tavares. 2018. Scientia Horticulturae 234:318-322. DOI: https://doi.org/10.1016/j.scienta.2018.02.002.

Abstract: The present study aimed to evaluate the effects of N, P, K, Ca, Mg and S deficiencies on the growth, mineral contents of silver vase bromeliad [*Aechmea fasciata* (Lindley) Baker], a species native to Brazil. Plants were maintained on modified Hoagland & Arnon nutrient solution with omission of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S) or complete solution (CS) totalizing seven treatments. Leaf nutrient contents of the treatments were analyzed to confirm the deficiencies. The first leaf deficiency symptoms appeared in cultivated plants from which nitrogen (N) was omitted. In fact, nitrogen was found to be the growth-limiting nutrient of silver vase bromeliad. Phosphorus-deficient plants had reddish leaves and showed necrosis in young leaves. K, Ca, Mg and S deficiency can only be determined by foliar analysis. The limiting nutrients to silver vase bromeliad growth were N > P = K > Ca = Mg > S in ascending order.

Different K:Ca Ratios Affected Fruit Color and Quality of Strawberry 'Selva' in Soilless System

Masoud Haghshenas, Mousa Arshad, and Mohammad Javad Nazarideljou. 2017. J. Plant Nutr. 41(2):243-252. DOI: https://doi.org/10.1080/01904167.2017.1385797.

Abstract: High quality fruit production is the cornerstone of marketability. Optimum plant performance depends on the balanced and timely availability of mineral nutrients. In addition to element concentrations, the ratio of nutrient elements in solution plays a determinative role in growth, productivity, quality, and nutrients uptake. In this experiment, the effects of different Potassium:Calcium (K:Ca) ratios (1.6, 1.4, 1.2, 1, 0.85, and 0.6) in nutrient solution were studied on quality attributes of strawberry 'Selva'. The highest and lowest leaf number and leaf area were observed in K:Ca 1.4 and 1, respectively. The highest fruit pH, electrical conductivity, total soluble solids/titratable acidity ratio, vitamin C content, ellagic acid, and color were resulted in K:Ca (1.4) ratio. K:Ca (1.6) ratio produced the highest content of protein. Moreover, K:Ca (0.85) ratio was the most effective treatment on fruit firmness. The increased quality attributes were observed in high K:Ca ratios, hence low K:Ca ratio resulted in increased fruit firmness. In conclusion, nutrient solution containing K:Ca ratios between 1 and 1.6 were suitable for producing strawberry 'Selva'. Taken together, K:Ca (1.4) was an appropriate ratio for producing strawberry 'Selva' in soilless culture with coconut fiber: perlite medium.

Effect of Nitrogen and Potassium Fertilization on Mineral and Amino Acid Content of Colored Flesh Potato Cultivar Blue Congo

Bogucka, B., and T. Elżbieta. 2018. J. Plant Nutr. 41(7):856-866. DOI: https://doi.org/10.1080/01904167.2018.1428749.

Abstract: The purpose of this study was to determine optimum rates of soil dressing with nitrogen (N) and potassium (K) fertilization in the cultivation of potato with purple-blue peel and flesh, affecting the qualitative composition of tubers of a less known potato cultivar called Blue Congo.
The experimental results proved that the optimum rates of fertilizers applied to soil for the cultivar Blue Congo are 80 kg N ha^{-1} and 150 kg K ha^{-1}. Application of 120 kg N ha^{-1} caused a decrease in the content of all macro- and micro-nutrients. In contrast, the content of all macronutrients was observed to increase up to the rate of 150 kg K ha^{-1}.
Micronutrients responded to the increase in the K rate in different ways. No effect of the differentiated rates of K was noted in the case of iron. Vitamin C responded by its lower content to the increased rates of both N and K. It was determined that isoleucine was the limiting amino acid for the *cv.* Blue Congo potato. The highest level of isoleucine was found at the N rate of 80 kg ha^{-1}.

Effect of Nitrogen, Phosphorus and Potassium Fertilizer on Growth and Seed Germination of *Capsella bursa-pastoris* (L.) Medikus

Yang, W. 2018. J. Plant Nutr. 41(5):636-644. DOI: https://doi.org/10.1080/01904167.2017.1415350.

Abstract: We investigated how plant height, number of stem and branch, seed production and seed germination of *Capsella bursa-pastoris* were affected by nitrogen (N), phosphorus (P) and potassium (K) fertilizer using a pot fertilizer experiment. Plant growth parameter was determined, and fully ripen seeds were tested for germination. *C. bursa-pastoris* exhibited great

phenotypic variation in plant height, number of stem and branch in relation to N, P and K supply. Seed production per plant was lowest in the control and low P treatment, and highest in NPK treatment. More than 16,000 seeds per plant were produced in treatments where N and P were applied together. A balanced N, P and K supply results in producing a high percentage and fast germinating seeds, while a deficiency of P and K together with a high N supply results in low germination ability and fast germinating of the produced seeds in *C. bursa-pastoris*.

Shift in Physiological and Biochemical Processes in Wheat Supplied with Zinc and Potassium under Saline Condition

Zafar, S., M. Y. Ashraf, and M. Saleem. 2018. J. Plant Nutr. 41(1):19-28. DOI: https://doi.org/10.1080/01904167.2017.1380825.

Abstract: Soil salinity is a serious abiotic factor affecting the production of crops by reducing potassium (K) uptake due to strong competition with sodium (Na) cations in the root regions. In calcareous soils, most of the nutrients precipitate in unavailable forms for plants. This study investigated the physiological and biochemical response of two wheat genotypes salt tolerant Abadghar and salt sensitive Pari-73 supplemented with K and zinc (Zn) nutrition. A factorial experiment with three levels of K (0, 50 and 100 kg ha^{-1}) and three levels of Zn (0, 25 and 50 kg ha^{-1}) based on a complete randomized design was employed. The results showed significant effect of treatments on chlorophyll (Chl) contents, water relations, nitrogen metabolism and yield attributes. The treatment K+Zn (100, 25 kg ha^{-1}) was the most effective in increasing grain yield. The results achieved highlight the importance of K and Zn nutrition in salt-stress conditions.

Read On

Root Discovery May Lead to Crops that Need Less Fertilizer

Mulhollem, J. 18 January 2018. Penn State News.

Differences in bean plant growth observed by researchers were striking. In the phosphorus stress treatment, the genotypes with greater reduction of their secondary root growth had increased root length, took up more phosphorus, and had larger shoots than genotypes with greater secondary root growth, which had thicker, less efficient roots.

View On

Let's talk about RICE.

See the Sustainable Rice Platform (SRP) video. IPI is a member of this important project.

Clipboard

New IPI Coordinator for India: Anat Cohen

Ms. Anat Cohen, IPI Coordinator for India, has over 23 years' experience working with farmers, dealers, extension workers, and researchers working on crop fertilization and plant nutrition. Her international experience includes agricultural research and extension programs and consultancies worldwide, especially in Israel, East Africa and India.

Ms. Cohen gained her BSc degree in agronomy in the field of soil and water sciences from the Faculty of Agriculture, Food and Environmental Quality Sciences at the Hebrew University of Jerusalem in Israel.

Ms. Cohen has comprehensive knowledge of a wide range of crops grown in Israel and elsewhere, including vegetables, field crops, banana, pomegranate, grapes, deciduous trees, coffee, citrus, avocado, mango, persimmon, potato, and groundnuts. As a field agronomist in Israel, she developed and implemented regular protocols in fertilization and plant nutrition for farmers for a variety crops. In India, Ms. Cohen worked for over 15 years on numerous field projects related to specialty fertilizers for a range of crops.

Ms. Cohen's expertise will be invaluable in the coordination of IPI's projects and extension programs in India.

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