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Essential role of potassium in diverse cropping systems

Edited by A.E. Johnston

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Proceedings of the Workshop C of the International Potash Institute

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Welcome address

Essential role of potassium in diverse cropping systems

Essential role of potassium in diverse cropping systems

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A steadily growing global population will ask for progressively more and better quality food. However, restricted land and water resources means that these justifyable demands can only be met by an increase in the productivity of the present cultivated land unless further deforestation and use of marginal land is accepted. Larger yields will require an increase in the supply of plant nutrients which must be available in the soil in both the right quantity and ratio to meet the needs of high yielding varieties. The use of mineral fertilizers and organic manures is essential to meet both current and expected future demand for plant nutrients. However, imbalances in nutrient supply are widespread, especially for potassium (K). Deficits in the K budget are increasing at alarming rates in many parts of the world. The immediate impact of an insufficient K supply is often hidden and the consequences of continuously mining the soil K capital are expensive to rectify. Any imbalance in nutrient availability, for example too much nitrogen (N) relative to K, does not allow a crop to achieve its full yield potential. Imbalances lead not only to low fertilizer use efficiency but also to poor crop quality, greater susceptibility to biotic and abiotic stress like pests, diseases, frost, heat and drought.

The half-day symposium of the International Potash Institute on the "Essential role of potassium in diverse cropping systems" addressed this issue at the 16th World Congress of Soil Science in Montpellier, France, 20-26 August, 1998. To inform those who gathered at the World Congress on the impact of balanced fertilization on yield, quality and the fertilizer use economy, a series of papers by speakers from different countries discussed the following items:

- K status and crop response in intensive systems with annual crops,
- K status and crop response as affected by economic considerations,
- Crop response under K at adverse climatic and/or soil conditions,
- Response of permanent crops to K,
- Future research needs and prospects.

Several posters also addressed these issues.

To reach a wider audience, these papers are now published by the International Potash Institute, Basel.

Session 1

Potassium status and crop response in intensive systems with annual crops

Long-term field experiments in intensive cropping systems in Germany*

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Introduction

In arable farming systems the nutrient supply of plants, through soil reserves and fertilization, is an important factor to sustain optimum plant production and soil fertility. The available nutrient content in the soil is influenced by the nutrient balance and further specific site conditions. An adequate supply of phosphorus (P) and potassium (K) is a prerequisite for the utilization of other important growth controlling factors such as nitrogen (N) and plant protection especially in intensive cropping systems characterized by large yields and high input levels (Loué, 1978). Twenty to thirty years ago, the K balance in German agriculture was positive (Bach *et al.*, 1997) and K reserves in the soil were built up to improve soil fertility. But during the last 15 years, the average K consumption has decreased from nearly 100 kg K_2O ha^{-1} down to 37 kg K_2O ha^{-1} of agricultural land (Statistical Yearbooks). This decrease is due to several reasons; e.g. decreasing product prices and the deteriorating economic situation of many farms, especially after reunification of Germany (this was most severe in the "new federal states"). Furthermore, better slurry management with decreasing nutrient losses, and better soil fertility with an increase in the depth of topsoils may also be responsible for the declining use of K.

Potassium content in the soil

Mainly because of decreasing profits, farmers took advantage of the K reserves in the soil and soil K mining became widespread, especially in arable farming systems (Baumgärtel, 1995). Unfortunately, a countrywide statistic about the exchangeable K content of soils does not exist. But for defined areas, it is very evident that a negative K balance leads to a decreasing content of exchangeable K in the soil, which threatens large crop yields. A number of long-term K field experiments have shown a clear relationship between soil K status and yield response to K fertilization (Kerschberger and Richter, 1987).

Yield

The increasing yield potential of many crops has concealed the risk of yield losses for many farmers. For example, today modern wheat varieties yield 7.3 t ha^{-1}

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* **Keywords**: potassium fertilization, optimum K rate, exchangeable K, yield response, economic response, long-term field experiments.

compared to 4.5 t ha^{-1} 20 years ago. In a long-term experiment lasting over 20 years on an orthic luvisol developed in a loess deposit, even on the plot without K, the yield of wheat increased from 4 to over 9 t ha^{-1} (Fig. 1). The increase in yield can be explained by new varieties and better plant protection, N fertilization, soil cultivation, etc. With such a large yield, most farmers do not expect that a nutrient deficiency could occur. Nevertheless, the results in Figure 1 with wheat show that it was possible to get a further significant increase in yield with an application of 100 kg K_2O ha^{-1}, especially in dry years (1990) when the increment was larger than the average. This shows that a high yield level is not only a reflection of a sufficient nutritional status of a crop, but on the contrary, it may induce the risk of a yield loss. The magnitude of the loss of yield due to insufficient K becomes greater as the yield level increases (Fig. 2). In the case of sugar beet, the effect is even more drastic than with wheat as indicated by the curves in Figure 2.

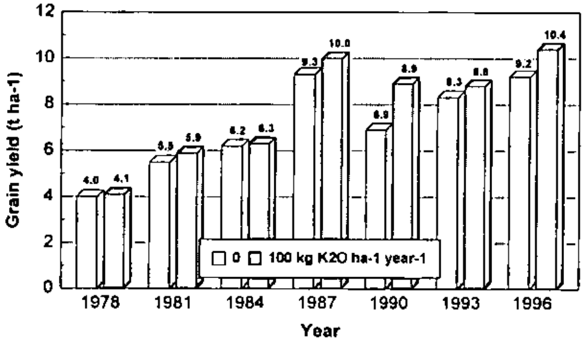

Fig. 1. Changes in wheat yields during the last 20 years of the long-term K experiment at Niestetal with 0 and 100 kg K_2O ha^{-1} year^{-1}.

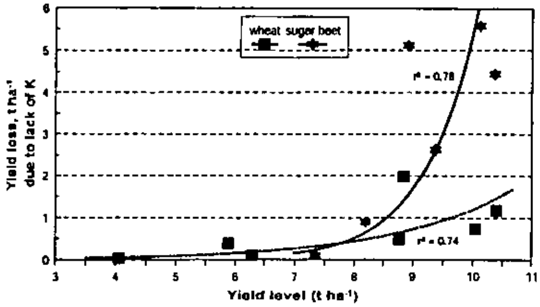

Fig. 2. Interaction between yield level of wheat given 100 kg K_2O ha^{-1} and sugar beet given 300 kg K_2O ha^{-1}, and the loss of yield due to K deficiency in the long-term K experiment, Niestetal.

The yield response to an application of K varies dramatically within a crop rotation as it was observed in the K experiment at Niestetal. The leafy crop, sugar beet, showed a sugar yield increase of 53% at the largest K fertilizer rate (Table 1). With only an 11% yield increase, the response of wheat and barley to K was much less. The yield optimum was often reached with the least amount of K. Nevertheless, with regard to the whole crop rotation, the largest K rate, 300 kg K_2O ha^{-1} year^{-1}, was profitable showing the greatest net return. This was caused by the very sensitive reaction of sugar beet to varying K supply.

Table 1. Impact of different K fertilizer rates on yield and economy of sugar beets and cereals in the long-term K experiment Niestetal 1978-1997.

kg K_2O ha^{-1} year^{-1}	Crop yield (t ha^{-1}) Sugar	Grain	Gross income after substracting the cost of the K (DM ha^{-1} year^{-1}) Sugar beet	Cereals	Crop rotation
0	5.94	6.78	3861	1491	2281
100	8.08	7.39	5202	1575	2784
200	8.56	7.44	5463	1537	2846
300	9.07	7.52	5743	1505	2918
LSD (5%)	0.88	0.25			

Economy

In Europe, leafy crops, e.g. potatoes, sugar beet and vegetables are cash crops and the gross margin is much higher than that of cereals. In the experiment at Niestetal, the gross income from sugar beet exceeds that of cereals by 3-4 times. For that reason, and because of the greater yield response, the K demand of this crop defines the necessary K content in the soil and K fertilization rate of the whole crop rotation.

Similar results were obtained in another series of 13 long-term K experiments on a number of typical sugar beet sites in South Germany. In this series, the average optimum K rate was 150 kg K_2O ha^{-1} year^{-1} for the whole rotation in all 13 experiments, even where all the crop residues remained on the field (Table 2). Calculated net returns were increased by an average of 147 DM ha^{-1} year^{-1} where the optimum rates had been applied. Based on this observation, the optimum K application rate was larger than the K offtake from the field at various locations. In intensive cropping systems, this K rate was determined mainly by taking into account the yield response of the sugar beet. Therefore, the optimum K content in the soil depends on the relative share of leafy crops within the crop rotation.

Table 2. Optimum annual K application rates, initial and final soil K content, and increase in net profitability in a sugar beet - wheat - barley crop rotation on 13 long-term experiments.

Loc.	Optimum K		Soil K content in mg K_2O 100 g^{-1} (CAL)[a]				Profit K_{opt}
	kg K_2O ha^{-1} $year^{-1}$	x greater than removal	initial	final K_0[b]	final K_{net}[b]	final K_{opt}[b,d]	DM ha^{-1} $year^{-1}$
1	223	2.4	22	15	20	32	234
2	139	1.9	27	16	20	25	147
3	222	0.9	29	16	26	25	162
4	250	2.7	27	19	22	24	111
5	140	1.4	30	19	19	25	204
6	195	0.8	13	6	13	12	183
7	204	1.8	16	12	15	17	249
8	0(108)[c]	0(0.9)[c]	22	17	20	17	0(29)[c]
9	0(120)[c]	0(1.2)[c]	22	16	18	16	0(93)[c]
10	283	3.1	23	16	19	22	212
11	0(171)[c]	0(1.2)[c]	17	9	11	9	0(92)[c]
12	0(111)[c]	0(1.4)[c]	21	21	17	21	0(64)[c]
13	290	3.3	23	12	14	25	412
Aver.	150	1.4	22	15	18	21	147

[a] Values of CAL extraction in mg K_2O 100 g^{-1} are generally similar to those obtained by NH_4-Ac extraction in mg K 100 g^{-1}.

[b] Final values are averages of the last three years of experiment; K_0, no K applied; K_{net}, K applied = K removed; K_{opt}, K applied at the optimum rate.

[c] Figures in brackets indicate the calculated values; because the yield increase due to the K application was statistically not significant, optimum K application was 0 kg K_2O ha^{-1}.

[d] Final K_{opt} values were obtained by interpolation for the optimum K application rate.

Site differences

From the results in Table 2, it is very obvious that optimum K fertilizer rates vary dramatically from one experimental site to another, although all locations had similar intensive cropping systems. Furthermore, even soils with an adequate K status at the beginning of the experiments according to the critical limits set by the state advisory authorities had large differences in the optimum soil K content.

This variability suggests that other factors influence the optimum K rate and are very site specific. They are the reserves of non-exchangeable K, K fixation capacity, clay content and clay mineralogy, soil structure, water availability, and effective rooting depth, which are normally not taken into account for interpreting the results of soil analyses for K recommendations (Lichtfuss and Grimme, 1987).

Furthermore, the differences between sites in the changes in the exchangeable K content in the soil where the application rate was adjusted to match the K removed by the crops from the beginning until the end of experiment, points to site specific effects.

On average of all 13 sites, a negative K balance caused a decrease in the content of exchangeable K in the topsoil, but the extent of this decline varied dramatically from site to site and varied between 0 and 2 mg K_2O 100 g^{-1} soil per year. Even on plots with an application rate corresponding to the K export from the field, a decline of the K content in the soil was observed at a number of locations.

On those plots with the optimum economic K rate, which was on average 1.4 times larger than the K export from the field, there was no considerable increase in the exchangeable K content of the soil except on one site. Significant K leaching on these medium to heavy textured soils can be excluded. Hence, K fixation must be the explanation for the observed decrease in exchangeable K on the plots with a zero K balance and the lack of any increase on the plots with the larger K rate. After the saturation of the K fixation capacity, the K fertilizer rate can be reduced to the level of K export from the field to sustain the optimum exchangeable K content in the soil.

Conclusion

In intensive cropping systems with large yields, it is necessary to sustain an adequate content of exchangeable K in the soil. With a decreasing K content in the soil, the risk of a yield loss will increase, especially for leafy crops like sugar beet, potato, or vegetables. The optimum K content in the soil can vary considerably from site to site depending on site-specific conditions. So, it is necessary to replace a general K recommendation to a site-specific recommendation, based on long-term K experiments under different site conditions. Leafy crops especially need a K fertilizer rate which is higher than the K export from the field by the harvested crops.

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Session 2

Potassium status and crop response as affected by economic considerations

Soil conditions of Belarus and efficiency of potassium fertilizers*

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Introduction

Raising and maintaining the level of soil fertility is of primary importance in the series of measures being taken to increase crop yields in the Belarus. This is mainly because the natural of soil-forming processes have led to the development of predominantly low-yielding sod-podzolic and swampy soils. In relatively favourable climatic conditions, the level of soil fertility is the most important factor limiting crop yields.

As a result of large scale water engineering, liming and the intensive use of organic and mineral fertilizers over the period 1965 to 1990, the productivity of arable land increased from 1.5 to 4.3 t ha^{-1} grain equivalent. A significant improvement of soil fertility status was also evident. However, the consumption of fertilizers and productivity of the agricultural land has declined strongly during recent years and the transition to a market economy. It is very important to prevent a decrease in soil fertility, especially soil potassium (K) status.

The quantitative parameters for evaluating soil fertility are determined by reference to the basic properties correlated with yields of cereals and potatoes grown on arable land and grasses grown in meadows and pastures. Since basic crop yields are closely related to the agrochemical properties of soils within a single type and texture class, soil fertility is commonly evaluated in terms of properties monitored every 4 years by soil analysis, e.g. pH and the phosphorus (P), K, calcium (Ca), magnesium (Mg) status and organic matter content as standard practice and also boron (B), copper (Cu) and zinc (Zn) contents as required. The monitoring of soil fertility and recommendations for the efficient use of fertilizers are the responsibility of the Agrochemical Service under the methodical management of the Belorussian Research Institute for Soil Science and Agrochemistry.

Soil potassium status and fertilizer application

Traditionally, the Republic of Belarus has used large amounts of K fertilizers. Over the period 1986-90, the average annual rate on arable land was 105 kg K_2O ha^{-1} plus 42 kg ha^{-1} in organic manure resulting in a positive balance of 38 kg K_2O ha^{-1}. The application of K fertilizers was reduced in 1995 to 44 kg K_2O ha^{-1}, and the resulting negative K balance was revealed by the results of soil tests, which indicated a fall in exchangeable K in soil in the last testing cycle (Table 1).

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* **Keywords**: potassium, soil testing, fertilizers, efficiency, crop yield, radionuclide.

Table 1. Application of fertilizers and fertility of arable soils in Belarus.

Factors	Years 1981-85	 1986-90	 1991-93	 1995	 1996
Fertilizer application ($N + P_2O_5 + K_2O$)					
kg ha^{-1} yr^{-1}	216	259	216	85	113
including N	76	88	72	31	42
P_2O_5	45	66	34	10	15
K_2O	95	105	70	44	56
Organic manure, t ha^{-1}	13.3	14.4	12.8	9.2	8.9
Crop yields, cereal units t ha^{-1}	3.4	4.3	3.9	3.0	3.2
Fertilizer contribution to yield increase, %	45	56	46	32	37
Exchangeable K_2O content in soil, mg kg^{-1}	156	172	183	-	174
Compared with the preceding period, mg kg^{-1}	+19	+16	+11	-	-9
Soils with low K_2O level (<80 mg kg^{-1}), %	18.3	13.7	10.4	-	13.0
P_2O_5 content in soil, mg kg^{-1}	141	173	190	-	182
Compared with the preceding period, mg kg^{-1}	+17	+32	+17	-	-8
Soils with low P_2O_5 level (<100 mg kg^{-1}), %	38.9	27.7	19.9	-	20.0
pH (1 M KCl)	5.61	5.81	5.89	-	5.99
Acid soils (pH < 5.0), %	19.8	11.8	8.2	-	5.7
Organic matter content in soil, %	2.04	2.18	2.20	-	2.21

Soil K status characteristics have been established on the basis of numerous laboratory analyses and long-term field experiments on the principle crops in geographically representative areas of the country. The K extracted by the appropriate reagent, appears to be the sum of water-soluble, exchangeable and some less readily soluble K, which constitutes an immediate K reserve for plants. Often, in practice, the K extracted is termed "exchangeable potassium". Exchangeable K is extracted from the sod-podzolic and peat soils by the Maslova method (1 M CH_3COONH_4 solution) or Kirsanov's method (0.2 M HCl solution in the ratio 1:5 soil:solution for mineral soils and 1:50 for organic soils) with subsequent flame-photometric determination.

This estimate of "exchangeable K" is not always sufficient to predict K fertilizer need. Then, we determine additionally that part of the non-exchangeable K, considered to be a potential reserve for crops (Pchelkin method, 1966). In sod-podzolic loamy and sandy loam soils of Belarus, water-soluble K amounts to 5-15%, exchangeable to 30-41% and non-exchangeable to 47-65% of the K extracted by the Pchelkin method. In field experiments, as well as the capacity indices mentioned above, K intensity in the soil is also measured (pK) or K potential (pK-0.5pCa) (Korzun, Skoropanova and Melnitchenko, 1984; Skoropanova, 1988). However, most practical recommendations are based still upon exchangeable K in the soil.

Fertilizer recommendations

Prediction of optimal K fertilizer rates requires a profound knowledge of the soil-plant system's response to a fertilizer input taking into account the specific climatic and management conditions at the farm level. Long-term field trials provide the most important data base from which optimal soil K status and optimal K fertilizer rates can be derived. The values of the desired soil K status and K fertilizer rates to raise the soil K status to the desired level are calculated from the test results on groups of soils having the same clay content.

A network of six long-term K fertilizer trials and numerous short-term trials in the main agricultural areas of the Republic of Belarus is used to obtain basic data for the economic and ecological optimization of both soil K status and fertilizer rates. The quantitative dependence of crop yields upon the exchangeable K content, soil acidity (pH), texture and the rates of K fertilizers has been established. The largest yields and effective crop response to K fertilizers on sod-podzolic soils were obtained with an exchangeable K_2O content of 300-350 mg kg^{-1} on loamy clay soil, 200-250 mg kg^{-1} on sandy loam, and 120-150 mg kg^{-1} on sandy soils. Liming of acid soils considerably improves the efficiency of fertilizer use (potatoes by 6-24%, winter rye by 20-40%, barley by 50-80%), therefore K rates are increased as pH increases up to the optimal level (Detkovskaya, Bogdevitch, Kulakovskaya *et al.*, 1986; Bogdevitch, 1988).

All crops respond well to K in Belarus. The results of long-term trials on most typical sandy loam soils show that K fertilizer efficiency (kg increase in crop per kg K_2O applied) is greater at lower rates of application (60-90 kg ha^{-1} K_2O) and on soils with low to optimum K contents (Table 2).

Table 2. Yield response to K fertilizers (kg crop per kg K_2O applied) on sod-podzolic sandy loam soils (1986-1997).

Crop	Fertilizer/crop price ratio	Potassium application kg K_2O ha^{-1}	Yield response, t ha^{-1} at an exchangeable K content (mg K_2O kg^{-1} soil) of			
			100-150	200-250	260-300	310-430
Barley	0.8	60	4.0	5.4	3.0	1.8
		90	3.7	3.2	2.2	1.5
		120	3.5	2.4	0.5	0.5
Potatoes	0.7	60	36	24	22	10
		120	21	11	9	9
		180	15	14	8	8
Corn (sillage)	4.0	60	89	70	-	-
		90	76	38	-	-
		120	53	7	-	-
Perennial grasses (hay)	1.6	60	8.3	8.8	5.5	5.0
		90	10.0	10.0	0.3	1.8
		120	7.2	8.0	0	0.8

The optimum content of exchangeable K greatly depends on the clay content and CEC and is lower on sandy soils than on soils of heavier texture. If the soil K content is close to optimum, the K fertilizer recommendation is calculated so as to replace the K removed in the targeted crop yield. For low K soils, the recommendations are increased by 110 to 140% of crop removal in the rotation. Soils with above optimum K content should receive less K fertilizer (30-60% of crop removal). Potassium fertilizers in Belarus are relatively very cheap nowadays. Therefore, the fertilizer/crop price ratios are very low (Table 2) and there are favourable conditions for a good economic return. The average rate of profitability of K fertilizer application is in the range 150-200%.

Potassium fertilizer recommendations for radionuclide contaminated land

A K fertilizer application system, in combination with NP-fertilizers, manure and liming, has been worked out for soils contaminated after the Chernobyl accident (Bogdevitch, 1992, 1997). Economically and ecologically acceptable rates of K were determined to ensure a stable level of soil fertility and minimize radionuclide uptake in crops and pastures. The recommended fertilizer rates were different for different soil types, K content of the soil and the intensity of land contamination by ^{137}Cs. When the K_2O content of soil achieved 200-300 mg kg^{-1}, there was a decrease in the ^{137}Cs content in agricultural crops by 1.5-2.5 times (Table 3), and in the ^{90}Sr content by up to twice. Soil K together with liming and water regime regulation decreased the radionuclides up to 6-10 times.

Table 3. Influence of exchangeable potassium content in sod-podzolic sandy loam soils on ^{137}Cs transfer factors (m^2 kg^{-1} 10^{-3}) for crop production.

Crop	K_2O content in soil, mg kg^{-1}				
	<80	81-140	141-200	201-300	>300
Oat, grain	0.42	0.25	0.21	0.18	0.11
Oat, straw	0.82	0.70	0.41	0.29	0.20
Winter rye, grain	0.10	0.10	0.07	0.05	0.05
Barley, grain	0.09	0.07	0.05	0.05	0.04
Barley, straw	0.38	0.24	0.19	0.16	0.14
Spring rape, seed	0.60	0.52	0.45	0.39	0.35
Clover, green	0.26	0.23	0.13	0.12	0.11
Natural grass, green	1.25	0.84	0.69	0.59	0.45
Potato, tuber	0.11	0.07	0.05	0.05	0.04
Carrot, root	-	-	0.10	0.06	0.05
Apple, fruit	0.06	0.05	0.04	0.03	-

New potassium fertilizer formulations

New types of granulated KCl with additives of plant growth regulators and micronutrients have been elaborated jointly with Belaruskaly. Yields in field trials were increased by 10-15% as compared with standard KCl (Naumova, Chripach, Bogdevitch *et al.*, 1996).

The implementation of recommendations based on scientific research data appear to be stopping the decrease of fertilizer consumption in Belarus. In the last two years, there has been an increase in the consumption of fertilizers; their use in 1997 was 59% greater than in 1995.

Conclusion

The scientific background for the effective and profitable use of K fertilizers for the main agroecological and economic regions of the country has been established. The optimum rates, methods of application and conditions for increasing the efficiency of use have been determined. Changes in soil data, indicated by samples taken at 4 year intervals on the control sites, confirm the tendency for an increase in the K content in the surface layer of arable soils, provided fertilizers and manure are used at the recommended rates and the farms are properly managed.

But still, there is an evidence of irrational use of fertilizer in many farms of Belarus. Intensive cropping with low rates of K fertilizers for long periods decreases the level of exchangeable K in the soil. On grassland, the removal of K by plants exceeds the amount applied in fertilizers and the K balance is thus negative in most regions of the country. This is a result of underestimating the significance of K in grass production.

The national policy for the use of K fertilizer requires significant correction to prevent a decline in soil fertility and crop production, and to maintain the environment, especially on the soils contaminated with radionuclides ^{137}Cs and ^{90}Sr.

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Efficiency of potassium fertilizers on soils with different levels of fertility*

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Introduction

Several zones can be distinguished in the Ukraine on the basis of the potassium (K) resources in the soils and in the parent rocks and the efficiency with which K fertilizers are used. There is a definite regularity by which the total and mobile K content increases in the direction from the north-west to the south-east and the efficiency of K fertilizers decreases in the same direction.

During the period of intensive fertilization between 1986 and 1990, the application of K fertilizers supplied 42 kg K_2O ha^{-1} to the sown area. On soddy podzolic soils, which are characterized by a low content of exchangeable K, and in the sugar beet growing areas, where 1.5 Mha of sugar beet are cultivated, the use of K was 100 kg K_2O ha^{-1} and its supply to the soil exceeded its removal by 10-15 kg ha^{-1}. An agrochemical survey revealed residual K reserves in soils, which affect the efficiency of K fertilizers. This has made it necessary to work out the requirement for K fertilizers relative to soil K status and to investigate K fertilizer transformations in the principle soils in the sugar beet growing areas, as well as the effect of residual K on fertilizer use efficiency.

Materials and methods

The investigations were carried out during a long-term experiment on a typical clay loam chernozem, containing 27% <0.001 mm and 51% <0.01 mm mineral fractions. Total K was 2.15% and the exchangeable K determined by extraction with 0.5 M (CH_3COOH) was 77 mg kg^{-1} of soil. Vermiculite, hydrous mica and mixed lattice minerals predominate in the mineral composition of the soil clay fraction. Before the experiment, the soil had not been cropped for more than 40 years.

In 1969-1970, at the beginning of the investigation reported here, soils with three different amounts of residual K were created by the application of 400, 800, 1200 kg K_2O ha^{-1}, these amounts were applied in two equal doses. In addition, there was a treatment without K. Subsequently, three annual treatments were tested: without fertilizers, animal manure (5 t ha^{-1} on average each year) and an organic plus mineral fertilizer treatment which tested 72 and 145 kg K_2O ha^{-1} each year.

The experiment was cropped in a six-course rotation with 50% of grains and 40% of tilled crops during 1971-1995 (four cycles of rotation). The experiments

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* **Keywords**: exchangeable potassium, fertilizers, yield.

reported here, therefore, studied the impact of different field crops and fertilizer systems on soil properties, yields and the efficiency of fertilizer use.

Experimental results

Cropping this chernozem for 26 years without fertilizer application decreased the humus content in the surface layer from 5.0 to 4.0%, the pH_{KCl} from 5.3 to 4.7 and the exchangeable cations from 25 to 21 $cmol_c\ kg^{-1}$ of soil, mainly due to the loss of calcium (Ca). The amount of total and exchangeable K in the soil without fertilizers, and hence with a negative K balance, did not essentially change, but the level of K mobility decreased by 30%.

With the increasing rates of K fertilizers, to make a K reserve in the soil, the content and relationship of the different K forms changed. In the first year, in the plough layer, the concentration of exchangeable K increased by 33, 79 and 104 mg $K_2O\ kg^{-1}$ soil, respectively, compared with the unfertilized soil. However, because the mobile K compounds transform to non-exchangeable forms and are removed in the harvested crops, the content of residual K decreased at the end the first rotation cycle (in six years) and did not exceed 4, 13, 18 mg $K_2O\ kg^{-1}$ soil, respectively, for the three K treatments. That is, the exchangeable K was now only 12, 16, 17% of the quantity produced in the first year as a result of the initial large applications of K. The content of fixed and non-available potassium increased by 20 and 15%, respectively, as compared with the treatment without fertilizers, thereby confirming a gradual transformation of the residual potassium into other forms.

Similar changes in the forms of K in this chernozem were observed during the whole experiment, and from this, it can be assumed that the various K forms in the soil are dynamic and able to maintain a definite balance between the exchangeable and non-exchangeable K when the K balance is both positive and negative.

The two larger concentrations of exchangeable K were maintained by regularly applying fertilizers, on average 72 and 145 mg $K_2O\ kg^{-1}$ soil annually. At the end of the fourth rotation, applying 145 kg $K_2O\ ha^{-1}$ each year to the soil with the largest initial concentration of exchangeable K increased the exchangeable K in the plough layer to 145 mg $K_2O\ kg^{-1}$ soil as compared with 77 mg $K_2O\ kg^{-1}$ soil where no K was applied, i.e. it doubled. The rate of K mobility increased under these conditions by three times. Thus, in this farming system with K applied each year, there was more available K than where no K was applied.

The accumulation of residual K proceeded more quickly on the treatments with the larger rates of fertilizer application, these fertilizers having been applied to make a reserve at the beginning of experiment. With the annual application of K fertilizers during four rotation cycles, the quantity of residual K where no K or 400 kg $K_2O\ ha^{-1}$ were applied initially was 14-17 mg $K_2O\ kg^{-1}$ soil, and where 800 and 1200 kg $K_2O\ ha^{-1}$ were applied originally, it was 20-25 mg $K_2O\ kg^{-1}$ soil.

In these investigations, some relationships were determined between the content of residual K in the soil, the yield of the crops and the efficiency of nitrogen (N), phosphorus (P) and K fertilizers. The increased yield of maize green mass on the treatments which also had N and P (180 kg ha^{-1} of primary nutrient) were 6.0, 6.5, 8.3 and 11.3 t ha^{-1} on soils with exchangeable K contents of 0, 12, 19 and 24 mg K_2O kg^{-1}, respectively. The effect of applying K fertilizers was less on soils with more exchangeable K than on soils with only small amounts; for the above treatments, the increase in yield was 45, 16, 11 and 0 kg of maize green mass per 1 kg of K_2O applied. Similar relationships were also found for other crops. On generalizing the multiannual data, the optimum levels of exchangeable K extracted by 0.5N CH_3COOH, were determined. The optimum level was defined as that at which K fertilizer gave no further increase in yield. These levels were as follows: 150-180 mg K_2O kg^{-1} soil (including 40-80 mg of residual K) for sugar beet; 100-150 mg (including 30-40 mg of residual K) for maize; 140-160 mg (including 40-80 mg of residual K) for winter wheat.

Discussion of experimental results

The application of large amounts of K fertilizer to create a reserve of K and the systematic use of K fertilizer throughout a rotation of crops change both the content of K and the relationships between the different forms of K in the plough layer of a typical chernozem. During the first one-two years after applying the large amounts of K, 400, 800, 1200 kg K_2O ha^{-1}, the content of the exchangeable K and its mobility as well as those of non-available K increased. When the balance of K was negative due to its removal in crops and due to the transformation processes of K within the soil, the content of mobile K had declined at the end of the first rotation cycle. However, the presence of the K reserves from the applied fertilizer, in spite of the above mentioned processes, suggests that the soil is able to keep some balance between the non-exchangeable and the exchangeable forms of K.

Within a crop rotation, the use of fertilizers at the maximum rate, 5 t of manure ha^{-1} plus 145 kg of K_2O ha^{-1} annually, provided a positive K balance. With the largest amount of applied K, the annual average supply exceeded removal by 34 kg K_2O ha^{-1}. Gradually the soil became saturated with K and the content of all soil K forms increased. With this treatment, the balance between the exchangeable and non-available forms was maintained at a higher level than on the treatment without K. The content of exchangeable K exceeded by 2 times the corresponding value for the unfertilized soil, and the content of the non-available potassium was 3 times larger. According to the Ukrainian classification, such a soil belongs to the class with an increased provision of K.

The results of these investigations also show that, even on a soil with a good soil K status, created by the systematic application of the maximum rate of K fertilizers, all the processes of K transformation and accumulation in such a clay loam soil takes place in the 0-40 cm layer. There were no significant changes in the K status of deeper soil layers with either mineral or organic fertilizers.

The residual K from fertilizers and manure positively affects soil fertility. The yields of all the crops closely correlated with the exchangeable K and increased as exchangeable K increased (especially on NP-fertilizer). The effect of K fertilizers is inversely proportional to the content of the residual K and there is no increase in yield above a definite level of residual K in the soil, this level being conventionally named "optimal". The optimal content of exchangeable K depends on the crop because different crops vary in their response to the K reserves in the soil. The best response to an increase in the soil K level was with sugar beet: its yield directly depends on the residual K in the soil.

The response of crops to a change in soil K depends on the crop as well as on the availability of N, P and K in the soil solution. The maximum effect is obtained by optimizing the ratio of all three nutrients. That is why K fertilizers were most effective on the NP fertilizer treated soil.

Conclusions

Potassium fertilizers applied both to create a reserve initially and thereafter annually, changed the content and relationships between the exchangeable and non-available K compounds in a typical clay loam chernozem in the 0-40 cm layer. The applied K gradually transformed into non-exchangeable forms but the soil was able to maintain a definite level of residual K in the plough layer during a long time (four cycles of a six-year rotation). The residual K has a positive effect to the yield and efficiency of N and P fertilizer use. The larger the residual K in the soil the smaller the effect of K fertilizers.

The dynamics of available potassium in Russian soils as affected by recent changes in the potassium balance*

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During the last 20 years, Russia has witnessed a very large scale "experiment" in agriculture. For 15 years from the 1970s, due to the development of a powerful chemical industry, the annual consumption of mineral fertilizers (N, P_2O_5, K_2O) reached almost 100 kg ha^{-1} of arable land including 25 kg of K_2O. In the last 5 years, consumption has fallen below 10 kg and the K_2O application has decreased to 1 kg. Our task now is to show how this "experiment" has affected the potassium (K) component of soil fertility and the productivity of agriculture. The "experiment" also produced strong arguments for attracting attention to the problem of soil fertility degradation, which can now be compared with an ecological stress. Some of these effects were predicted from the results of existing scientific experiments but the results were not taken into consideration when decisions were taken.

The average data for each 5-year period for K fertilizer consumption show a decline in all the economic regions of Russia (Fig. 1) and by 1994-1996 consumption was no more than 1 kg ha^{-1}, on average, in Russia. At the same time, the application of N and P fertilizers has decreased but, to a considerably smaller extent.

Analyzing simultaneously data for fertilizer K consumption, K balance and the proportion of soils with a small content of exchangeable K (K_{exch}), it is possible to see that the situation is very different in the various regions. In the first period, with positive K balances in the Western and Central regions, there was only a small % of soils with little exchangeable K and in the subsequent years (1991-1995) when there was a negative balance, the situation did not change greatly. Also, in zones with chernozem soils where only small amounts of K fertilizers were used and, hence, with a constant negative K balance, the proportion of soils with little exchangeable K is rather stable. In the course of "the global Russian experiment", a degree of stability in the different regions with various levels of soil K was revealed.

The complex macroanalysis of soil fertility conditions allowed the development of a general strategy for the promotion of K fertilizer use and measures for the delivery of the fertilizer in the regions most requiring it. This is especially true for those areas where the crops with high requirement for K, sugar beet, potato, vegetables, are grown.

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* **Keywords**: potash fertilizers, soil, crops, consumers, regions.

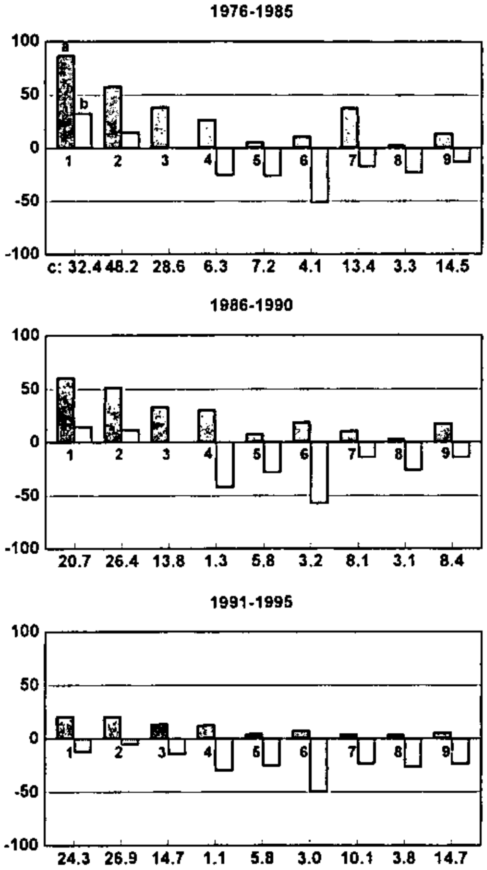

Fig. 1. Dynamics of soil K status in different regions of Russia: (a) consumption of potassium fertilizers as K_2O, kg ha^{-1}; (b) balance of K_2O, kg ha^{-1}; (c) percentage of arable soils with a low exchangeable K level. Regions: 1. N. West, 2. Center, 3. Volgo-Vyatka, 4. Chernozem, 5. Volga, 6. N. Caucasus, 7. Ural, 8. Siberia, 9. Far East.

Appreciable differences in K status indices occur not only on a macrolevel, but also at a lower, regional level, for example, in the Vladimir region (Table 1). The data characterizing this area are more representative and reflect the natural variability of the soils of the region more precisely. There was a rather slow accumulation of K_{exch} in soil with inputs of K fertilizer and faster decrease in K_{exch} after the interruption in the application of K. In the Vladimir region where quite large amounts of K fertilizers were applied over many years, it was shown on sandy soils that the average K content increased by 60% during 20 years and then decreased by 30% in 5 years.

Table 1. The effect of changes in the input of potassium on soil exchangeable K and cereal yields in the Vladimir region.

Factors	Years						
	1971	1979	1984	1986	1992	1995	1992-minus 1995
				Sandy soils			
Input of K fertilizers, kg ha^{-1}	45	56	62	61	46	3	-43
K exch. in the soil, mg kg^{-1}	85	103	117	124	135	101	-34
Yield of grain crops, t ha^{-1}	1.20	1.30	1.30	1.85	1.45	1.17	-0.28
				Loamy soils			
Input of K fertilizers, kg ha^{-1}	30	46	64	64	62	9	-53
K exch. in the soil, mg kg^{-1}	111	127	145	152	149	131	-18
Yield of grain crops, t ha^{-1}	1.95	2.30	2.15	2.15	2.45	2.00	-0.95

For the same two periods of time, on loamy steppe soils of this region, the increase was 34% and the decrease 14%. As a result of the decrease, the yield of grain crops declined with the K level in the soil. On sandy and loamy soils in the Vladimir area, after a long period of using K fertilizers, there was little difference in K_{exch} but a large difference in yield (Table 1). Then of course, it was necessary to recommend different fertilizer rates. The same was so in other regions too.

In the six districts of Ryazan region with soddy-podzolic soils, the percentage of soils with a low K level in 1991 was 32%, in 1997 it was 48%. In the same number of districts in the steppe zone, with similar sized differences in K balance the values were 32 and 26% in 1991 and 1997, respectively.

In the three districts of N. Novgorod region, on sandy soils there was an average K balance of +17 kg K_2O ha^{-1} for 5 years 1991-1995 and the balance became -13 kg K_2O ha^{-1}, on average, in 1994-1995. The effect on the average content of K_{exch} was a decrease from 161 to 123 mg kg^{-1}. In the districts with soils with a large amount of clay and an average negative K balance of -17 kg K_2O ha^{-1} in 1991-1995, which became -30 kg K_2O ha^{-1} in 1994-1995, the content of K_{exch} decreased from 163 to 144 mg kg^{-1}.

There are many such examples. For a correct interpretation of all the results, it is necessary to analyze in detail the condition of agriculture of each region and even farm. Only in this case, is it possible to give useful and economically expedient recommendations.

Unfortunately, the practice of agriculture on the farm does not make use of the many experimental results from the state research stations. For example, in the Central region where most of the population lives, there is a rather intensive level of agricultural production, mainly on soddy-podzolic soils with a relatively low initial level of fertility and a large number of research organizations.

It was established in the field experiments in this zone that for crops requiring a good supply of K, a negligent attitude to K fertilizers was extremely short sighted. After four years of an experiment on the loamy soil of the Moscow region, the increase in yield of potatoes from applying K was already equal to the effect of nitrogen (N) and phosphorus (P) fertilizers and in the 9th year, the largest effect of K was obtained. According to these results, a large negative effect on yields would be expected if K fertilizers were not used for almost 5 years.

The effect of K on all crops in the long-term field experiment on poor sandy soils at the Lubertsy Research Station (Moscow region) increased with successive rotations. In the first rotation, the increase was 1.3 and after 8 years it was 6.6 t ha^{-1} of fodder units.

The effect of K in the field experiment at Ramenskaya Research Station has increased with time. The yield increases after 5, 10 and 15 years were (in %) 5, 22 and 43 for winter wheat; 25, 34 and 61 for potatoes; 6, 44, 46 for barley; 33, 57, 43 for vicia-oat mixture and 17, 30, 41 for the 4 rotations as a whole.

On a heavy loamy clay soil at Dolgoprudnaya Research Station, the yield of fodder beet without K, 43.1 t ha^{-1}, was increased by K by 2.5 t ha^{-1} at the start of the experiment. By the 4th year, the yield without K was 17.6 t ha^{-1} and the increase with K was 11.9 t ha^{-1}.

As a result of systematically not applying K fertilizers, the effect of variations in weather conditions has increased sharply. In the long-term field experiment with barley of Sudogodskaya Research Station, K increased yield on average in five rotations by 0.5 t ha^{-1} or 22% (compared to the yield with NP) but the increase was 3.0 t ha^{-1} or 312% in 1997, an extreme year for weather effects on this crop.

According to the data of two long-term field experiments with winter wheat at the Ramenskaya Research Station, the largest relative increases in yield from K fertilizers were observed in unfavourable years. In most cases, this was not because of large differences in the content of K_{exch} in the soil.

Another characteristic of soils, determined in the long-term field experiments, is the relatively slower accumulation of K_{exch} as a result of K fertilizer application compared with the decrease in K_{exch} after stopping the application of K fertilizer. This is confirmed by the results of the long-term field experiment begun in 1965 on a loamy soil when after 10 years of applying different amounts of K, no further K was applied for the next 15 years (Fig. 2). The larger the amount of K applied and higher the level of soil K achieved, the greater the rate of decline. Where small amounts of K were used then the changes were not very great. Such a picture was also seen in the Vladimir region and many others in Russia.

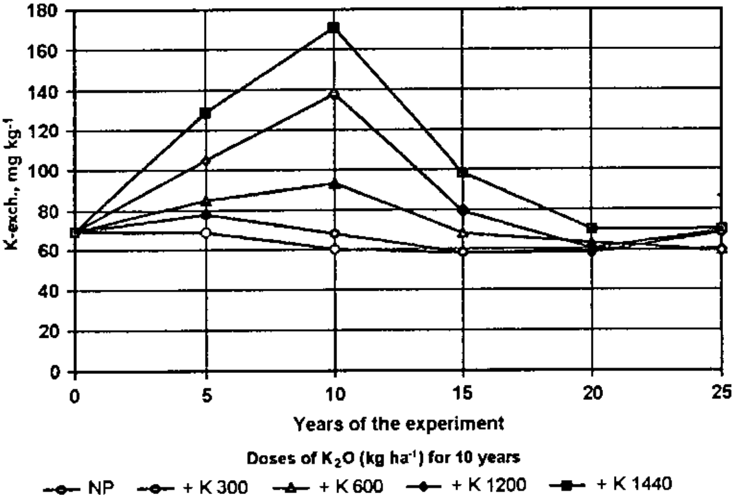

Fig. 2. Changes in K_{exch} in the soil during 10 years of K application and then during 15 years without K.

Detailed soil investigations in all field experiments have indicated a small alteration in the potential reserves of soil K and non-significant changes in K_{exch}

content on NP treated soils. It has been found that soils without K for a long time have a low restoration rate of the initial level of K_{exch}.

Only a small amount of K was taken up by ryegrass (3 cuts) from the soils taken from the NP treatment in the long-term field experiment despite the considerable potential reserves of K (Table 2). On NPK treatments where the K_2O balance was -60 and -4 kg ha^{-1} respectively, the ryegrass took up almost twice the amount of K than the increase in K_{exch} after 15 years of K treatment in the field experiment.

Table 2. Amount of the residual K_2O after growing of crops in the long-term field experiment for 3 crop rotations (15 years) on loamy soil.

Factors	NP	NPK1*	NPK2*
Offtake of K_2O in the field experiment, kg ha^{-1}	218	358	456
Balance of K_2O, kg ha^{-1}	-218	-60	-4
K_{exch} after 15 years, mg kg^{-1}	63	101	138
Offtake of K_2O in ryegrass in the pot experiment, mg kg^{-1}	69	64	156

* K1, K2: 298 and 452 kg K_2O ha^{-1} respectively.

According to the results of our researches a weak extract like 0.001 M $CaCl_2$ gives better information about the degree of K availability in the soil, especially if the level of soil fertility is not very high. Now, in the State agrochemical service, 0.2 N HCl is used and this gives a distorted picture about K availability in the soil. In the present situation in agriculture, the range of agrotechnical and economic conditions in Russia is huge. Recommendations will be more precise if they are given for smaller areas or for separate farms. One result of this "state experiment" has been to confirm earlier experimental data from the research farms but the price has been very expensive.

Session 3

Crop response at adverse climatic and/or soil conditions

Interrelationship between water and nutrient supply and response to potassium*

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Introduction

Plant growth rate, development and final crop yield all depend upon environmental factors such as light, temperature, water and nutrient availability. The role of water is unique because of its dual function, i.e. nutrient and medium of nutrient movement and root growth through soil.

The problems of water - nutrient relationships are not only associated with arid or semi-arid areas, but also with the humid areas of the world (Anderson *et al.*, 1992; Giunta *et al.*, 1995; Hamblin *et al.*, 1990). In the latter areas, crops exposed to occasional dry periods may yield less than expected on the basis of the amounts of applied nutrients. This study evaluated the significance of the potassium (K) supply to the plant in regions like Poland where both climatic and soil conditions considerably limit potential crop production.

The background to agricultural production in Poland

Soil resources and fertility

In Poland more, than 50% of arable soils are sands or loamy sands in the surface horizons and these textures predetermine most of the physical and chemical properties. The surface horizons contain only very small amounts of clay and organic matter (<2%) and as a result, the soils have a small cation exchange capacity (CEC < 10 $\text{cmol}_c\ \text{kg}^{-1}$). In addition, they are susceptible to acidification which exerts a negative influence on soil properties, reduces yields and restricts the growing of crops sensitive to low pH (Komisarek, 1995).

Nutrient mineral resources, i.e. the content of plant available mineral nutrients, might be used as a basic index of soil fertility. In the period 1987-92, only for phosphorus (P) were more than 50% of arable soils classified as having a satisfactory level of this nutrient. The situation was much worse for K and, in particular, for magnesium (Mg). For K, between 1975 and 1989, the sum of the K applied as fertilizer (80 kg K_2O) and in organic manure (35 K_2O ha^{-1}) resulted in a positive balance of 20 kg K_2O ha^{-1} year^{-1} (Fotyma *et al.*, 1992). However, this positive K balance was partly due to the fact that the ratio of $N:P_2O_5:K_2O$ was 1:0.62:0.76 and the small amount of N led to small yields (Table 1). Consequently, the offtake of K was small leading to a positive K balance. Thus, the imbalance of the applied nutrients seems to be the main reason for the lower than potential crop yields even in years with favourable weather conditions.

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* **Keywords**: water shortage, K fertilization, triticale growth stage, yield response to K.

Climatic conditions

Climatic conditions in Poland are not very favourable for cultivated plants because of the frequent deficit of precipitation during the vegetative season. In addition, shortages of rainfall occur in combination with high temperatures leading to increased evapotranspiration. The frequency with which evapotranspiration exceeds precipitation and lack of extra water supply (irrigation) is probably the main reason for the relatively low efficiency of applied fertilizers. The susceptibility of crop yields to water shortages increases in the order: winter cereals, spring cereals, potatoes, sugar beet, fodder crops (Dziezyc, 1993; Farat *et al.*, 1995).

Another feature of the Polish climate unfavourable for crop yields is the frequency of droughts. In the period 1951-1990, there were 21 droughts lasting a total of 122 months, i.e. 25% of the period. The longest periods of drought occurred in 1951, 1953, 1954, 1959, 1963, 1964, 1969, 1976, 1982, 1983, 1989, 1992, 1993. Apart from long-term droughts, short-term dry weather periods, causing disturbances in plant growth and yield losses, occurred in different seasons of the year (Farat *et al.*, 1995).

As a result of unfavourable soil and climatic conditions in Poland, it should not be surprising that the yield potential of crops is small and yields vary considerably. In years with favourable climatic conditions, as in 1990, major crops yielded from 59% (for rye) up to 86% (for spring barley and winter rape) of their potential yields. In years with unfavourable weather, e.g. 1992, the yields of these crops only reached 45%, 57% and 65%, respectively of their yield potential (Table 1).

Table 1. Potential and actual crop yields in Poland.

Crop	Yields					
	Potential		Actual			
			1990		1992	
	t ha^{-1}	%	t ha^{-1}	%	t ha^{-1}	%
Winter rye	4.4	100	2.61	59	1.96	45
Winter wheat	4.7	100	3.75	80	3.06	65
Spring barley	4.1	100	3.52	86	2.35	57
Oats	4.4	100	2.84	65	1.84	42
Potatoes	31.0	100	19.80	64	13.30	43
Sugar beet	48.6	100	38.00	78	29.40	60
Winter rape	3.5	100	2.41	86	1.82	65

Data from Dziezyc (1993) and FAO (1993).

Long-term assessment of crop response to potassium fertilization

There are two ways to evaluate crop response to K; the first and the oldest is based on the effect of non-balanced nutrition or even lack of a given nutrient on yield and its quality. The first long-term static fertilizer experiments started more than 150 years ago in England while in Poland they were started in 1923. The size of the increase or decrease in yield depends on many factors. These include soil texture, mineralogy, nutrient availability, soil water status and crop. It is well known that under K stress, the smaller the soil clay content and the larger the crop K requirement, the greater will be the decrease in yield. These rules constitute the basis of the so-called "exhaustion" experiments. Cropping with grasses is mainly used as a means of decreasing the level of plant available K. The majority of experiments made in Poland in the 1970s and 1980s were aimed at assessing plant response to increasing rates of K fertilizer (Fotyma *et al.*, 1992; Stepien, 1995). It was found that a small negative balance, up to 50 kg K ha^{-1}, does not effect K availability. As shown in Table 2, the response of potatoes to applied K depended on the level of exchangeable K (K_{ex}) and fertilizer rate. On the basis of these results, which are typical, it can be stated that the lower the soil K_{ex} and the amount of K applied, the better the agronomic efficiency of the applied fertilizer K. It was found that crop yield response to K fertilization was significant primarily on soils with significantly less than 100 mg kg^{-1} K_{ex}. Those studies also showed that the application of 90 to 150 kg K_2O ha^{-1} maintained a constant level of plant available K. Thus, higher K rates are not necessarily productive, but they may increase soil K reserves. This problem is related to the so-called "residual effect" of previously applied fertilizer K. It was found experimentally that six years of applying K at a double K rate increased soil K reserves to a level allowing its utilization by crops for up to six years (Fotyma *et al.*, 1992). However, as in the case of plant response to annual K fertilization, the residual effect depends on many factors determining plant growth during the growing season. In the case of the experimental data presented in Table 2, the agronomic efficiency of residual K was extremely low compared to the effect of direct K fertilization ranging from about 1 to 17 kg tubers kg^{-1} residual K_2O. The reason was a long period of drought which occurred in the last year of the experiment, i.e. 1992.

Table 2. Agronomic efficiency of K fertilizers applied to potatoes*, kg tubers kg^{-1} K.

Level of exchangeable K	K applied, kg ha^{-1} 70	140	280
Very low	55.7	39.3	23.0
Low	42.9	27.5	17.0
Medium	45.9	24.6	18.2
High	36.4	25.4	13.2

* Calculated from the data of Stepien (1995), mean of 6 years.

There are some soils in different parts of the world (including Poland) which do not need large amounts of K fertilizer because they release large amounts of K. It was on this kind of soil that, in 1957, a long-term experiment was established at the Brody Agricultural Station (Poznán Agricultural University). The soil is naturally rich in exchangeable and total K in the whole rooted soil volume. The response of crops, such as winter rye, spring barley and potatoes to nutrient supply was very specific. The grain yield of cereals was only slightly decreased by withholding K fertilizer (Blecharczyk *et al.*, 1993).

Potatoes (Fig. 1) responded more to weather conditions than did rye. The greater response of potatoes to fertilization was accompanied both by higher coefficients of variation and the level of yield. The largest yields were on the FYM treatments, which supports the well known fact that the uptake of one nutrient is much influenced by the supply of others. However, in good years like 1994, 1996 and 1997 with adequate summer rainfall, even NK fertilization gave relatively large yields which, for all treatments, decreased in the following order: FYM = NPK > NK > PK > K > control. The countrywide yield in the period of this experiment was about equal to that of the control treatment.

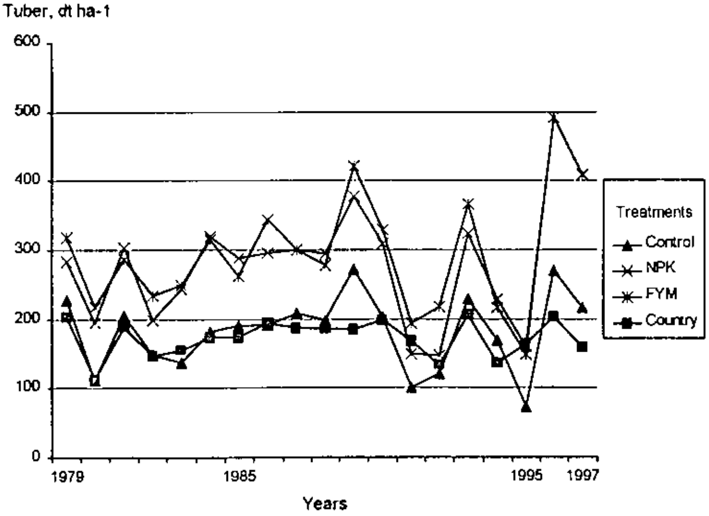

Fig. 1. Effect of fertilization on tuber yields of potatoes (Blecharczyk, pers. comm.).

Short-term manifestations of crop response to K fertilization

To elucidate the effect of water and K availability on crop yield, an exhaustion-type field experiment was established in 1991 at the Brody Research Station (Agricultural University in Poznán, Poland) on a loamy sand developed on the underlying sandy loam. In the years 1993-1995, the spring triticale cv "Gabo" was grown as a test crop. The experimental design was quite simple comprising of two levels of applied K (0 and 100 K_2O ha^{-1}) and four water treatments, which were control (rainfall only), irrigated to 70% FC, and drought imposed at the beginning of growth stage (GS) 30 and at GS 60. The moisture stress at particular stages of triticale growth was achieved by a static rain shelter designed to cover an experimental area of 72 m^2.

Only mean results for 1994 and 1995 are shown, because the drought which occurred in 1993 did not allow continuation of the experimental treatments. The yearly mean amount of water reaching the canopy was: control (natural precipitation) 238 mm; irrigated plots (70% FC) 329 mm; drought imposed from GS 30 to GS 60 (GS 30) 170 mm and drought imposed from GS 60 to GS 73 (GS 60) 184 mm, respectively. As shown in Table 3, the water and K interaction significantly influenced the final grain yield. With respect to the imposed drought at both K levels, the grain yield decreased as follows: 70% FC > control > D - GS 60 > D - GS 30. Thus, plants grown on the K fertilized treatments were only able to partly decrease the negative effect of water stress. However, the extent of the yield decrease strongly depended on K fertilization and the effect of K supply increased in the opposite direction to that for water. In comparison with the yield obtained on non-fertilized K plots, K fertilization increased grain yield by 123% when drought occurred between GS 30 and GS 60. A very significant effect of K was also found when water stress was imposed at the grain filling stage. In the absence of K, plants exposed to rainfall yielded 54% more than those droughted between GS 60 and GS 73 but when supplied with K, the difference was only 11%.

Table 3. The effect of water and potassium supply on triticale grain yield, t ha^{-1} (mean of 2 years).

K treatments	Water treatments				Mean
	Control	70% FC	D* - GS 30	D* - GS 60	
K -	5.45	6.62	2.56	3.53	4.54
K +	7.23	7.33	5.72	6.52	6.70
Mean	6.34	6.98	4.14	5.02	

D* Drought imposed from GS 30 to 60 (GS 30) or from GS 60 to 73 (GS 60) (adapted from Wyrwa, 1997).

The great effect of applying K to triticale on its ability to minimize water stress was confirmed by yield parameters such as agronomic and physiological indices and yield per unit of water applied (Tables 4 and 5). Data shown in Table 4 highlight two facts: (i) the large recovery of applied K by triticale grown under favourable K and water conditions, and (ii) increasing values of all parameters under water shortages both natural and experimentally imposed. The productivity per unit of water highlights the effect of K and the ability of the soil to deliver K from natural resources as long as the water supply was less than optimum for plant growth. The most striking results are not those from the imposed drought treatments but for plants grown under natural rainfall conditions where the lack of K decreased productivity by 25% compared to the K fertilized treatments (Table 5). The largest yield per unit of water use occurred when drought was not imposed until grain filling on well-fertilized soil.

Table 4. Efficiency of applied potassium, mean for 2 years.

Water treatments	Agronomic efficiency kg grain kg^{-1} K applied	K recovery %	Physiological efficiency kg grain kg^{-1} K uptake
Control	17.8	78	22.7
70% FC	7.1	66	10.8
D* GS 30	31.6	77	41.1
D* GS 60	29.9	94	31.8

D* See Table 3 for details (adapted from Wyrwa, 1997).

Table 5. Grain yields per unit of water applied, mean for 2 years (kg grain. l mm^{-1} water).

Water treatment	Potassium treatment		
	-K	+K	mean
Control	22.9	30.4	26.7
70% FC	20.1	22.3	21.2
D* GS 30	15.1	33.6	24.4
D* GS 60	19.8	35.4	27.6
Mean	19.5	30.4	

D* See Table 3 for details (adapted from Wyrwa, 1997).

It is well known that two weeks before anthesis, ears are very sensitive to adverse environmental conditions such as shading, water and temperature stresses. However, the most surprising result was the response of triticale to the simultaneous effect of water and K stress. It was observed that plants fertilized with K, irrespective of water treatments, took most of the K in the period from GS 30 to GS 60 (Fig. 2). At the same time, K uptake by plants not given K was very variable due to water availability. Plants grown on watered and control plots partly compensated their K uptake at the later growth stages, taking up the largest amounts at the GS 60-73. Watered plants took up almost the same amount of K as fertilized ones, but control plants significantly less. Potassium uptake by water stressed plants was also compensated at later growth stages but this uptake was much smaller compared to watered plants.

The negative effect of K and water shortages occurring during both the reproductive and grain filling growth stages of spring triticale were observed in symptoms generally associated with nitrogen (N) metabolism. The most important was related to accelerated leaf senescence. At growth stage 73, which is highly important for final grain yield, plants grown under favourable K supply still maintained large areas of green leaf which took up to 66% of their total biomass. On the other hand, the shortage of K decreased the share of green leaves by 40%, while water stress decreased the share by 50%. The accelerated senescence was accompanied by a simultaneous decline in chlorophyll content.

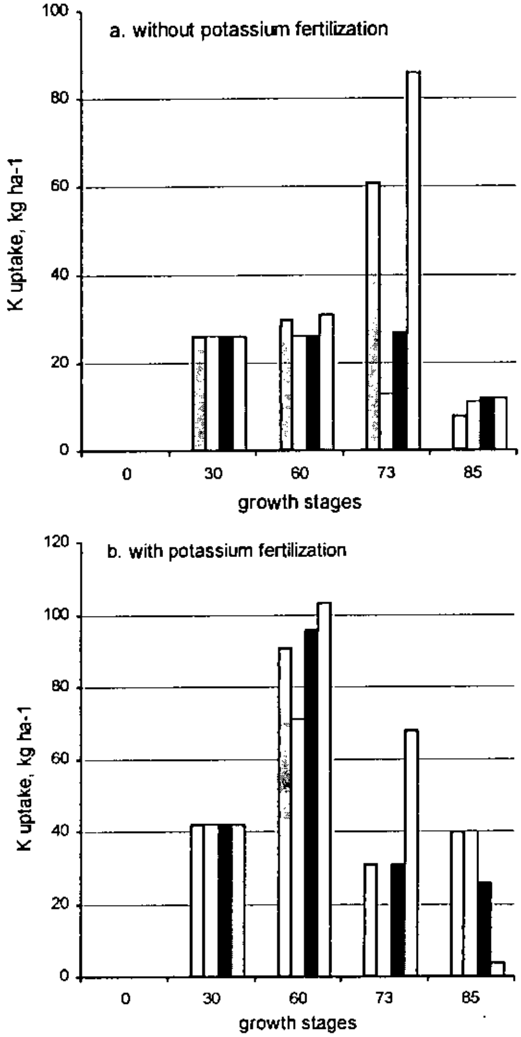

Fig. 2. Potassium uptake by spring triticale at different growth stages. Control □ ; drought between GS 30 and GS 60 □ ; drought between GS 60 and GS 73 ■ ; soils irrigated to maintain 70% FC □.

Conclusions

- In many humid areas of the World, including Poland, sound, sustainable management of water should take into account relationships between water and K supply.
- Adequate K fertilization practice seems to be one of the cheapest ways to diminish the negative effect of naturally occurring, short-lasting drought on crop growth and yield.
- The proper management of soil K also seems one of the ways to exploit crop production potential and increase N fertilizer efficiency.
- Annual yield variability might be partly explained by imbalanced plant nutrition and, as a result, decreased productivity per unit of water use.

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Potassium and leaf water relations under saline conditions[*]

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Abstract

A field experiment with satsuma mandarin nursery trees sought to find treatment strategies to overcome the effects of salinity due to seawater intrusion. Irrigation was practised at five different levels (0.65-2.0-3.5-5.0 and 6.5 dS m^{-1}) of saline water and fertigation at three levels (0-100-200 g K_2O $tree^{-1}$) of potassium (K).
The effects of enhanced K on leaf water status and gas exchange capacities were examined by measuring leaf water potential, relative turgidity, succulence index, stomatal density and gas exchange characteristics. The result revealed significant effects of K on several of these parameters which confirm the impact of K in overcoming salinity.

Introduction

Soil salinity is a worldwide problem, inhibiting the growth of most plants. Large areas of land in arid and semi-arid regions cannot support crops because of salt accumulation in soil profiles. Salinization also exists in topographically, low-lying lands near to sea shores where seawater intrudes into coastal aquifers (Mc Kersie and Leshem, 1994).

The reduction of growth caused by high levels of salinity is possibly related to osmotic effects as low soil water potentials and ionic imbalances induce toxicities or deficiencies of nutrients. The latter especially includes decreased potassium (K) and calcium (Ca) supplies and cellular compartmentation (Kafkafi and Bernstein, 1997). It is reported (Mengel and Kirkby, 1987) that in plant tissues, salinity affects different metabolic processes such as CO_2 assimilation, protein synthesis, respiration or phytohormone turnover. To some degree, plants can cope with salinity through some regulatory processes like excluding the uptake of excess ions or secreting them into vacuoles (Rains, 1972). For this reason, plants subjected to salinity require additional energy and deplete storage carbohydrates and thus are poor in energy status and have an impaired CO_2 assimilation (Mengel and Kirkby, 1987). Although general osmotic effects are always emphasized, specific ion effects are important as well. Maas (1993) stated that citrus is more sensitive to chloride (Cl), claiming that Cl increases the succulence of plant tissue while sulphate (SO_4) decreases it. Kafkafi and Bernstein (1997) reported that high levels of K and low levels of sodium (Na) should be maintained in the cytoplasm to

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[*] **Keywords**: salt stress, potassium, citrus.

manage salt stress. These authors suggested that high internal K is essential for metabolic processes and to reduce Na influx. It is also suggested that in saline soils, even if K seems to be sufficient, a Na induced K deficiency may occur (Mc Kersie and Leshem, 1994).

On the other hand, Lloyd *et al.* (1989) reported that in citrus, both rootstocks and scion have a specific effect on salt tolerance and the variation may result from the degree of Na or Cl ion exclusion. In terms of Na exclusion, Trifoliata was found to be more effective than Troyer citrange. In the Ege region of Turkey, Troyer citrange started to replace Poncirus trifoliata as a rootstock for satsuma mandarins because of its tolerance to large amounts of calcium carbonate ($CaCO_3$) in the soil. However, in areas where salinity is a problem, due to seawater intrusion, more valid data need to be collected.

A field experiment sought to find treatment strategies to overcome the effects of salinity due to seawater intrusion in the satsuma growing region of Turkey. In the experiment, the effects of enhanced K on leaf water status and gas exchange capacity of satsuma mandarins were examined under saline conditions.

Material and methods

A field experiment with satsuma mandarin (cv. Owari) nursery trees budded onto Troyer citrange rootstock was established in 1996 with trees spaced at 3 m between rows and 2.5 m within rows. Irrigation was with saline water at five levels of salinity (0.65-2.0-3.5-5.0 and 6.5 dS m^{-1}) and fertigation at three levels 0 (control)-100-200 g K_2O tree^{-1}. Recommended amounts of nitrogen (N) and phosphorus (P) fertilizers were applied additionally. The design was a randomized block with 4 replicates and 3 trees per treatment. The physical and chemical properties of the experimental soil are in Table 1 and the Cl, Na and K concentrations in the leaves are in Table 2.

Table 1. Some physical and chemical properties of the experimental soil.

pH	$CaCO_3$ %	Texture	EC_e	Total N %	H_2O-ext. P mg kg^{-1}	NH$_4$OAc ext. mg kg^{-1} K	Ca	Mg
7.35	1.16	Sandy	550	0.137	500	300	3550	100

Table 2. Leaf sodium, potassium and chloride concentrations in 1996 with respect to salinity and applied potassium* (Anaç *et al.*, 1997).

Salinity levels ($dS\ m^{-1}$)	Cl (%)			Na (ppm)			K (%)		
	K0	K1	K2	K0	K1	K2	K0	K1	K2
0.65	0.119	0.181	0.129	203	265	218	1.05	1.22	1.43
2.00	0.214	0.369	0.100	473	458	438	1.01	1.21	1.41
3.50	0.494	0.271	0.395	388	622	507	0.94	1.14	1.19
5.00	0.654	0.784	1.110	1093	1258	1241	0.96	1.40	1.35
6.50	0.865	0.583	1.046	1772	2489	1105	0.86	1.12	1.44

* K0, K1, K2: 0, 100, 200 g K_2O tree^{-1}.

The following measurements related to leaf water status were carried out at intervals in 1996 and 1997 on full-size leaves of the current season's growth:

- Leaf water potential was measured by a pressure chamber (PMS Model 1003) during the day at predawn and early noon.
- Relative turgidity (%) was calculated as the ratio of the leaf water content of the freshly picked leaves to the water content of leaves immersed in distilled water for four hours (Hepaksoy *et al.*, 1997).
- Succulence index was determined as the water content per unit area of leaves (Romero-Aranda and Syvertsen, 1996).
- Stomatal density was counted at five different areas on laminae of five leaves.
- Gas exchange characteristics were measured between 9.00 and 10:00 h by a portable photosynthesis system (CI-301 PS, CID, Inc.) using an open system chamber with a window area of 2.5 cm^2. The mass flow rate was formulated according to the temperature. During the measurements, the average photon flux density, temperature and relative humidity values were 1834 $\mu mol\ m^{-2}\ s^{-1}$, 31.9°C and 32.3% respectively.

Results and discussion

Leaf water potential

Leaf water potential, determined at predawn and early noon in August 1997, seemed to increase parallel with increasing salinization (Table 3). Potassium had a significant effect on this parameter at the early noon determination. As the rate of K increased, the effect of increased salinity was lessened significantly. In the plots that received no K, the salinity levels were statistically grouped into four as 6.5-5.0; 5.0-3.5; 3.5-2.0 and 0.65 dS m^{-1}. With the smaller amount of applied K, there were three distinct water potential groups, whereas, with the larger amount of K, the effects of all levels of salinity, excluding the fresh water, were not statistically different. Thus, K overcame the negative impact of salinity within the range of 2.0 and 6.5 dS m^{-1}. Although similar tendencies were observed in the predawn pressure chamber measurements, the effects were not statistically significant.

Succulence index

The effect of treatment on the succulence index values for the leaves are shown in Table 4. Statistical analyses showed that the succulence of the leaf tissues was significantly affected by the time span (months) and increased K and salinity levels. At the lowest salinity level, there was no statistical difference in the succulence index with time - July to September. However, the higher levels of salinity created two statistically different groups, generally the values in August and September were similar and different to those in July.

Table 3. Effect of time of day, salinity and potassium on leaf water potential and relative turgidity (August 1997).

Salinity, dS m^{-1}	Water potential (Bar)								Relative turgidity (%)			
	predawn				early noon							
	K_0	K_1	K_2	Mean	K_0	K_1	K_2	Mean	K_0	K_1	K_2	Mean
0.65	5.6	5.4	5.1	5.37	17.1	15.5	11.9	14.83	93.97	96.73	90.91	93.87
2.00	5.5	5.6	5.1	5.40	20.7	17.7	17.3	18.57	91.07	89.41	91.64	90.71
3.50	6.4	6.1	6.2	6.23	22.4	17.7	17.7	19.27	94.46	87.68	91.08	91.07
5.00	5.5	6.7	6.8	6.33	24.1	18.4	17.8	20.10	89.47	79.50	91.84	86.94
6.50	7.5	6.4	6.5	6.80	24.4	23.1	19.0	22.16	92.79	93.08	92.37	92.75
Mean	6.10	6.04	5.94		21.74	18.48	16.74		92.35	89.28	91.57	
F values	Time**; Salinity**; Potassium**; Salinity: n.s.; Potassium: n.s.											

Table 4. Effect of growth period, salinity and potassium on leaf succulence index in 1997.

Salinity levels, dS m^{-1}	July				August				September				Grand mean (I)
	K_0	K_1	K_2	Mean	K_0	K_1	K_2	Mean	K_0	K_1	K_2	Mean	
0.65	21.0	21.1	21.2	21.1	22.2	21.2	21.3	21.6	22.4	21.6	21.5	21.8	21.5
2.00	21.9	20.2	19.6	20.6	22.6	22.4	21.9	22.3	22.4	23.0	21.9	22.4	21.8
3.50	20.4	21.2	20.6	20.7	22.7	23.6	22.7	23.0	23.0	23.5	22.9	23.1	22.3
5.00	21.0	20.7	22.2	21.3	24.0	24.3	22.9	23.7	24.4	24.4	23.3	24.0	23.0
6.50	21.3	22.2	19.9	21.1	25.9	25.1	24.2	25.1	25.8	25.8	24.8	25.5	23.9
Mean	21.3	21.1	20.7	21.0	23.5	23.3	22.6	23.1	23.6	23.6	22.9	23.4	22.5
F values	Month**; Salinity**; Potassium**												

The effect of increasing salinity was not significant in July following the salt application in June. However, in later months generally the highest salinity level was statistically different from the other salt treatments. The impact of K on succulence was marked; as the K rates increased the succulence index decreased. The index at the highest level of K was the smallest and statistically different from the control and first K level. Romano-Aranda and Syvertsen (1996) reported that the leaf succulence for grapefruit and orange leaves, determined as 16.3 and 16.5 respectivelly, were not significantly affected by foliar applied N and NaCl under greenhouse conditions.

Relative turgidity

There were no differences in relative turgidity (%) values regardless of treatments (month, salinity and K). This result may be due to the thick cuticle layer in citrus leaves and consequent slow influx of water. This suggests that an extension of the immersion period in distilled water may be required to test for treatment effects. However, the results for August 1997 (given in Table 3) show a tendency for decreases in relative turgidity (%) with increased K, particularly with the largest amount of K, where results were lower compared to those of the control (K_0). A significant correlation ($r = -0.347^{**}$) was found between the amount of applied K and relative turgidity values and thus confirms these results (Romera-Aranda and Syvertsen, 1996).

Stomatal density

Reduced stomatal number is a mechanism for adaptation to prevent water loss. Statistical evaluation of the stomatal density data (Table 5) showed that neither of the treatments exerted any significant effect. However, data using a quadratic equation to relate stomatal density and applied K rate was signifieant at the 5% level, the lowest number per mm^2 being found in the plot that received 100 g K_2O $tree^{-1}$.

Net carbon dioxide assimilation

The net CO_2 assimilation rate was related mainly to the intercepted photosynthetically active radiation (data not shown). In August 1996 and 1997, the net CO_2 assimilation rate showed a similar response to the applied salinity and K. The data in Table 5 show that the net CO_2 assimilation rates were significantly correlated with salinity of the irrigation water and applied K. The quadratic effects were more pronounced in both cases. The net CO_2 assimilation per unit area, averaged over all salinity levels, was largest at 100 g K_2O $tree^{-1}$ followed by 200 g K_2O $tree^{-1}$. The control plot, which did not receive any additional K, had the lowest photosynthetic rates at all but the lowest salinity levels. The suppressive effect of salinity on the photosynthetic rate per unit leaf area became more significant because there was a decrease in leaf area (Anaç *et al.*, 1997) which consequently limits the photosynthetic capacity of the canopy.

Table 5. The effect of salinity and potassium on stomatal density and net carbon dioxide assimilation.

Salinity level (dS m^{-1})	Stomatal density (number mm^{-2})				Net CO_2 assimilation (µmol CO_2 m^{-2} s^{-1})			
	K_0	K_1	K_2	Mean	K_0	K_1	K_2	Mean
0.65	691.3	686.0	693.3	690.2	27.8	28.6	20.1	25.5
2.00	768.5	600.3	688.3	685.7	21.1	27.8	23.0	23.9
3.50	741.5	711.5	832.3	761.8	14.4	23.5	16.5	18.1
5.00	720.8	687.3	713.0	707.0	16.5	29.5	23.6	23.2
6.50	706.0	699.5	798.0	734.5	23.8	26.2	34.2	28.0
Mean	725.6	676.9	744.9		20.7	27.1	23.5	
F values	Salinity: n.s.; Potassium: n.s.; Salinity: **; Potassium: **							

Conclusion

The results obtained in the field trial performed with satsuma mandarin budded onto Troyer citrange rootstock showed a marked effect of salinity on growth suppression (Anaç *et al.*, 1997) and water status of the leaves. The experimental soil had properties typical of the Ege region, i.e. it was rich in available Ca (Table 1). Under saline conditions, Na induced K deficiencies even at sufficient levels of available soil K are reported (Mc Kersie and Leshen, 1993). Kafkafi and Bernstein (1997) claim that high levels of K and low levels of Na are necessary to cope with salt stress. The availability of the external water solution was reduced by salinity which in turn affected the water status of the plants. Decreasing the transpiration rate is a way to improve the water status of the plant and thus reduce the accumulation of Na and Cl in the leaves (Golombeck and Lüdders, 1993). The decreases in mesophyll area exposed to internal air spaces affect the diffusion of CO_2 to the site of carboxylation in the chloroplasts (Romero-Aranda *et al.*, 1997). Our data for several growth parameters showed significant effects of K in overcoming salinity.

The 100 g K_2O tree^{-1} application rate, especially, seems to justify further attention because there were high net CO_2 assimilation rates parallel with lower relative turgidity, stomatal density and leaf Cl values. Long-term evaluation of these parameters is necessary to finalize the combined effects of K and salinity on leaf gas exchange properties.

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Potassium fertilization of groundnut in Saurashtra region, India*

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Abstract

The contention that the soils of the Saurashtra region of India are well supplied with available potassium (K) and that groundnut in this region needs no K has done more harm than good in the last 30 years, because groundnut responds to the application of K. The reasons are: (i) the low K supplying capacity of the soils, (ii) monocropping with groundnut during the last 60 years, (iii) the increasing area and production of summer groundnut. At least 21% of soils need K fertilization. The soil critical limit is 145 kg K_2O ha^{-1} for groundnut. A K application at 80 kg K_2O ha^{-1} together with the recommended amount of nitrogen (N) and phosphorus (P) increases the yield and quality of the crop significantly. The adhoc application of NPK is harmful and K application should be based on soil analysis.

Introduction

Globally, India ranks first with respect to area (30%) and second (29%) in the production of groundnuts. Groundnut sustains an internal trade of worth Rs. 475 M. Among the states, Gujarat contributes 30% of the total production in India. Of the 30%, about 85% comes from the five districts of the Saurashtra region which, therefore, are regarded as the oil bowl of the State. However, the productivity is only 1200 kg ha^{-1} for many reasons, but a major factor is continuous monocropping of groundnut during the last 60 years, which has caused multinutritional problems in the soils (Golakiya and Patel, 1996). Potassium is one of these factors (Malavia and Golakiya, 1994). In this context, research was started with the following objectives:

- To assess the soil K status and critical limits of K in the soil and plant.
- To study the field response of groundnut to K.
- To study the interaction of K with other nutrients.
- To know the K uptake pattern of groundnut.
- To observe the crop response to K and the soil K status in a long-term fertilizer experiment (LTFE).

Methods and materials

Saurashtra (20°-39'N lat. & 60° long.) is a Western peninsular region of India. The climate is arid to semi-arid, potential evapotranspiration (PET) is 1873 mm and

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* **Keywords**: potassium, fertilization, groundnut, India.

rainfall is low (761 mm) and erratic (CV 55%). Most of the rains (monsoon) occur during 38 rainy days between 21 June and 21 September, the kharif season. Crops grown during the summer season (February to May) must be irrigated. The topography is undulating and parent material varies with soil catana. Different aspects of the K nutrition of groundnut have been studied during the last decade at the Department of Agricultural Chemistry and Soil Science, Gujarat Agricultural University, Junagadh, India. They have included a survey of about 560 soil samples, whose physio-chemical properties have been analyzed using standard methods. Clay was determined using the international pipette method (Piper, 1950), and lime ($CaCO_3$), electrical conductivity and pH using methods described by Jackson (1973). The cation exchange capacity (CEC) was determined using the method described by Chapman (1965).

Soil status and critical limits of potassium

Various categories of K were determined in the soil extracts by flame-photometry. They included total K (Pratt, 1965), available K (Hanway and Heidal, 1952), water soluble K (McLean, 1961) and HNO_3 soluble K (Sutton and Sey, 1958). Exchangeable K was calculated by deducting water soluble K from available K.

Twenty surface soils representing medium, black calcareous (Vertic Ustocrept) soils were collected for a pot experiment to determine the critical limits of K. The experiment was done in iron pots, 37.5 x 60 x 25 cm, each holding 60 kg of soil. Potassium was tested at 0, 50, 100 kg K_2O ha^{-1} equivalent applied as pure KCl, and 25 kg N and 50 kg P_2O_5 ha^{-1} equivalent was applied as urea and DAP to all pots. The treatments were replicated twice in a randomized block design, Groundnut cv. GAUG-10 was sown and grown to maturity during the summer season. Plant samples at 30 days after sowing (DAS) and at harvest were dried, ground and a subsample digested in a mixture of HNO_3 and $HClO_4$ (3:1) and analyzed for K by flame-photometer. Soils were extracted for K using 1N NH_4OAc. The critical limit for K for groundnut and soil were determined by plotting percentage yield against available soil K and plant K concentration, respectively (Cate and Nelson, 1965). Brays % yield was calculated as:

$$\% \text{ yield} = \frac{\text{yield without K}}{\text{yield at optimum K level}} \times 100$$

Field response of groundnut to potassium

Locations: Replicated trials, two each in summer 1996 and kharif 1997, on the K nutrition of groundnut, cv G-4 and G-20, were undertaken on different farms on the university campus. The six treatments in quadruplicate were control, 40, 80, 120, 60+60 kg K_2O ha^{-1} and 10 t FYM ha^{-1} allocated in a randomized block design. Simultaneously six non-replicated trials (also in summer and kharif) with the same treatments and variety were conducted on farmers fields. Yields of haulm and pod were measured at harvest.

Seasonality: Groundnut grown in kharif and summer always responded differently to K. The season effect has been deduced by pooling the location effect. In kharif, groundnut response varies with the timing of the monsoon. To cover a wider time span, results from about 95 trials, conducted by the Department during 1981 to 1986 on the K nutrition of groundnut, have been related to the % rainfall during the critical growth period, namely 47 to 67 DAS. The average rainfall during this critical period is about 90 mm.

Dry spells: Field studies have been conducted to understand the effect of dry spells on groundnut fertilized with 60 kg K_2O ha^{-1} and a 2% spray of KCl. Single, double and triple periods of water stress were imposed during flowering, pegging and pod development. The yields of pod and haulm were measured.

Residual effects: One of the replicated summer trials at the university farm was extended to measure the residual effect of summer fertilization on groundnut grown in the kharif season.

Interactions of potassium with other nutrients

Three field trials with groundnut, cv. G-2, were conducted during summer 1992, 1993 and 1994 to measure the KxN, KxS and KxZn interactions. Four levels of K, control, 30, 60 and 90 kg K_2O ha^{-1} and three levels each of N, S and Zn, 0, 50 and 50 kg element ha^{-1} were superimposed on that of K and replicated three times in a randomized block design. Yields of pod, haulm and oil were measured at harvest.

Potassium uptake pattern

Weekly soil and plant samples were collected from groundnut grown on a medium black calcareous clay with 40% clay, pH 8.3, EC 0.3 dS m^{-1} and available K_2O 130 kg ha^{-1}. All plots received 25 kg N and 50 kg P_2O_5 ha^{-1}. Weekly soil and plant samples were analysed to determine the K uptake pattern.

Response of groundnut to potassium and soil potassium in a long-term field experiment (LTFE)

A long-term fertilizer experiment with a groundnut-wheat-maize cropping sequence is in its 10th year on the university farm. The treatments comprise control, recommended amounts of NP and NPK and NPK as per soil test. Total yield and K status in the first and tenth year are discussed here.

Results and discussion

Soil status and critical limits

The total K and non-exchangeable K in the Saurashtra soils followed, in order, the sequence of pedogenic weathering which is basalt > mixed parent material > limestone > sand stone (Table 1). A similar trend was observed with available K in the soils.

Table 1. Physico-chemical characteristics of the soils and categories of potassium in important soil groups of the Saurashtra region, India.

Soils	Greatgroup	Clay content (%)	$CaCO_3$ (%)	O.C. (%)	EC dS m^{-1}	pH (1:2.5)	CEC (cmol$_c$ kg^{-1})
Shallow black (basal trap)	Ustortheets	28.2	5.75	0.24	1.40	8.06	50.07
Shallow black (limestone)	Ustortheets	20.0	50.00	0.96	2.05	8.20	31.81
Shallow black (sandstone)	Ustortheets	16.3	3.25	0.42	1.50	8.15	24.28
Medium black (basal trap)	Ustochrepts	39.2	5.50	0.36	2.90	8.48	61.65
Deep black (basal trap)	Chromusterts	48.3	9.75	0.50	2.75	8.33	69.64
Mixed medium black and red (limestone)	Ustochrepts	51.2	12.25	0.60	2.33	8.45	64.69
Coastal shallow	Ustorthents	35.0	14.25	0.63	6.90	8.15	56.33
Coastal deep (saline)	Ustifluvents	19.3	8.25	0.42	4.40	8.48	61.38
River coastal Deep	Ustochrepts	29.2	13.25	0.47	2.00	8.48	44.00
Stony	Ustorthents	28.2	5.25	0.27	1.45	8.33	55.97
Mean		25.8	12.75	0.49	2.77	8.31	49.67

Table 1. Continued.

Soils	Forms of K (cmol$_c$ kg^{-1})					Groundnut
	Total K	Exch. K	Water soluble K	HNO$_3$ soluble K	Fixed K	yield (av.) kg ha^{-1}
Shallow black (basal trap)	18.99	0.23	0.026	1.08	0.84	3000
Shallow black (limestone)	13.65	0.26	0.009	0.32	0.07	2500
Shallow black (sandstone)	11.90	0.23	0.014	0.60	0.36	3000
Medium black (basal trap)	7.18	0.29	0.006	0.87	0.58	1800
Deep black (basal trap)	17.37	0.83	0.017	2.18	1.35	2100
Mixed medium black and red (limestone)	13.64	0.40	0.024	0.87	0.47	3500
Coastal shallow	12.94	0.31	0.006	0.92	0.61	2400
Coastal deep (saline)	16.23	1.01	0.027	2.66	1.55	900
River coastal Deep	17.01	0.73	0.016	1.74	1.01	1600
Stony	13.65	0.49	0.008	1.12	0.63	1200
Mean	14.25	0.48	0.015	1.22	0.75	2444

About 79% of soils contained large amounts (>280 kg K_2O ha^{-1}) available K, 18% were medium (140-280 kg K_2O ha^{-1}) and only 3% has less than 140 kg K_2O ha^{-1}. Therefore, it was highly important to establish the critical limit of K in the soil and the groundnut plant. From the pot experiment on 20 soils, it was concluded that 145 kg K_2O ha^{-1} is the critical limit of available K in the Saurashtra soils (Fig. 1). Similarly, the critical concentration of K in the pod at 30 DAS was 0.9% K and about 0.46% K at harvest.

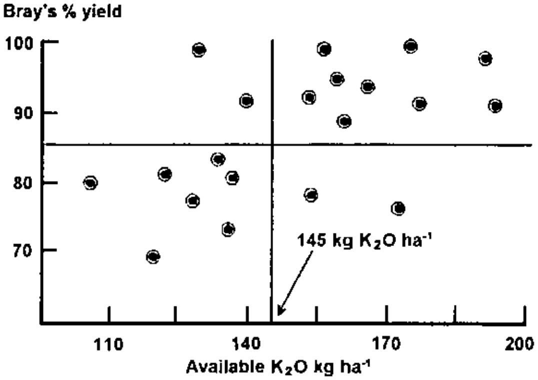

Fig. 1. Soil status of available K and its critical limits in the soils of the Saurashtra region, India.

Field response of groundnut to potassium

Locations: The response to K was location specific (Table 2). In the summer season, pod and haulm yields were increased by 36 and 32% respectively at Site I when 80 kg K_2O ha^{-1} was applied. This was because the soils were low in available K.

Interestingly, pod and haulm yields were increased by 25 and 17%, respectively, with 80 kg K_2O ha^{-1} at Site II even though this soil had 712 kg K_2O ha^{-1} available K. This type of result has been reported elsewhere (Patel *et al.*, 1993). The explanation lies in the physical chemistry of Saurashtra soils. The capacity factor (PBCk) increased whereas intensity (AReK-D, G) and quantity factors decreased with increasing clay content in the Saurashtra soils (Mehta and Shah, 1956). The value of AReK-D should be between 0.0027 to 0.034 $(Ml^{-1})^{0.5}$ to provide balanced K nutrition (Woodruff, 1955). These values for Saurashtra soils range from 0.0011 to 0.005 $(Ml^{-1})^{0.5}$ which are considered to be on low side. This understanding of intensity parameters offers a good explanation why on some soils apparently sufficient in NH_4OAc extractable K, the crop responds to K fertilization. At Site III, pod yields were either not increased or were decreased by applying K, the decrease was 32% compared to the control with 40 kg K_2O ha^{-1}. The reason was soil salinity (1.7 dS m^{-1}) combined with that of water (3.4 dS m^{-1}).

Table 2. Groundnut response to potassium in different locations in the Saurashtra region, India.

Treatments kg K_2O ha^{-1}	Summer season*					
	Site I Yield (kg ha^{-1})		Site II Yield (kg ha^{-1})		Site III Yield (kg ha^{-1})	
	Pod	Haulm	Pod	Haulm	Pod	Haulm
Control	1660	2261	1728	1969	1010	1349
40	2104	2865	2058	2263	692	1468
	(21.1)	(21.1)	(16.0)	(13.0)	(-31.6)	(8.1)
80	2587	3337	2304	2370	1010	1349
	(35.8)	(32.2)	(25.0)	(16.9)	(0)	(0)
120	2375	3125	2304	2403	810	1468
	(30.1)	(27.7)	(25.0)	(18.1)	(-19.8)	(8.1)
60+60	2358	2781	2387	2428	746	1310
	(29.6)	(17.8)	(27.6)	(18.1)	(-26.1)	(-2.9)
FYM (10 t ha^{-1})	1677	2434	1883	2195	1250	1429
	(1.0)	(7.1)	(8.2)	(10.3)	(23.7)	(5.9)
CD (0.05%)	375	354	-	-	-	-
CV %	9.68	6.94	-	-	-	-
Soil properties						
pH	8.30		7.50		7.30	
EC, dS m^{-1}	0.30		0.18		1.70	
K_2O, kg ha^{-1}	109		712		155	

* Summer season: irrigated.

( ): Percentage increase / decrease over control.

Table 2. Continued.

Treatments kg K_2O ha^{-1}	Kharif season*					
	Site II Yield (kg ha^{-1})		Site III Yield (kg ha^{-1})		Site IV Yield (kg ha^{-1})	
	Pod	Haulm	Pod	Haulm	Pod	Haulm
Control	900	1349	1065	3274	969	2353
40	959	1397	1128	3289	997	2436
	(6.2)	(3.4)	(5.6)	(5)	(2.8)	(3.3)
80	1042	1728	1097	3289	1080	2685
	(13.6)	(21.9)	(2.9)	(5)	(10.3)	(12.3)
120	1065	1397	1159	3368	1024	2464
	(15.5)	(3.4)	(8.1)	(2.8)	(5.4)	(4.5)
60+60	1006	1492	1175	3133	983	2409
	(10.6)	(9.6)	(9.4)	(-4.5)	(1.4)	(2.3)
FYM (10 t ha^{-1})	1018	1681	1065	2350	1080	2381
	(11.6)	(19.8)	(0)	(-39.0)	(10.2)	(1.2)
CD (0.05%)	-	-	-	-	-	-
CV %	-	-	-	-	-	-
Soil properties						
pH	7.60		7.10		7.20	
EC, dS m^{-1}	0.18		1.20		0.38	
K_2O, kg ha^{-1}	269		392			

* Kharif season: rainfed.

( ): Percentage increase / decrease over control.

The effect of FYM on both pod and haulm yields was positive at Site III as opposed to the negative effects of KCl. The data at two locations, Site I and Site II, when averaged show that the shelling and % oil were increased by 3 and 2%, respectively, with 80 kg K_2O ha^{-1}.

During the kharif season at Site II (k), the pod yield was increased by 16% with 120 kg K_2O ha^{-1} and the haulm yield by 22% with 80 kg K_2O ha^{-1}. At Site III (k), there were only small changes in yield. At Site IV (k), pod and haulm yields were increased by 10 and 12% with 80 kg K_2O ha^{-1}. In the pooled results for the locations, shelling percentage was increased by only 1.0 to 1.6% and oil content was not affected by K.

Seasonality: The pooled results for summer groundnut show that maximum pod and haulm yields were obtained with 80 kg K_2O ha^{-1} which increased yield by 31 and 26% respectively. The yield data was related best by a quadratic equation (Fig. 2). The same amount of K increased the yields of haulm and pod of rainfed groundnut by only 12 and 10%. On the whole, the response of groundnut to K under rainfed conditions is small. There exists a synergism between rainfall and crop response to K.

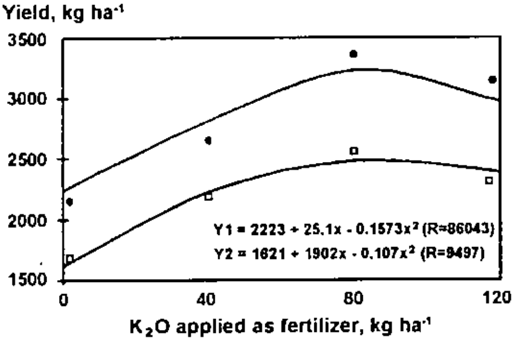

Fig. 2. Average response of groundnut to potassium, • haulm yields (Y1), □ pod yields (Y2).

Even though adequate amounts are applied, fertilizer cannot increase crop yields when there is too little rainfall. For example, yields of groundnut testing balanced fertilization (Table 3) show that yields were increased by 15 to 23%, when the critical period rainfall was above average. The crop response was less than 10% when the critical period rainfall was below the average rainfall. Thus, rainfall is the major factor modulating groundnut response to balanced fertilization during the kharif season when the coefficient of variance is up to 15% compared to 6 to 9% in the summer. Similarly, haulm/pod ratio was 1.97 in the kharif season whereas it was 1.21 in summer. Thus, larger yields with greater stability and higher conversion of photosynthates in the reproductive organ in summer favours the crop response to K fertilization.

Table 3. Effect of rainfall on groundnut response to potassium.

Year	No. of trials	Yield with NP* kg ha^{-1}	% response to K over NP	Critical period rainfall (% of average)
1981	16	505	8.0*	86
1982	35	1270	23.1	136
1983	11	778	15.3	102
1984	16	1023	18.2	112
1985	10	757	5.0*	81
1986	7	505	6.2*	68

* Non-significant results.
N: 12.5 kg ha^{-1}; P: 25 kg P_2O_5 ha^{-1}; K: 40 kg K_2O ha^{-1}.

Dry spells can occur at any stage during the growing period in rainfed groundnut. The effect of wet and dry cycles can occur at different phenophases and this was tested on summer groundnut (Golakiya and Patel, 1988). Potassium, at 60 kg K_2O ha^{-1} as KCl or as a 2% K solution applied as a spray were tested to study the yield response and physiological role of K in sustaining crop production during a dry spell (Table 4). In the absence of dry spells, K applied at 60 kg K_2O ha^{-1} increased yield by 10% and when applied as a 2% spray, yield was increased by 6%. Applying K did not increase yield when there were dry spells to the yield in the absence of dry spells but for each dry spell treatment K did increase yields. Repeated occurrence of drought stress conditions decreased yield by up to 75%.

Table 4. Effect of potassium and drought stress on groundnut yields.

Number of dry spells	Yield of pod (kg ha^{-1}) Control	60 kg K_2O ha^{-1}	2% K spray
Control (no dry spell)	1957	2150 (10)^1	2062 (6)^1
Single	1486 (24)^2	1613 (9)^3 (25)^2	1538 (4)^3 (35)^2
Double	835 (57)^2	1039 (24)^3 (52)^2	892 (7)^3 (57)^2
Triple	485 (75)^2	612 (21)^3 (72)^2	524 (8)^3 (75)^2

[1] % increase in pod yield over control due to soil or foliar application of K.
[2] % decrease (over control) in yield as a result of periodic drought cycles.
[3] % increase in pod yield at each dry spell treatment.

Residual effect of K: The residual effect of K applied to summer groundnut on the kharif crop was considerable. Haulm and pod yields were increased by 32 and 22% respectively, by the residue of 40 kg K_2O ha^{-1} and yield increases were similar following a split application of 120 kg K_2O ha^{-1}. The residual effect of the 80 and 120 kg K_2O ha^{-1} treatments was poor perhaps because these two treatments had a large direct effect which left little plant available K residue.

Thus, the magnitude of the groundnut response to K depends on the intensity factors of K, available soil K status, soil properties, rainfall pattern and the season.

Interaction of K with other nutrients

Potassium interacts with other nutrients to promote groundnut yields (Table 5) especially with N. The haulm and pod yields were increased by 21 and 16% with the $K_{30}N_{25}$ treatment. Similarly, the interaction between K and S was also synergistic and significant, the $K_{60}S_{50}$ treatment increased pod yield, shelling % and oil by 17, 2 and 0.5%, respectively. The $K_{60}Zn_{50}$ interaction was significant and positive also, the pod yield being increased by 27%.

Table 5. Interaction of potassium with other nutrients.

Interaction	Plant part	S/NS	Positive/ negative	Magnitude (%)
$K_{30}xN_{25}$	Pod	S	Positive	16%
	Haulm	S	Positive	21%
$K_{60}xS_{50}$	Pod	S	Positive	17%
	Shelling	S	Positive	2%
	Oil	S	Positive	0.5%
$K_{60}xZn_{50}$	Pod	S	Positive	27%

S/NS: significant/non-significant.

K_{30}: 30 kg K_2O ha^{-1}; N_{25}: 25 kg N ha^{-1}; S_{50}: 50 kg S ha^{-1}; Zn_{50}: 50 kg Zn ha^{-1}.

Potassium uptake pattern

Potassium uptake by groundnut ranges from 30 to 130 kg K_2O ha^{-1}, of which about 8% is in the kernels and 14 and 78% in the shell and haulm respectively. For a crop growing for 108 days and taking up about 130 kg K_2O ha^{-1}, about 59 kg was taken up during the 60 to 108 day period. The mean daily K absorption rate was greater than 1.23 kg K_2O ha^{-1} after the first 30 days. However, the peak uptake rate was observed at around 60 days. The soil available K was also lowered during this period. The difference in sorption and soil supply of K varies with soil and may be large even on soils having an appreciable quantity of available K. For this reason, the crop responds to an application of K. The recycling of K in groundnut is larger than with some crops as almost 92% of the K is in the shell and haulm which remains in the field.

Response and status of K in LTFE

Potassium response has been studied in a 15-year old long-term fertilizer experiment (LTFE) with groundnut-based intensive cropping (Patel *et al.*, 1994). Compared to the yields of total biomass in the first year, those in the tenth year had decreased by 22, 18 and 3% in the NP, NPK and NPK-ST (soil test) treatments, respectively (Table 6). Basing the K application on soil K values resulted in a smaller decline in yield than applying a uniform K application.

Table 6. Total groundnut biomass production in the first and tenth years of a long-term field experiment.

	Yield kg ha^{-1} in		
Treatment	Year 1	Year 10	Decrease
Control	10084	5686	4398
NP	16595	12987	3608
NPK	23602	18386	4216
NPK(ST)	23714	23069	645

Summary of K fertilization in groundnut in the Saurashtra region of India

- At least 21% soils need K fertilization.
- The soil critical limit is 145 kg K_2O ha^{-1}. The critical limit in the plant is 0.90% K at 30 days after sowing.
- Potassium fertilization (80 kg K_2O ha^{-1}) increased the yield and improved the quality of groundnut.
- NxK, KxS and KxZn were positive interactions.
- Recycling of K is maintained in soil via the K returned in the haulm.
- Potassium is depleted quickly in the soil under intensive cropping.
- A split application of 120 K_2O ha^{-1} was not beneficial.
- Residual effects of K & FYM were important.
- Soil test based addition of K sustained soil productivity.

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Session 4

Response of permanent crops to K

Efficiency of potassium and magnesium in China's tea gardens

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Abstract

Tea is an important commercial crop in subtropical and tropical areas of China. Most tea gardens were established on red earth (Inceptisols and Ultisols) which are low in organic matter, strongly leached and acidic. Furthermore, these soils usually contain marginal amounts of available nutrients. Analyses of typical soil samples from various tea growing regions of China indicate that the natural capacity of the soil to supply potassium (K) and magnesium (Mg) is generally poor and consequently does not meet plant demand at the present production levels. Continuous cultivation of tea without K and Mg fertilization leads to serious depletion of soil K and Mg reserves. Accordingly, K and Mg fertilization greatly increased yields of green tea, black tea and oolong tea. In addition, the quality of these tea types was improved and economic analyses further indicated that K and Mg fertilization is profitable. Furthermore, K application increased the ability of tea plants to withstand drought and infestation of fungal diseases. In conclusion, the results confirmed that K and Mg fertilization was an important measure to improve the productivity of tea soils in China.

Introduction

China has the largest tea growing area in the world with a total of 1.06 Mha of which most is in the mountainous and hilly areas of the tropical and sub-tropical regions south of the Yangtze river. Most tea (70%) is planted on Inceptisols, Ulti- and Oxi-sols which have a very low inherent fertility, little organic matter and are strongly leached and acidic. Usually, they contain marginal amounts of available nutrients. Low fertility and availability of plant nutrients led to limited productivity and reduced the competitiveness of Chinese tea in both the domestic and overseas markets.

Since the 1980s, the use of mineral fertilizers has been increasing. This has greatly changed the situation and increased the level of yield markedly. The mineral fertilizers used were mainly nitrogen (N) (formerly ammonium sulphate, ammonium bicarbonate and recently urea) and in certain cases phosphorus (P). A recent survey covering over 100 tea plantations in 7 provinces showed that the N : P_2O_5 : K_2O ratio of mineral fertilizers used in tea gardens is 1.0 : 0.33 : 0.02. Obviously, K and other nutrients are rarely applied. The unbalanced supply of nutrients has led to some serious problems, as tea plants absorb nutrients at a ratio of 1.0 : 0.45 : 0.75 which is greatly different from the ratio applied. This means that, in particular, the input of K in tea plantations is much less than what is required. As a result, the K reserves in soils under tea are depleted rapidly. Potassium deficiency of tea plants and its effect on productivity has been increasingly reported (Lin *et al.*, 1991; Lin, 1982; Wu and Ruan, 1994). A similar observation has been made for magnesium (Mg), due to the fact that soils under tea were inherently poor in Mg, and cultivation practices, which wholly neglected this nutrient, further depleted soil reserves. This paper, therefore, aims in the first place to present results showing how the application of these two nutrients affect growth, yield, quality, economics and plant health under the conditions in representative tea growing areas in China. Another focus is on recent research results regarding the supply capacity and efficiency of K and Mg application in tea garden soils.

Soil potassium, and magnesium contents and supply capacity

Potassium contents of tea soils, release characteristics and supply capacity

Depending on the parent material, the total K content of the soils varied between 8.0-20.8 mg g^{-1} and about 96% of the samples contained total K in amounts larger than 10 mg g^{-1} (Table 1b). Soils developed from basalt and red sandstone contained only marginal amounts of K, while the soils developed from quaternary red clay were medium and soils from gneiss, granite and plate shale contained the largest amounts of total K.

The K pools in soils may generally be described as water soluble, exchangeable, non-exchangeable and mineral K, the latter being in the lattices of minerals (Martin and Sparks, 1985). The former two are the forms readily available whereas the non-exchangeable pool is slowly available and the mineral K is available only very slowly to plants. Hence, in general, water soluble and exchangeable K are analyzed to determine "K availability" and to deduce fertilizer recommendations.

The overall content of exchangeable K was small and about 70% of the soil samples collected contained less than 80 mg kg^{-1}. Only in a few soils was the exchangeable K larger than 100 mg kg^{-1}. These latter soils were mainly from the northern regions or well managed tea gardens and hence may be regarded as exceptional. Therefore, for the majority of soils, severe K deficiency may be expected.

There is increasing evidence that the analysis of exchangeable K is not a sufficiently adequate parameter for a detailed evaluation of the K status and for predicting the K supplying potential of soils. This is because under intensive cropping, when the quantity of exchangeable K is small, a large proportion of K taken up by plants may be supplied from the non-exchangeable pool (Martin and Sparks, 1985). For tea as a perennial crop, which grows on the same site for several decades, this fact seems to be particularly crucial because a large proportion of the crop's K demand can be met from the non-exchangeable pool.

The non-exchangeable K in the soils ranged from 101 to 820 mg kg^{-1} depending on the soil type and location (Table 1b) and, on average, accounted for 2.1% of the total K.

Table 1a. Soil number, type, taxonomy order, parent material, pH and soil organic matter of the survey samples from tea fields in China.

Soil	Soil type	Taxonomy order	Sampling site	Parent material	pH	Organic matter %
1	Lateritic red earth	Oxisol	Yinde, Guangdong	Limestone	4.5	2.45
2	Lateritic red earth	Inceptisol	Guiling, Guangxi	Limestone	4.6	1.07
3	Lateritic red earth	Inceptisol	Guiling, Guangxi	Limestone	4.3	1.27
4	Red earth	Alfisol	Qiyang, Hunan	Quaternary red clay	4.9	1.14
5	Red earth	Ultisol	Hengshan, Hunan	Quaternary red clay	4.8	2.19
6	Red earth	Alfisol	Xiugu, Jiangxi	Red sandstone	5.0	1.69
7	Red earth	Ultisol	Shangrao, Jiangxi	Quaternary red clay	4.8	1.04
8	Red earth	Ultisol	Songtao, Guizhou	Granite	5.0	1.79
9	Red earth	Ultisol	Lanqi, Zhejiang	Quaternary red clay	4.8	1.06
10	Red earth	Inceptisol	Shaoxing, Zhejiang	Granite	3.8	0.92
11	Red earth	Alfisol	Shengxian, Zhejiang	Basalt	4.9	1.41
12	Yellow-brown earth	Alfisol	Jingtan, Jiangsu	Loess	5.2	1.80
13	Yellow-brown earth	Alfisol	Liyang, Jiangsu	Loess	5.2	1.08
14	Yellow-brown earth	Alfisol	Langqi, Anhui	Loess	5.0	1.57
15	Yellow-brown earth	Alfisol	Xuanzhou, Anhui	Loess	5.1	1.61
16	Yellow-brown earth	Inceptisol	Zhaoyang, Hubei	Granite	5.0	2.43
17	Yellow-brown earth	Alfisol	Baokang, Hubei	Plate shale	5.0	1.03
18	Brown earth	Inceptisol	Rizhao, Shandong	Genesis	5.2	1.78

Source: Soil and Fertilizer Institute (1995).

Table 1b. Soil number, total K, nitric acid soluble K and exchangeable K in soils corresponding to those in Table 1a.

Soil	Soil type	Total K	HNO_3-K	Ex-K	6 Ex-K	Ex-K/ HNO_3-K	6 Ex-K/ HNO_3-K
		mg kg^{-1}		mg kg^{-1}		%	
1	Lateritic red earth	10.4	101.2	44.6	71.4	44.1	70.6
2	Lateritic red earth	10.7	216.2	94.3	121.5	43.6	56.2
3	Lateritic red earth	10.7	145.6	61.2	82.5	42.0	56.7
4	Red earth	13.5	226.5	66.4	94.3	29.3	41.6
5	Red earth	15.2	251.6	64.7	86.4	25.7	34.3
6	Red earth	8.0	106.8	59.3	76.5	55.5	71.6
7	Red earth	12.5	300.1	68.2	89.2	22.7	29.7
8	Red earth	14.5	312.3	74.6	109.9	23.9	35.2
9	Red earth	11.4	219.6	76.2	119.5	34.7	54.4
10	Red earth	18.0	260.4	93.9	129.6	36.0	49.8
11	Red earth	9.0	108.9	30.8	60.1	28.3	55.2
12	Yellow-brown earth	12.4	420.2	70.4	106.5	16.8	25.3
13	Yellow-brown earth	12.4	411.6	69.1	105.0	16.8	25.2
14	Yellow-brown earth	11.8	451.7	168.2	208.2	37.2	46.1
15	Yellow-brown earth	13.7	366.9	54.2	82.8	14.8	22.6
16	Yellow-brown earth	12.4	400.0	69.3	101.1	17.3	25.3
17	Yellow-brown earth	17.3	820.5	134.9	177.8	16.4	21.7
18	Brown earth	20.8	612.6	88.5	121.7	14.4	19.9

6 Ex-K = sum of six sequential extractions by NH_4OAc.
Source: Soil and Fertilizer Institute (1995).

The yellow-brown earth and brown earth soils (Alfisols and Inceptisols) generally contained more non-exchangeable K than the red soils and the lateritic red soils (Ulti- and Oxisols). The percentage of non-exchangeable K increased and the ratio of exchangeable- to non-exchangeable- K decreased in samples taken geographically from the north to the south (Table 1b). A clear K distribution pattern throughout China (Latitude increases with the soil number) can therefore be detected. According to the existing K availability classification system, 16 of the 18 samples showed medium to very low levels of non-exchangeable K (Table 2).

Sequential soil extraction by NH_4OAc was used to simulate the dynamics of K release from the available and to some extent the slowly available K pool in soils under continuous tea cropping. The plotted curves indicated that there was no significant difference among the various soils in the release of available K (not shown), but the proportion of non-exchangeable K (% total K extracted) was less in yellow-brown and brown earth than in the red and lateritic red soils. This suggests that the former soils are characterized by a stronger K supplying potential. About 50 to 80% of total extractable K was released by the first extraction while the last three extractions accounted for only 8-34% of the total K extracted. Soil K could still be extracted by NH_4OAc after five extractions but the amount was very small being inadequate to meet the continuous K demand by plants for growth.

Table 2. Classification of the potassium availability status of 18 soil samples from Chinese tea gardens.

K status	1 M NH_4OAc mg kg^{-1}	No. of soils	1 N HNO_3 mg kg^{-1}	No. of soils
Very low	<33	1	<56	0
Low	33- 69	8	66- 166	4
Medium low to			166- 330	7
medium	69-125	7	330- 500	5
Medium high to			500- 750	1
high	125-166	1	750-1160	1
Very high	>166	1	>1160	0

Magnesium content, release characteristics and supply capacity of soils growing tea

The exchangeable Mg in the tea soils ranged from 2 to 240 mg kg^{-1} with about 50% of the soils being below 40 mg kg^{-1} (Table 3), which is considered as the critical level for tea production. The lateritic red soils generally contain less Mg than the other soil types. The non-exchangeable Mg, extracted by boiling HNO_3 for ten minutes, ranged from 60 to 2000 mg kg^{-1}. The lateritic red soils and the red soils generally contained less than 100 and 200 mg kg^{-1} of this fraction, respectively. On the other hand, the yellow brown and brown earth soils usually contain more than 500 mg kg^{-1} Mg. Similarly to K, there was no significant difference in the curves of Mg release by serial extraction with NH_4OAc but the percentage of total Mg in six sequential extractions to non-exchangeable Mg was considerably lower in yellow-brown and brown earth than in the red and lateritic red soils. This indicates that the former soils have a stronger Mg supplying potential. The extent to which Mg was extracted from the soil very largely depended on soil type. Of the total extractable Mg, 10 to 80% was released in the first extraction and 9-60% during the subsequent 3 extractions. These differences (Table 3) may be attributed largely to the variation in clay content as well as clay mineralogy.

Table 3. Magnesium content of selected soils from tea fields in China.

Soil	HNO_3-Mg	Ex-Mg	6 Ex-Mg	Ex-Mg/ HNO_3-Mg	6 Ex-Mg/ HNO_3-Mg	Ex-Mg/ 6 Ex-Mg
		mg kg^{-1}			%	
1	58.8	1.8	13.8	3.0	23.4	12.7
2	74.3	10.8	23.2	14.5	31.2	46.6
3	95.6	37.6	51.0	39.3	53.3	73.7
4	133.1	70.5	96.5	53.0	72.5	73.1
5	166.8	21.8	35.8	13.1	21.5	60.9
6	87.8	14.1	26.1	16.0	29.7	54.0
7	422.5	79.8	97.1	18.9	23.0	82.2
8	667.5	132.9	160.0	19.9	24.0	83.1
9	126.3	58.5	75.4	46.3	59.7	77.6
10	205.6	12.3	28.5	6.0	13.9	43.2
11	78.7	14.1	27.1	17.9	34.4	52.0
12	1190.0	202.5	231.0	17.0	19.4	87.7
13	900.0	78.6	98.2	8.7	10.9	80.0
14	560.0	42.3	55.6	7.6	9.9	76.1
15	802.5	24.8	38.8	3.1	4.8	63.9
16	940.0	181.8	212.3	19.3	22.6	85.6
17	2057.5	235.8	269.3	11.5	13.1	87.6
18	1496.0	91.6	114.4	6.1	7.6	80.1

6 Ex-Mg = sum of six sequential extraction by NH_4OAc.

Trends in potassium and magnesium contents in soils as affected by the duration of cultivation and fertilizer application

Continuous cultivation and harvest of tea without adequate replenishment of K and Mg may lead to serious depletion of these two nutrients in tea soils. Field experiments conducted in green and black tea growing areas showed that annual K and Mg removals by harvest were 94 and 9.6 kg ha^{-1} at Yingde and 31 and 2.9 kg ha^{-1} at Hangzhou, respectively (Table 4). The differences are explained by the amount of biomass removed which is much lower in green tea (only tips are harvested) (Hangzhou) compared to black tea (Yingde), where the harvest comprises two leaves and the bud.

Table 4. Average yearly nutrient balance sheet during 1992-1996, kg ha^{-1}.

Treatment	Input		Output		Balance	
	K	Mg	K	Mg	K	Mg
	Hangzhou					
Control	0	0	31	2.9	-31	-2.9
K_1	125	0	37	3.2	88	-3.2
K_1Mg	125	21	46	3.2	79	17.8
	Yingde					
Control	0	0	94	9.6	-94	-9.6
K_1	125	0	108	10.0	17	-10.0
K_1Mg	125	21	118	11.4	7	9.6
	Anqi*					
Control	0	0	33	2.9	-33	-2.9
K_1	125	0	39	3.4	86	-3.4
K_1Mg	125	21	40	3.5	85	17.5

* Two years.

As a result, the exchangeable K and Mg in the surface horizon of those plots without K and Mg application decreased substantially (Table 5). The content of exchangeable K was reduced by 28% and 44% at Hangzhou and Yingde during the five years, respectively. Meanwhile, the K quantity/intensity (Q/I) analysis indicated that the values were increased by K fertilization. In contrast, the values of Ar^k_e and ΔK_0 in the control declined from 0.0065 to 0.0024 (mol l^{-1})$^{-1/2}$ and -0.163 to -0.028 cmol$_c$ kg^{-1} at Hangzhou during 1994-1995. At the same time, the available Mg in the soil decreased by 75% and 74% of the original values, respectively (Table 5).

However, if K was applied in adequate amounts, the balance of K between input and output in harvest can be positive (Table 4). Soil analysis for the 0-20 cm depth showed that K and Mg were accumulated in this soil horizon, due to placement around the trees (Table 6). The unexpectedly large accumulation of K may be due mainly to the methodological approach of banding the K fertilizer around the tree and collecting soil samples from the same spot. An improved sampling technique will have to be used in the future.

Table 5. Change in available potassium and magnesium in tea soils.

Site	Duration	Exchangeable K			Exchangeable Mg		
		Initial	End	Difference	Initial	End	Difference
		mg kg^{-1}					
Hangzhou, Zhejiang	1992-1996	106	76	-30	62	15	-47
Yingde, Guangdong	1992-1996	58	33	-25	20	5	-15
Hangzhou, Zhejiang	1995-1997	98	74	-24	n.d.*	n.d.*	n.d.*

* Not determined.

Table 6. Changes in exchangeable K and Mg in soils (0-20 cm) by fertilizer application at Yingde (1996).

Treatment	Exchangeable K mg kg^{-1}	Exchangeable Mg mg kg^{-1}
Control	76.3	15.4
K_1	273.4	77.7
K_1Mg	310.7	98.6

Surprisingly, K application increased the exchangeable Mg content and vice versa. A possible explanation for this could be an enhanced desorption of the cation from the non-exchangeable pool by the increased supply of its counter cation.

Yield responses of different types of tea to potassium and magnesium application

Potassium application increased yields of all three tea types (Table 7). Combined K and Mg application led to the greatest yield increases of between 17%-28% for green tea, 9%-38% for oolong tea and 10%-18% for black tea, respectively. One of the most remarkable effects of these two nutrients was the increase in the proportion of high quality green tea. The combination of larger yields and improved quality led to higher income and hence profits (Table 7).

Effects of potassium on resistance of tea to drought and disease

Unfavourable environmental conditions such as drought, chill, high temperature injury, diseases and pests are important factors limiting crop production and leading to yield reductions as well as to poorer quality. A study was carried out therefore, to test whether an application of K would improve crop resistance to these stress conditions.

Resistance to drought

Potassium plays a crucial role in the plants' water relations. Both water use efficiency by tea plants and their growth can be improved substantially by applying K under drought and high temperature conditions. This can be shown by results from a pot experiment (Figure 1), where no young tea plant survived under serious drought when soil moisture was maintained below 45% of field capacity (FC). Exposed to medium drought, i. e., when the soil moisture was at 55% and 65% of FC, plants receiving no K had survival rates of only 66.7% and 88.9% whereas the survival rates increased to 88.9% and 100%, respectively, if K was supplied (Figure 1).

Table 7. Overall efficiency and net profit from K and Mg application over control.

Experimental site	Tea type	Duration	Yield increase, %	Average yearly net profit, Yuan ha^{-1}	Average yearly net profit, US$ ha^{-1}
			due to K		
Yingde, Guangdong	Black tea	1992-1996	5-16	1164	142
Hangzhou, Zhejiang	Green tea	1992-1996	10-23	5712	697
Anqi, Fujian	Oolong tea	1992-1993	9-29	2088	255
			due to Mg		
Yingde, Guangdong	Black tea	1992-1996	3- 4	459	5
Hangzhou, Zhejiang	Green tea	1992-1996	3- 9	2268	277
Anqi, Fujian	Oolong tea	1992-1993	8-18	1464	179

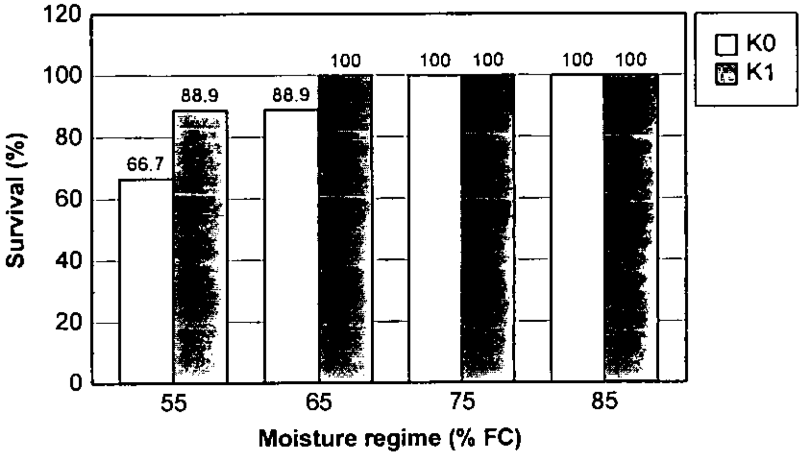

Fig. 1. Survival rate of young tea plants under varied soil moisture regime with and without K.

The biomass and K accumulation in plants receiving K fertilizer also increased substantially. Furthermore, under drought, the requirement for K is larger than under normal conditions, which could be shown in a field experiment. Applying double the amount of K usually recommended, increased the yield significantly only in 1994 a drought year (Figure 2).

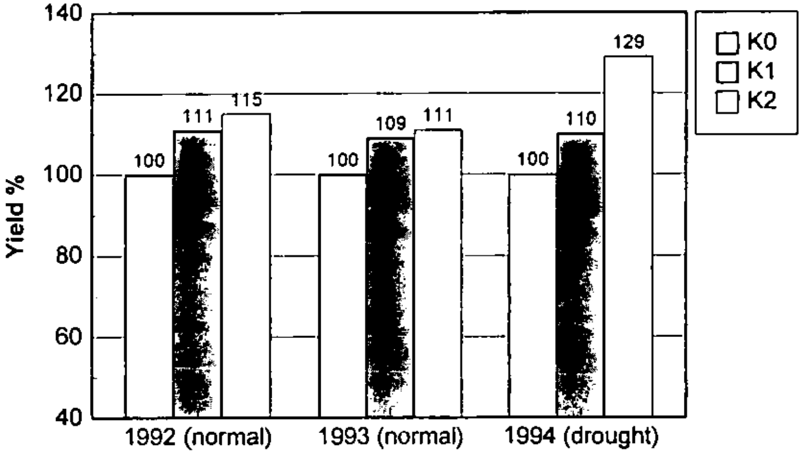

Fig. 2. Yield response of tea to potassium application under different weather conditions.

Diseases

By improving the nutritional status of plants, their susceptibility to pests and diseases may be reduced. This is explained by enhancing the ability of tea plants to better withstand the biotic stresses. In a pot experiment, K drastically reduced the incidence of anthracnose, an important fungal disease in tea (Figure 3).

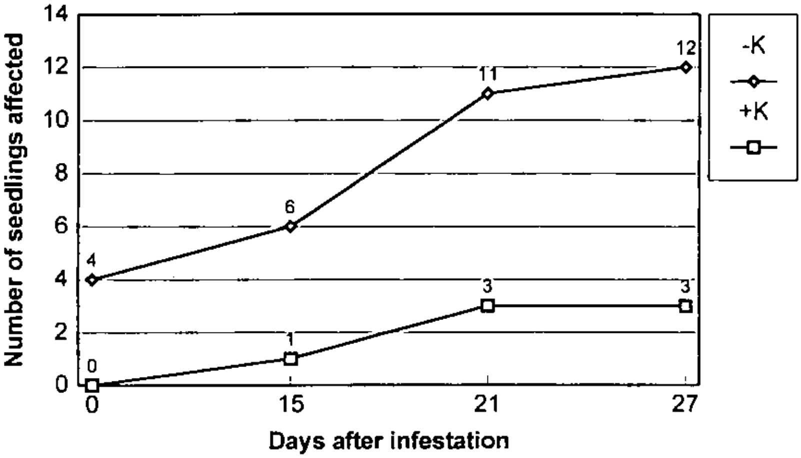

Fig. 3. Effect of potassium nutrition on the resistance of tea plants to anthracnose.

Fertilizer recommendations

Recommendations for K and Mg should be based on the soil exchangeable K and Mg and on the yield expectation, the aim being to maintain the nutritional balance and to obtain the maximum economic return from fertilization. Table 8 shows the recommended rates of K and Mg for an average soil (sandy loam). Unfortunately, owing to the absence of soil data, because the majority of tea gardens do not analyze the soils, recommendations are not based on soil texture analysis. For the time being, this is a clear disadvantage which needs to be overcome to improve recommendations.

Table 8. Recommended amounts of potassium and magnesium for tea gardens (yield > 2250 kg ha^{-1}) based on exchangeable K and Mg in the soil (sandy loam).

Available K in soil (mg kg^{-1})	<50	50-80	80-120	120-150	>150
K_2O application (kg ha^{-1})	340	230	180	120	60
Available Mg in soil (kg ha^{-1})	<10	10-40	40- 70	70-120	>200
MgO application (kg ha^{-1})	30-40	20-30	10- 20	5- 10	0

Potassium and Mg fertilizers may be applied as basal or as top dressings, the timing of application depending on the tea type (Table 9). The yield of Gunpowder tea was hardly affected when the K was applied. However, for regions where spring tea is particularly important, e.g. in the Longjing area, it is recommended to apply K as a basal dressing in the autumn when the harvest of the crop has just finished. Where large amounts of K and Mg fertilizers have to be applied, the application should be split into two, one as basal dressing in autumn and one as top dressing in spring before budding (around the beginning of March). On the other hand, if all three seasons are of similar importance (as with Gunpowder tea at Shengxian), K may be applied as a top dressing before each plucking season. This may even improve the efficiency of applied nutrients especially on light-textured soils (Table 9).

Table 9. Effect of potassium timing on tea yields at Shengxian and Hangzhou during 1995-1997.

	Treatment		
	-K	Basal dressing	Top dressing
	Shenxian, Gunpowder tea		
Total of 3 years (t ha^{-1})	72.76	79.02	79.51
Percentage	100	108.6	109.3
	Hangzhou, Green tea, Longjing tea		
Total of 3 years (t ha^{-1})	21.89	25.27	23.74
Percentage	100	115.4	108.5

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Potassium dynamics in the nutrition and fertilizer management for the oil palm (*Elaeis guineensis* Jacq.) in the 21st century

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Introduction

The past three decades have witnessed a phenomenal expansion in world palm oil production from a mere 0.9 Mt in 1967 to 17.4 Mt in 1997. Of this total, South East Asia accounts for about 85%, with Malaysia and Indonesia being the top two producers (Table 1).

It is envisaged that by 2020, palm oil production could double to reach 35 Mt and supersede soybean oil in top position. This expected growth will come both from additional areas in cultivation as well as increases in yield, which is now about 3.2 t ha^{-1} of oil.

Table 1. World production, Mt, of the major vegetable oils.

Year	Soybean	Palm	Rape seed	Sunflower
1967	3.0	0.9	1.6	3.3
1987	15.6	8.0	6.5	6.9
1997	20.3	17.4*	11.1	9.1
[2020		35.0]		

* South East Asia 15.0 Mt
Source: Oil World 1998, Hamburg.

Effective fertilizer programmes, providing balanced nutrition, are based on both fertilizer experiments and management experience and have contributed to the increases in yield per hectare and total production. Estimates of the nutrients in the palms producing 17 Mt oil in 1997 are shown in Table 2. Fertilizer use will be sustained and prospects for an increase in consumption are promising, especially in the case of potassium (K). However, to sustain the competitive edge of palm oil, it is imperative that the most cost-effective fertilizer options are sought taking into account all the critical factors. This paper deals with K, the principal nutrient in oil palm nutrition.

Table 2. Estimates of total nutrient uptake by palms producing 17 Mt oil.

Component	N	P	K	Mg
	('000 t)			
Bunch dry matter	292.8	39.4	317.5	70.7
Vegetative dry matter	404.6	49.0	537.5	137.7
Total	697.4	88.4	855.0	208.4

Update on "state of the art" of fertilizer management

Nutrition and growth

As the largest oil producing plant, the oil palm is relatively research friendly. It has moderately large nutrient requirements and vivid foliar symptoms are displayed for deficiencies of K, magnesium (Mg), nitrogen (N), boron (B) and copper (Cu).

The quantitative nutrient requirements for vegetative growth and fresh fruit bunch production from initial planting to 15 years of age in the field were studied comprehensively by Ng and Thamboo (1967), Ng *et al.* (1968a), and Ng *et al.* (1968b, 1969). Their main findings were:

- Potassium was the predominant nutrient required, followed by N, Mg and phosphorus (P) while micronutrients could not be overlooked, particularly B and Cu.
- A large increase in nutrient uptake occurs from the second year of planting, consonant with growth physiology, reaching a peak at about year 8-10 (Fig. 1).

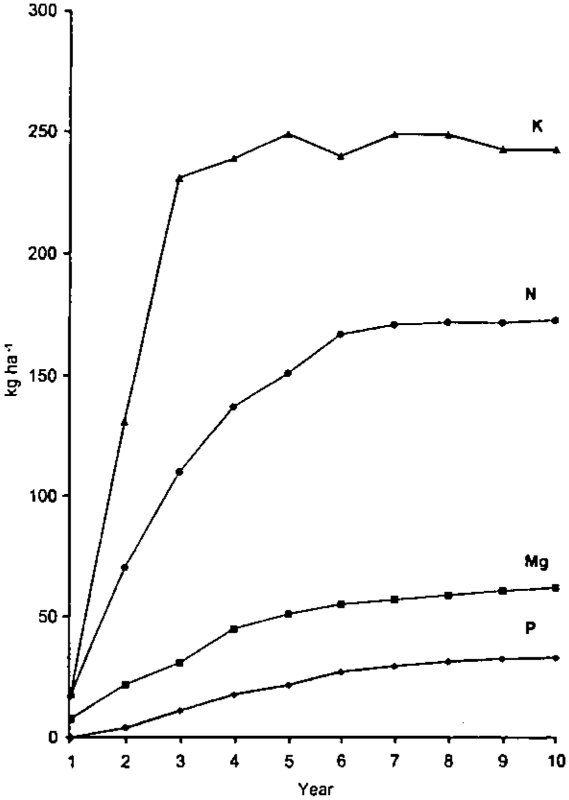

Fig. 1. Nutrient uptake of oil palms during the first 10 years after planting.

- The partition of assimilates favours vegetative biomass production over that of bunch production, implying that a basic quantum of nutrients goes first to vegetative dry matter production (Table 3).

Table 3. Growth data for mature palms grown in Malaysia and Nigeria.

Country	Crop growth rate	Vegetative dry matter $t\ ha^{-1}$ annually	Bunch dry matter
Malaysia (a)	30.7	16.4	14.3
Nigeria (b)	18.3	14.3	4.0

(a) Ng *et al.* (1968a)
(b) Rees and Tinker (1963)

Application of findings on biomass production and nutrient uptake

Prior to large scale commercial application, the new data on nutrient uptake were evaluated thoroughly in factorial experiments, designed to determine optimum balanced nutrient regimes, for major soil types varying in K status (Ng, 1967). Early experimental results, reported by Hew *et al.* (1973), showed that:

- early yield responses to P and K could be obtained;
- yields in the initial 3-4 years of cropping were appreciably larger than envisaged (Table 4).

Table 4. Typical responses to major nutrients on three soil types growing oil palm in Malaysia.

Experi-ment	Soil	Treatment		Years	Cumulative yield ($t\ ha^{-1}$)
		Material	kg^{-1} palm		
1	Typic Kanhapludult from shale	CIRP	0.0	4th-7th	84.71 (100)
		CIRP	1.8	4th-7th	102.37 (121)
		CAN	0.0	4th-7th	90.99 (100)
		CAN	3.2	4th-7th	99.12 (109)
		KCl	0.0	4th-6th	91.01 (100)
		KCl	2.5	4th-6th	99.46 (109)
2	Typic Kandiudult from sandstone	KCl	0.0	4th-6th	60.42 (100)
		KCl	2.7	4th-6th	77.93 (129)
3	Typic Kandiudult from granite	KCl	0.0	4th-6th	43.89 (100)
		KCl	2.7	4th-6th	48.81 (111)

CIRP = Christmas Island rock phosphate
CAN = Calcium ammoniun nitrate
KCl = Potassium chloride

These experimental findings were then applied to new commercial plantings on a range of soils in the early 1970s and results have been presented (Ng, 1983; Ng and Thong, 1985; Ng *et al.*, 1990). These results, together with data for plantings in the 1980s, reaffirm that optimal balanced nutrition, coupled with other best management practices, incorporated into the Maximum Exploitation of Genetic Yield Potential (MEGYP) concept (Ng, 1983; Härdter *et al.*, 1997) is capable of achieving oil yields of 6.5-7.0 t ha^{-1} for large planting blocks, while for individual fields of 30-40 ha in size, yields of 8.5-9.0 t ha^{-1} were obtained (Fig. 2).

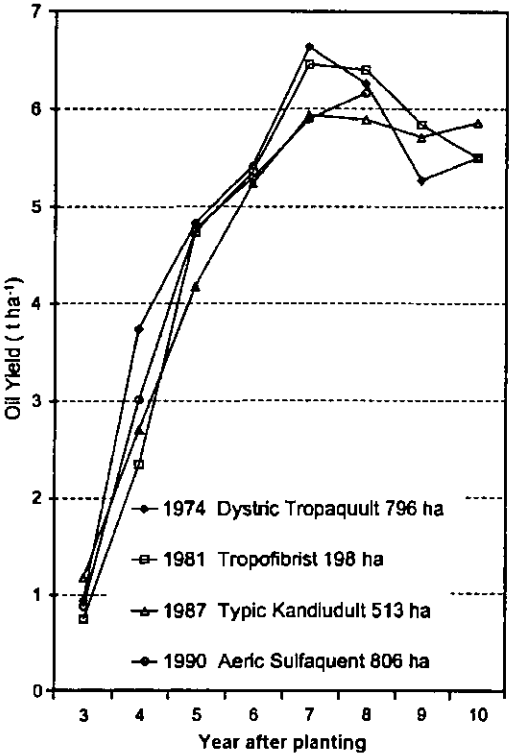

Fig. 2. Reproducibility of MEGYP yields via optimal balanced nutrition.

Strategic options for more cost-effective fertilizer management

Notwithstanding the favourable outlook for future increases in fertilizer consumption, the oil palm industry cannot afford to lower its guard in an ever competitive edible oil market, especially with the advent of genetically modified edible oil seeds. New priority options need to be established in good time and the following are probable contenders:

- Nutrient recycling via non-burning of vegetative biomass.
- Better exploitation of soil K resources.
- Greater emphasis on oil productivity rather than on fruit bunch productivity.
- Planting of clonal oil palms produced by proven tissue culture technology.

Recycling of nutrients by non-burning techniques

After the serious haze problem in 1997, both Indonesia and Malaysia banned open burning in land clearings. Von Uexküll (1985) was the first to propose non-burning but there was no response. The recent ruling is not entirely adverse to the oil palm industry, especially when replanting with oil palms. The potential amounts of recycled nutrients, particularly K and sulphur (S), are shown in Table 5 (Ng, unpublished) and these amounts are probably adequate for the first, immature, period of growth.

At a projected annual replanting rate of 150,000 ha in South East Asia over the next decade, considerable cost savings are possible. However, it must be stressed that the precise quantities of the available nutrients from the palm residues under different soil and climatic conditions have still to be ascertained experimentally.

Table 5. Potential nutrients that can be recycled by non-burning of oil palm biomass at replanting.

Nutrient	kg ha^{-1}
N	250- 300
P	40- 50
S	60- 80
K	1000-1300
Ca	600- 800

Exploiting soil potassium resources

It is a matter of concern that relatively little in-depth research has been undertaken into the K dynamics of soils cultivated to oil palm. In Malaysia, early studies by Ng (1967) indicated significant variations in soil K status amongst major soil types. The more dominant Ultisols and Oxisols were low in K while the more clayey alluvial soils (Inceptisols and Entisols) had larger K buffering capacities. In combination with fertilizer trial results, the data on soil K variation has justified different inputs of K to mature palms, based on soil K characteristics (Fig. 3).

However, it cannot be over-stressed that a great deal of in-depth research on soil K, inclusive of clay mineralogy, still needs to be done in South East Asia, to develop more cost-effective programmes of K fertilization for oil palms.

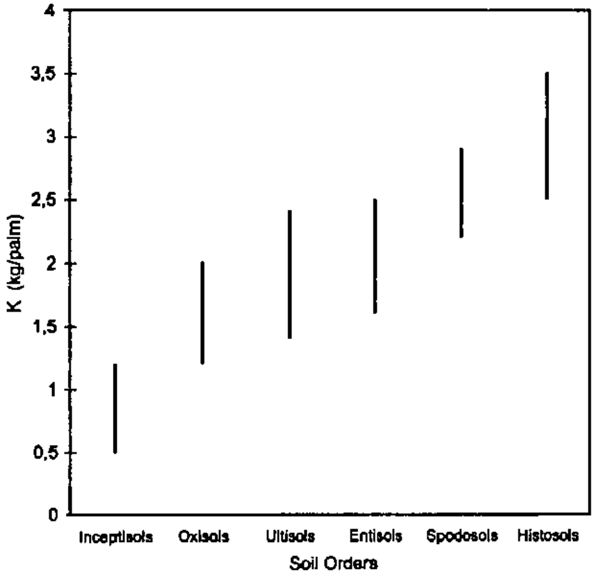

Fig. 3. Potassium input to oil palms according to soil type.

Oil versus bunch productivity

The marketable commodity in world trade is palm oil and it is probably opportune to focus more on the yield of oil rather than on that of fresh fruit bunches (FFB). This will become more pertinent as costs of labour, transport and primary processing increase with time.

While K has been shown to increase the yield of fruit bunches, it has tended to decrease the percentage of oil in the fruit (Forster *et al.*, 1988). Using the data of Forster *et al.*, it can be shown that it may be more profitable to produce a given yield of oil via a regime which focussed on improvements in the oil extraction rate in the bunch (Table 6).

Table 6. Cost benefit of two options for greater oil productivity.

Parameter	Option 1	Option 2
Oil yield, t ha^{-1}	6.0	6.0
Bunch yield, t ha^{-1}	30	27
Oil extraction rate, %	20	22.2
KCl input	65	58
Harvesting and processing costs, \$ ha^{-1}	540	486
Total cost, \$ ha^{-1}	605	544

$ = USD

It should be pointed out that a greater oil extraction rate in fruit bunches is unlikely to be attained unless K is in balance with other key nutrients which are implicated in oil biosynthesis. The pursuit of better oil productivity would be more worthwhile with tissue cultured, clonal palms which have a much larger oil yield potential than seedlings.

Advent of clonal palms by tissues culture

The theoretical annual potential yield of the oil palm has been estimated at 17 t ha^{-1}, which is well above the current good average plantation yield of 6 t ha^{-1}. It is only through cloning via somatic embryogenesis that commercial yields can make a quantum leap to within striking distance of the theoretical potential yield.

Clonal palms have been planted since the late 1970s but progress in the 1980s was slowed by floral abnormality problems in ramets (Corley *et al.*, 1986). However, more recent work by a Malaysian group (Khaw and Ng, 1997) has shown that the abnormality problem can be minimized and commercial clonal plots have outyielded conventional seedlings by 30% on average (Simon *et al.*, 1998). In a small (0.42 ha) test plot planted in May 1993 in the state of Sarawak, good yields were obtained for a single clone during the first three years after planting (Table 7).

Table 7. Yield of fresh fruit bunches (FFB) and oil, t ha^{-1}, during the first three years after planting of clone AGK 19 and Deli Dura x Pisifera (DxP) cultivar in Sarawak.

Months after planting	FFB		Oil	
	AGK 19	DxP	AGK 19	DxP
25-36	24.2	10.7	5.8	2.0
37-48	50.1	17.8	12.5	3.9
49-60	46.6	24.6	14.0	6.4

If the kernel oil yield of 1.0 t ha^{-1} is added, the total oil yield from clone AGK 19 in the 5th year of planting would have reached 15.0 t ha^{-1}, which is nearly 90% of the theoretical maximum yield potential.

Such yield levels are unlikely to be obtained regularly on a large commercial basis. But based on results reported by Khaw and Ng (1997), it is entirely plausible to envisage increases in mean yields from 6.0-6.5 t ha^{-1} to 8.5-9.0 t ha^{-1} by planting clonal oil palms in well managed plantations.

It is commonly opined that clonal palms will require more fertilizers, which is correct on an individual palm basis. However, on a unit tonnage of palm oil basis, clonal palms will be more efficient in nutrient usage, as first alluded to by Woo *et al.* (1994); their updated data is shown in Table 8. If world production of the next 17.0 Mt of oil were to be produced by clones, there could be a significant reduction of nearly 200,000 t of total N, P, K, Mg nutrient input.

Table 8. Nutrients required per unit oil production by clones and seedling palms.

Planting material	N-P-K-Mg-B kg ha^{-1}	Oil yield t ha^{-1}	Oil production (kg) per 100 kg nutrients
Clones	400	8.0	2000
Seedlings	360	6.0	1667

From the view point of environmental protection, especially the conservation of dwindling tropical rainforests (Ooi *et al.*, 1992, 1995), clonal oil palms in the next century should be highly advantageous. For a further expansion of palm oil production of 17 Mt, over the next 20 years, only 2 Mha of tropical rainforest will need to be sacrificed if clones are planted, as opposed to 3 Mha if seedlings were used. Also, the higher oil yielding clones would be not only more efficient in fertilizer usage but would generate smaller volumes of mill effluent discharges. Thus, the output-input energy ratio would be appreciably higher than the figure of 9.5 computed by Härdter *et al.* (1997).

It is thus obvious that the sooner tissue cultured palm clones are available in large quantities commercially, the less will be the pressures on dwindling resources of rainforest and the quality of water courses. Hence, it is timely to re-invigorate research into the tissue culture of oil palms which began 30 years ago.

Greater research focus on optimal nutrient balance

As the global vegetable oil market becomes more competitive, palm oil producers will need to focus more sharply on efficiency and productivity of oil rather than on that of fresh fruit bunches, because oil yield had tended to stagnate in the 1990s. In the near to medium term, this can be partly achieved by selecting planting materials with higher oil content in the bunches, but in the longer term, only clonal palms, produced by proven tissue culture techniques, can produce the quantum leap in oil productivity desired.

With this projected shift of emphasis to oil productivity, optimal nutrient balance becomes critical, as illustrated in Table 9. If K is out of sync with Mg, B, S and calcium (Ca), oil productivity may fall because:

- Boron is important for successful pollination and fruitlet development.
- Magnesium plays a role in the activation of enzymes involved in oil biosynthesis.
- Non-optimal or inadequate S status (Ng *et al.*, 1988) may also retard oil productivity in bunches as it is a constituent of the enzyme acyl ACP thioesterase.
- High Ca status would suppress both Mg and K metabolism, thereby decreasing oil yield.

Thus, it is evident that if the potential for improved oil productivity, especially of clones, is to be fully exploited, much more research into the biochemical roles of key nutrients in oil biosynthesis is required. The oil palm industry as a whole should not maintain an equivocal attitude on this major scientific issue.

Table 9. Impact of unbalanced nutrient management on palm oil productivity.

Nutrient applied	Antagonism with	Impact of imbalance on		
		Bunch production	Oil extraction rate	Oil yield
K	Mg	+	-	-
	B	-	-	-
S	P	-	+	-
Ca	Mg	-	-	-
	K	-	-	-

+ positive; - negative.

Conclusion

Prospects for world palm oil production to double by 2020 are bright and efficiency in nutrient management will continue to contribute to this growth and K will maintain its premier status as a major nutrient.

However, the pressures from economic competition in the global market will compel palm oil producers to be more efficient and cost competitive. In this context, more cost-effective fertilizer management strategies must be sought. The priority options would encompass conservation and recycling of biomass and nutrients during land preparation, better exploitation of soil K resources, greater priority on oil productivity, optimization of nutrient balances and greater momentum on commercial planting of tissue cultured, clonal planting materials.

If all these techniques are developed and implemented in a concerted fashion, and supported by more intensified research, the future of the world palm oil industry would be better assured.

Acknowledgement

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Session 5

Future research needs and prospects

The essential role of potassium in diverse cropping systems: Future research needs and benefits

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Abstract

Recommendations for potassium (K) fertilizer applications are based on defining the critical level of readily available K in soil. Below the critical level there is an unacceptable loss of yield and above it yield is not increased by adding more K. Thus there is great potential benefit to farmers in improved recommendations. A knowledge of slowly available (fixed) K based on a knowledge of readily available (exchangeable) K and soil mineralogy would give improved precision and certainty in setting critical values for exchangeable K.

Four categories or pools of soil K are recognised based on the availability to crops of the K in each pool. These are soil solution or soluble K (immediately available), exchangeable K (readily available), fixed K (slowly available) and lattice or matrix K (very slowly available). Existing evidence suggests that there is an equilibrium between the amount of K in each of the first three pools with a rapid reversible transfer between solution- and exchangeable-K and a less rapid, but nevertheless important reversible transfer between exchangeable- and fixed-K. Thus as K^+ ions are taken up by roots from the soil solution they are replenished by the release of K^+ held on cation exchange sites, associated either with the mineral matrix or with other organic matter.

In unimproved soils the K on cation exchange sites is replenished by the weathering of K-bearing minerals (lattice or matrix K), so that the K supply to plants depends on the amount and rate of release of this K. The K status of agricultural soils depends on the K balance in previous years, (K balance = K applied *minus* K removed). When the K balance is positive the excess K accumulates in both the exchangeable and fixed pools. Large amounts of K can be held in both pools, depending on soil mineralogy, and this is a valuable reserve of K.

There is no rapid, analytical method for determining fixed K. Some evidence suggests, however, that there may be a fairly constant relationship between exchangeable- and fixed-K, which is independent of the amount of exchangeable K over the range of values usually found in agricultural soils, but probably dependent on soil mineralogy.

Fixed K is important because it can support the supply of plant available K during the growing season and periods of maximum demand. This is especially important

when root exploration of the soil is limited by factors like poor soil structure, lack of water, limited rooting depth and root diseases. This benefit of fixed K will not decrease the amount of K, which should be applied when a soil is below its appropriate critical value, or when the critical value is being maintained by replacing K offtake in harvested crops.

Knowledge of the presence or not of fixed K gives greater certainty about the reliability of K recommendations under a wide range of farming systems. This is especially so for advisors in the tropics and some developing countries. Unlike advisors in the developed countries, they frequently do not have the benefit of the many years of experience and the results of innumerable field experiments on which to base and improve K recommendations.

Introduction

The essential, irreplaceable role of comparatively small amounts of potassium (K) in a number of biochemical and physiological roles in plants is well established. So too is the preferred, but not essential need for much larger amounts of K as an osmoticum to control turgor in plant cells. There are an increasing number of scientific papers which identify the role of K in improving crop quality, enhancing pest and disease resistance, increasing crop water use efficiency, especially where water is a major growth limiting factor, and benefiting the cold tolerance of crops. It is also well established that plant roots take up K^+ ions from the soil solution and that in its various functions within plants K exists as the positively charged cation. Set against the comparatively straight forward understanding of these very important functions of K in crop production is the often conflicting evidence of the response of field grown crops to inputs of K in either fertilizers or manures. This paper briefly discusses the need for a better understanding of some aspects of soil K and its availability to plants.

The response of crops to soil and fertilizer potassium

The apparent conflict of evidence about crop responses to soil and fertilizer K is well illustrated by data from the Saxmundam Experimental Station in Suffolk, eastern England. The soil is a sandy clay loam, with about 25% clay (Hodge, 1972). Although the station has been a part of IACR-Rothamsted only since 1965, experiments were first started there in 1899 (Johnston, 1987). Each of the two major experiments had four blocks, one each for the four crops, swedes, spring barley, grain legume and winter wheat grown in rotation each year. Rotation 1 tested ten treatments which remained unchanged until 1965. They were farmyard manure, bonemeal, unmanured and nitrogen (N), phosphorus (P) and K applied singly and in various combinations. All treatments were applied cumulatively each year. The early results showed that it was essential to supply P before there was any response to N (Williams and Cooke, 1971 and references therein). There was very little or no response to K, the rate of release of K from soil reserves appeared adequate to produce maximum yields of the cultivars grown at that time. In 1965, it was decided to stop the P test and plots given none previously then got 44 kg P ha^{-1} annually whilst those given P previously continued to receive 22 kg ha^{-1} each year. The double rate of P quickly raised the Olsen P level to equal that on the plots with the single rate. The K test was continued but the amount of K applied was increased to 104 kg ha^{-1} each year.

The lack of, or only very small difference in yield between plots given no K since 1899 and those receiving 53 kg ha^{-1} annually for 70 years was of considerable importance to the correct use of K fertilizers on these and similar soils in South East England. Therefore from 1970 K was studied in greater detail. First the response of two K demanding crops, grass and lucerne, was tested. By autumn 1976, lucerne yields were poor due to an increasing infestation of crown wart of lucerne (*Urophlyctis alfalfae*) (MacFarlane, 1976). The lucerne, therefore, was ploughed up to grow arable crops to see whether they now responded to K because the lucerne had removed a further 520 kg K ha^{-1} from soils without K since 1899. This was in addition to over 3000 kg K ha^{-1} removed from soils by crops grown between 1899 and 1969 (average of four plots without K, taken from Cooke *et al.*, 1958 and Williams and Cooke, 1971). On K treated plots there was a small negative K balance (-220 kg ha^{-1}) after the 7 years of lucerne, following a near zero K balance during the previous 70 years (Cooke *et al.*, 1958; Williams and Cooke, 1971). The arable crops grown during 1977-80 were winter wheat, winter barley, winter beans (*Vicia faba*) and potatoes and each was grown three times except that spring barley replaced winter barley in the first year. Each of the original ten treatment plots was split to test extra fertilizer K, 52 kg ha^{-1} for cereals and beans, 208 kg ha^{-1} for potatoes.

In 1976, soils with and without K since 1899 had 166 and 113 mg kg^{-1} exchangeable K (K_{exch}) respectively. The average yield of each crop grown between 1977 and 1980 on these two soils and the response by each crop to the K fertilizer applied to it are in Table 1. For the soil and season the yields of all three cereals were good and the soil without K since 1899 gave yields equal to those grown on soil given K each year. On neither soil did the cereals respond to freshly applied K. Best yields of beans were above average and of potatoes about average for crops grown without irrigation. In contrast to the cereals, both beans and potatoes yielded much less on soils without K than on those with K. A further important observation was that applying K to both beans and potatoes grown on soils with least K failed to increase yields to those obtained when the crops were grown on soils with more K_{exch}. Similar results showing the benefit of K reserves for some crops but not others have been obtained on other soils (Johnston *et al.*, 1970).

Table 1. Exchangeable K in soils in 1976 with (K) and without (no K) potassium since 1899 and response by arable crops during 1977-80 to soil potassium (-K) and applied potassium fertilizer (+K).

	no K		K*	
K_{exch} in 1976 mg K kg^{-1}	113		166	
Crop and treatment 1977-1980	-K	+K*	-K	+K
Winter wheat, grain t ha^{-1}	8.49	8.54	8.50	8.60
Winter barley, grain t ha^{-1}	7.58	7.74	7.69	7.71
Spring barley, grain t ha^{-1}	5.68	5.68	5.71	5.86
Field beans**, grain t ha^{-1}	2.52	3.60	4.42	4.38
Potatoes, tubers t ha^{-1}	28.8	39.6	43.1	44.0

* Annual K applications 1899-1964, 53 kg ha^{-1}; 1965-1980, 104 kg ha^{-1}
1977-1980, 52 kg ha^{-1} for cereals and beans, 208 kg ha^{-1} for potatoes

** *Vicia faba*

Soil potassium reserves and their value

Soil K reserves in the experiment described above benefited some crops but not others. It might be expected that the magnitude of the benefit would depend on both the size of the K reserve and also on the crop grown. This poses the question, "to what extent should K reserves be increased"?

When crops are grown under conditions in which only one factor is limiting, then an exponential or Mitscherlich type response curve relating yield to increasing levels of that one factor would be expected (Figure 1). The x-axis can be increasing concentrations of readily soluble P or K determined by a method of analysis known to relate to plant available levels of that nutrient in soil. From the curve a critical value, for example K_{exch}, can be estimated for a yield of say 95% of the asymptotic or plateau yield. Examples from experiments on the silty clay loam at Rothamsted are shown in Figures 2, 3 and 4. Yields of winter wheat (Figure 2) increased by 1.8 t ha^{-1} to reach 8 t ha^{-1} as K_{exch} increased from 55 to 100 mg kg^{-1}. Spring barley, however, yielding 6 t ha^{-1} showed no response as K_{exch} increased above 80 mg kg^{-1} (Figure 3), but in the same experiment on the same soil, the yield of sugar, from sugar beet, increased up to 200 mg K kg^{-1} (Figure 4). In Figures 2, 3 and 4 the scatter in the individual data points may be due to the amount of K taken up from the subsoil or from fixed (slowly available) K; the latter will be discussed later. For both these sources of K the amount and relative distribution of roots in the surface and subsoil would be important. Figure 5 for field beans (*Vicia faba*), with data from Rothamsted experiments averaged over a number of years is a very good example of a yield response curve from which a critical value of K_{exch} for this crop and soil could be determined.

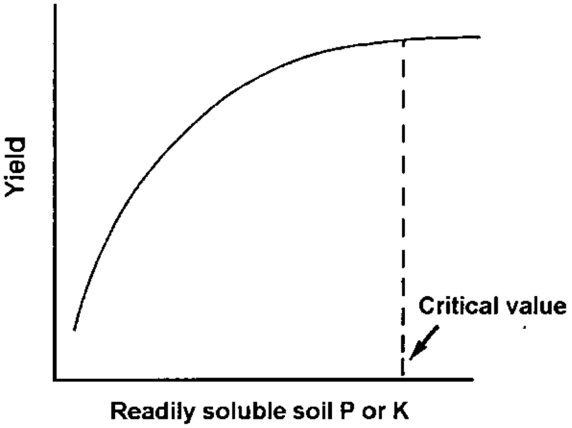

Fig. 1. Schematic relationship between yield and readily soluble soil P or K based on an exponential response model.

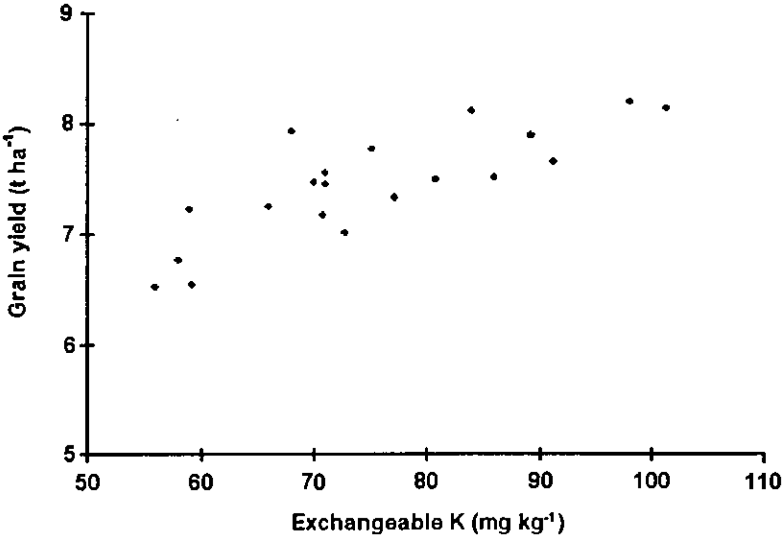

Fig. 2. Relationship between the yield of winter wheat, grain t ha^{-1}, and exchangeable K in soil. The Exhaustion Land Experiment, Rothamsted. (Personal communication, P.R. Poulton and A.E. Johnston).

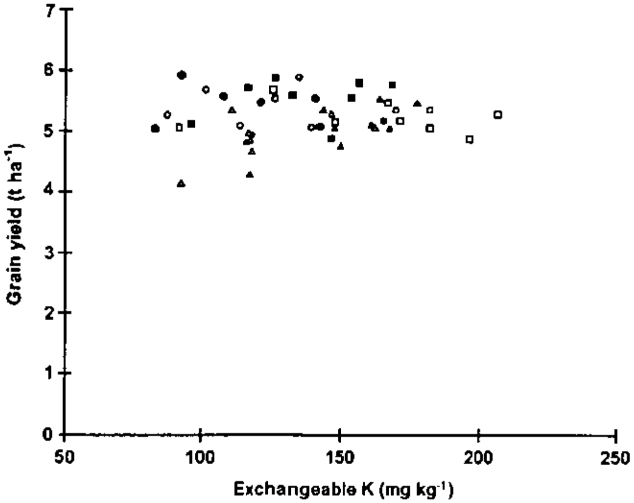

Fig. 3. Relationship between the yield of spring barley, grain t ha^{-1}, and exchangeable K in soil. Different symbols for different cropping and fertilizing histories 1848-1970 (Johnston and Goulding, 1990).

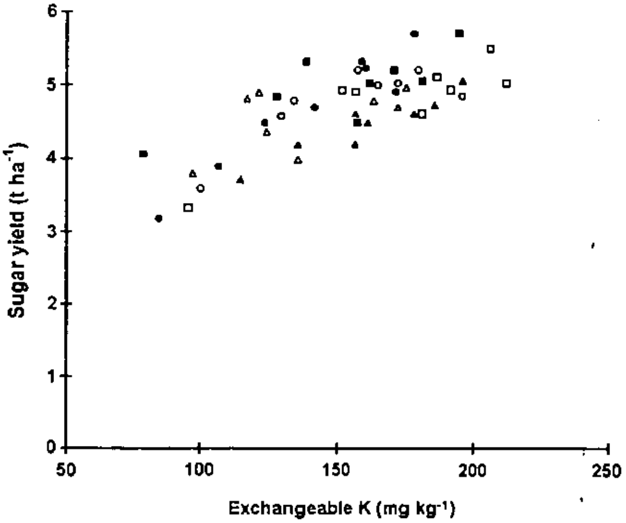

Fig. 4. Relationship between the yield of sugar (from sugar beet), and exchangeable K in soil. Different symbols for different cropping and manuring histories 1848-1970 (Johnston and Goulding, 1990).

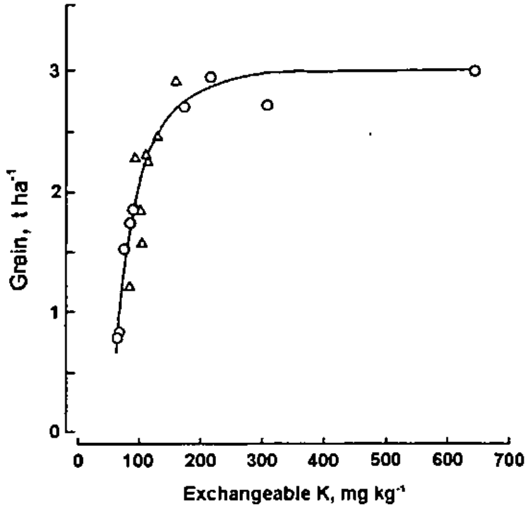

Fig. 5. Relationship between the yield of field bean, *Vicia faba*, grain t ha^{-1}, and exchangeable K in soil. Different symbols for average yields over a number of years from two experiments (Johnston, 1997).

Measuring readily available potassium

Many different extractants have been used to estimate readily available K in soil. Most involve replacing K^+ with another cation. Knop (1871) used a solution of ammonium chloride whilst Prianishnikov (1913) was probably the first to suggest using neutral ammonium acetate (2M). Today many laboratories use ammonium nitrate rather than acetate because the acetate anion interferes with the determination of K in some advanced flame photometric instruments. There is also a tendency to use reagents which will extract more than one element in amounts which can be calibrated satisfactorily with crop responses. Such reagents include ammonium acetate - acetic acid (pH 4.8), calcium lactate, calcium acetate lactate and ammonium acetate lactate. Although these methods extract different amounts of K the amounts are all very strongly correlated. Other more time consuming methods, many based on quantity/potential and quantity/intensity relationships and equilibrium K potentials have also been suggested, for examples of their use see Johnston and Addiscott (1971).

Johnston and Goulding (1990) reviewing routine methods of soil analysis concluded that K_{exch} determined by extraction with neutral ammonium acetate provided a good estimate of the availability of soil K to plants. However, responses by crops to K fertilizer would depend on the crop, soil type, structure and depth, weather and other similar factors. The importance of the crop factor is shown by the data in Table 1 and Figures 3 and 4.

The availability of potassium to plants

Although K_{exch} is a good predictor of the probable amounts of K readily available for crop uptake it is appropriate to ask whether improvements are possible so as to further improve fertilizer K recommendations.

From early work on soil and crop K a conceptual framework was developed to aid discussions on the relationships between K inputs, K in crops and soil K (Figure 6). Within this framework, K in the soil solution and the various pools or categories of soil K were shown in a linear relationship with reversible transfer between the different pools. Such a generalised figure appears in many publications. In some early publications the exchangeable K was divided into two subgroups namely readily exchangeable K and difficulty exchangeable K. This was probably an attempt to explain discontinuities in cumulative K uptake - time relationships determined in some exhaustive cropping experiments. However, Reitemeirer (1951) suggested that exchangeable K was best defined by reference to the method of determination and that "difficulty exchangeable" K was best considered as fixed or non-exchangeable K. Wiklander (1954) in his review continued with this nomenclature; namely soluble K, exchangeable K, fixed (or not directly exchangeable K) and lattice or native K.

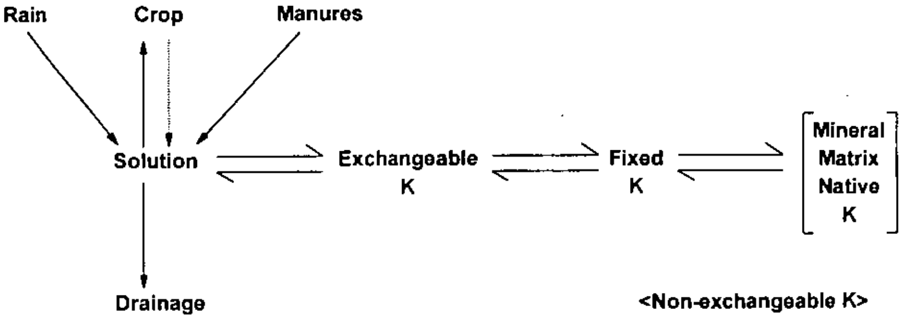

Fig. 6. A simple schematic linear representation of the potassium cycle in the crop-soil system.

Proof of the transfer of K between pools can be inferred from data from long-term experiments at Rothamsted where positive and negative K balances (kg K ha^{-1}) during a number of years can be related to changes in K_{exch} (also in kg K ha^{-1}) in the top 23 cm of soil. Soil weights for the top 23 cm are known with reasonable accuracy but losses of K from the topsoil and K uptake by crops from the subsoil are not known and have been ignored. Table 2 gives data from 1856 to 1974 for the Exhaustion Land experiment where mostly cereals were grown (Johnston and Poulton, 1977). From 1856 to 1901 K was added in fertilizers and from 1876 to 1901 in farmyard manure (FYM), the K balance was positive and reserves accumulated in soil. From 1901 to 1974 no more K was applied and the crops depleted the accumulated soil K reserves. Although K additions ceased after 1901 the soils were not sampled until 1903; this discrepancy probably leads to an extremely small error. Table 2 shows that the increase in K_{exch} between 1856 and 1903 accounted, on average, for only 26% of the K balance, the remainder was presumably in the fixed pool. Data for the 72 years when K was being taken up from the soil reserves can be divided into two periods. From 1903 to 1951 mainly spring barley was grown without N until 1941 and then with only 63 kg N ha^{-1} from 1941 to 1951. Thus average yields and K offtakes for this period were small. Probably because the soil was not stressed to supply K the decrease in K_{exch} accounted for 56 and 85% of the negative balance on the FYM- and fertilizer-treated plots respectively. After 1952 increasing amounts of N were applied to cultivars with an ever larger yield potential and yields and K offtakes increased. However Table 2 shows that a much smaller proportion of the negative K balance was now accounted for by the decrease in K_{exch}, 9 and 15% or the FYM- and fertilizer-treated plots respectively. Much of the K taken off in the crops had come from non-exchangeable reserves as the soil was stressed to supply more K (Johnston and Poulton, 1977).

Table 2. Potassium balances and changes in exchangeable K in the 0-23 cm layer of a silty clay loam soil during 1856-1974. Exhaustion Land Experiment, Rothamsted (adapted from Johnston & Poulton, 1977).

Period and treatment		K balance in period, kg ha^{-1}	Change in exch. K, kg ha^{-1}	Change as a % of K balance
K added 1856-1903				
FYM*		+2250	+520	23
Fertilizers		+3760	+1100	29
K taken up from reserves				
(FYM)**	1903-51	-850	-480	56
	1952-74	-640	-60	9
(Fertilizers)	1903-51	-1080	-920	85
	1952-74	-750	-110	15

* FYM added 1876-1901 only.

** (FYM) and (Fertilizers) plots given FYM and PK before 1901 none since.

Table 3 shows similar data for K balances and their effect on K_{exch} for the Garden Clover experiment at Rothamsted (McEwen *et al.*, 1984 and references therein). Red clover (*Trifolium pratense*) has been grown each year since 1854 but it proved difficult to maintain yields. By the 1950s, it was thought that lack of K was, in part, responsible for the small yields and in 1956 a test of K was started. The data in Table 3 show that without K addition between 1956 and 1966, there was a negative K balance (-246 kg ha^{-1}) but there was apparently a very small increase in K_{exch}

which was probably related to sampling and analytical error. This supports the view (see e.g. Wiklander, 1954) that exhaustive cropping lowers K_{exch} to a value below which it does not fall further. Where K was applied average annual yields were increased from 2.2 to 4.6 t dry matter ha^{-1} and there was a positive K balance (+617 kg ha^{-1}) during the 11 years. However, the increase in K_{exch} was equivalent to only 42% of K balance. In 1967 it was decided to stop the K test and start a test of pest and disease control because these were thought to be major factors causing the small yields. To equalise K_{exch} on soils with and without K during 1956-66, 437 kg K ha^{-1} was applied to the plot without K. The increase in K_{exch} was equivalent to only 33% of this large application of K. From 1968 to 1978, 250 kg K ha^{-1} was applied each year but K offtakes were not large because yields were still affected by pests and diseases. Of the large K balance (+ 1667 kg ha^{-1}) only 41% was accounted for as an increase in K_{exch} The annual K application was then decreased to 125 kg ha^{-1} but much improved pest and disease control resulted in much larger yields from 1979-83. In this period there was a large negative K balance of which only 38% was accounted for by the decrease in K_{exch} In each period the change in K_{exch} did not account for all the K balance; there had been reversible transfer between exchangeable and fixed K.

Table 3. Potassium balances and changes in exchangeable K in the 0-23 cm layer of a silty clay loam soil during 1956-1983. Garden Clover Experiment, Rothamsted.

Period	Average K applied annually kg ha^{-1}	Total K balance in period kg ha^{-1}	Exchangeable K, kg ha^{-1}, at start and end of each period			Change in exch. K as % of K balance
			At start	At end	Change	
1956-66	None	-246	171	194	+23	-
	136	+617	171	431	+260	+42
1967	437	+437	194	338	+144	+33
1968-78	250	+1667	375	1065	+690	+41
1979-83	125	-1494	1065	502	-563	-38

Recent changes in thinking about the relationship between soil potassium pools

The linear relationship between soil K pools (Figure 6) doesn't readily fit all situations. After much thought and discussion Syers (1998) recently published a modified conceptual framework to further understanding between soil and crop K (Figure 7). Within this framework the main pools or modes of occurrence of soil K are related as a triangle not linearly as in Figure 6. This change is crucial because it indicates that K can pass reversibly between the soil solution and the fixed K pools. In addition, Figure 7 shows an assessment of the likely plant availability of the K in each pool, namely immediately, readily, slowly and very slowly available K. This conceptual framework also more readily includes those soils where clay minerals like feldspars weather sufficiently rapidly to meet the demand for K by small yielding crops. It is probable that K transferring between pools will do so *via* the aqueous phase. The data in Tables 2 and 3 readily support the framework outlined in Figure 7.

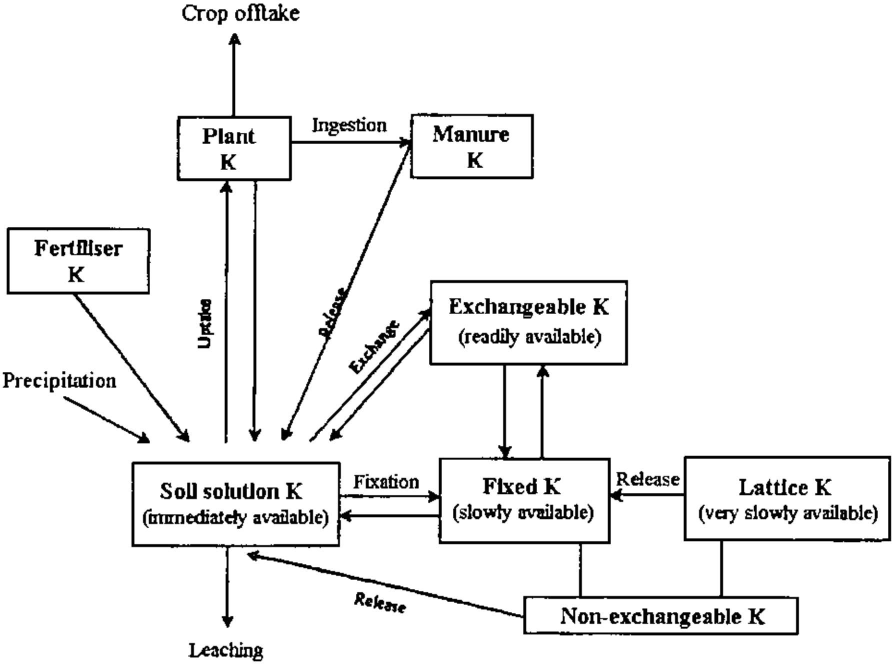

Fig. 7. The potassium cycle in the soil-plant-animal system showing the triangular relationship between soil solution, exchangeable and fixed potassium (adapted from Syers, 1998).

The importance of fixed potassium in crop nutrition

Both conceptual frameworks (Figures 6 and 7) highlight the importance of fixed K but at present there is no rapid analytical method to determine it. Terms like immediately, readily and slowly available K are useful in discussing plant-soil K relationships but they are extremely difficult to define easily. Better are terms which are defined by the analytical procedure used for the determination (i.e. operationally defined) such as exchangeable K, calcium acetate lactate-K.

Figure 7 indicates that fixed K is non exchangeable K which has accumulated as a reserve of K from one of two sources. The first is the weathering of soil minerals. The second is the accumulation of residues from past K applications, mainly as fertilizers or organic manures. This will have happened where crop husbandry practices have resulted in a positive K balance. Boiling 1 M nitric acid has been widely used to estimate so-called fixed K by subtracting K_{exch} from the total extracted by the acid. But on many soils repeated boiling with successive aliquots of nitric acid can dissolve K though in ever decreasing amounts. So it is difficult to obtain a precise estimate of fixed K by this method.

Laboratory studies to characterise soil potassium

The removal of K^+ from the soil solution by root uptake and its replenishment by K_{exch} and fixed K can be mimicked by the use of calcium resins. Such resins act as an infinite sink for K diffusing into the solution. Using multiple extractions, time related cumulative K release curves in the form $\Sigma K : t^{1/2}$, can be constructed (Figure 8) (Goulding, 1984). By fitting a linear spline (Ross, 1980) the curves can be separated into two, three, four or more linear segments which can be related to soil K pools. The Newport series soil in Figure 8 is a sandy soil (8% clay) and the data were best fitted by two segments. The much heavier textured Denchworth series soil (49% clay) released K at four different rates (R1 to R4). The final very slow release segment probably represents K release from clay minerals or K deeply embedded in the mineral lattice. By extrapolating each linear segment back to the y-axis the amount (mg kg^{-1}) of K released (M1 to M3 for the Denchworth soil) can be estimated. Often M1 is closely related to K_{exch} and it could be assumed that M2 and M3 represent fixed K released at two different rates.

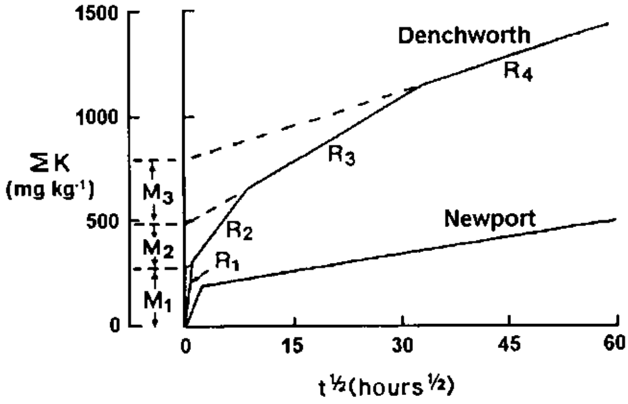

Fig. 8. Relationship between the cumulative K release to Ca-resin and time for two soils with differing clay content, Denchworth soil 49% clay, Newport soil 8% clay (Goulding, 1984).

Glasshouse experiments to characterise soil potassium

Exhaustive cropping of soils with a crop like ryegrass, has been used frequently to determine the release of nutrients, including K, from soils. As with K release to resin, cumulative K uptake curves can be plotted in the form $\Sigma K : t^{1/2}$. Figure 9 shows data from one such experiment at Rothamsted (Johnston and Mitchell, 1975) (For details of the field experiment from which the soils were taken see Johnston and Penny, 1972). Soils 1 to 6 (Fig. 9) were from plots 1 to 6 of the Agdell Rotation experiment on the nutrition of arable crops grown in rotation. Each plot had had a different cropping and manuring history since 1848. In 1958, the plots were halved and one half continued to grow arable crops. The other half was sown to grass the aim being to see how much of the estimated reserves of P and K accumulated from past fertilization could be recovered.

In the glasshouse experiment seven harvests were taken over a period of 540 days. Figure 9a shows K removed in the glasshouse cropping from the soils which had grown arable crops in the field from 1958 to 1970, Figure 9b shows comparable data for the soils which had grown grass for 12 years. All 12 curves can be divided into four linear segments. Exhaustive cropping with grass for 12 years in the field experiment had apparently removed most of the K reserves which had accumulated between 1848 and 1951 in plots 1 to 4 (Figure 9b). The four segments to each of the six curves suggests that there was still some exchangeable- and fixed-K which were in equilibrium. Figure 9a shows that the exhaustive cropping in the glasshouse removed K reserves accumulated from the positive K balance during 1848-1951. The amounts removed in 540 days in the glasshouse experiment were about equal to those removed during 12 years in the field experiment (Johnston and Mitchell, 1974). Interestingly, the final fourth segment of each curve for these six arable soils were not parallel. This suggests some variation between the soils which was probably in the amount of clay and hence K in the sub-samples used for the experiment. This relationship between clay content and K availability could be one factor to be considered in the spatial variability of within-field crop yields. However, it is probable that where soil reserves of fixed K have accumulated then these will buffer supplies of crop available K and yield variability due to varying clay content and K availability will only occur when there is very large variation in the clay content of the soil within a field.

The similarity of the shapes in the cumulative K release curves obtained with calcium resin and with exhaustive cropping is interesting and suggests that both methods are estimating K from similar pools or reserves. There is a large difference, however, in the time involved for such experiments, 150 days to obtain the data in Figure 8, 540 days for that in Figure 9.

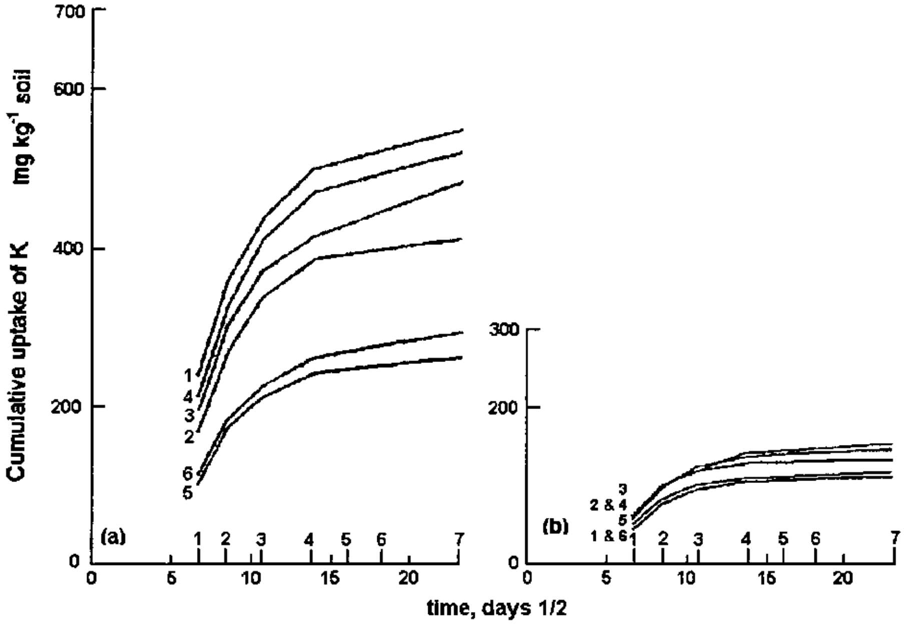

Fig. 9. Relationship between cumulative K uptake by ryegrass in pots and time for 12 soils of known cropping and manuring since 1848.
Manuring once every 4 years 1848-1951; plots 5 and 6, unmanured; plots 3 and 4, P K Na Mg (K 1884-1951 only); plots 1 and 2, NPK Na Mg.
Cropping plots 2 4 6 turnips barley clover wheat
plots 1 3 5 turnips barley fallow wheat
From 1952 to 1970, no K was applied.
From 1958 to 1970, one half of each plot grew grass to exhaust the residues (grass soils, Fig. 9b), the other half continued to grow arable crops (arable soils, Fig. 9a). On the arable soils, the larger uptake of K on plots 6 and 4 compared to 5 and 3, respectively, is probably related to differences in clay content of the soils (adapted from Johnston and Mitchell, 1974).

Using cumulative potassium release data

The data from exhaustive cropping can be used in various ways (Johnston and Mitchell, 1974). The K uptake (expressed in mg K kg^{-1} soil) can be related to initial K_{exch} The data from the experiment used to derive Figure 9 show a very strong relationship (r = +0.94) (Figure 10). This suggests that at least for one soil type and restricted soil volume, K_{exch} is a good indicator of K availability. This supports the conclusion of Johnston and Goulding (1990) from field experiment data that K_{exch} is as good a predictor of K availability, at least in the short term, as any other measure of readily extractable K.

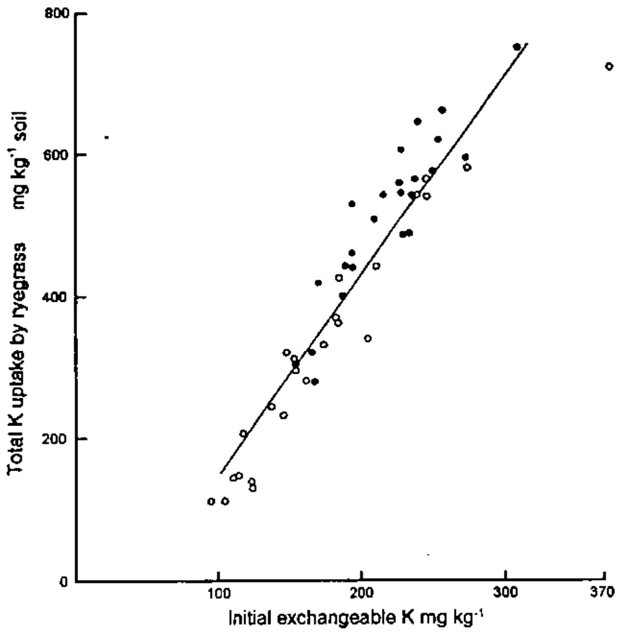

Fig. 10. Relationship between K uptake by seven harvests of ryegrass in the pot experiment and the initial exchangeable K in the soils. O, arable soils; ●, grass soils (see legend to Fig. 9) (adapted from Johnston and Mitchell, 1974).

The release of fixed K can be calculated by subtracting the change in K_{exch} during the experiment from the total K uptake. It is essential to determine K_{exch} on the moist soil at the end of the experiment because it was observed that K_{exch} increased appreciably on air drying the exhausted soils. The increase in K_{exch} on air drying field soils with adequate K reserves was usually quite small (Johnston, unpublished data) and would not justify analysing moist soils for advisory purposes. Soils are usually dried and sieved before analysis for advisory purposes to aid satisfactory subsampling for analysis.

Wetting and drying cycles as under field conditions usually result in added K going to both exchangeable and fixed K reserves (Warren and Johnston, 1962). The release of fixed K can be related to initial K_{exch} (Figure 11) and for this one soil there was a strong relationship (r = +0.87). Also, and perhaps more interestingly, the release of fixed K can be related to the decrease in K_{exch} (Figure 12) and again these two factors were strongly correlated (r = +0.90). For this data set Figure 12 shows that the uptake of fixed K was about twice that of K_{exch} Such strong relationships could be expected if there is a reversible transfer between K_{exch} and fixed K leading to the establishment of an equilibrium between the two.

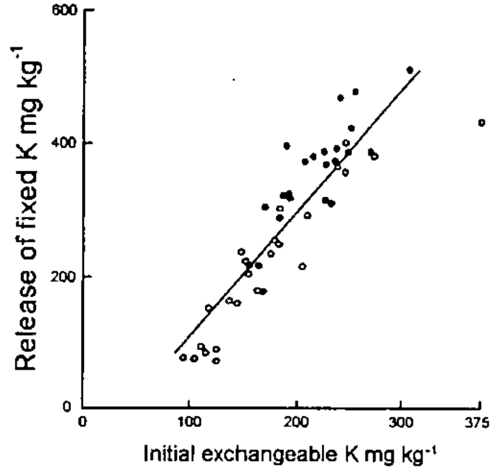

Fig. 11. Release of fixed (non-exchangeable) K related to initial exchangeable K. O, arable soils; ●, grass soils (see legend to Fig. 9) (adapted from Johnston and Mitchell, 1974).

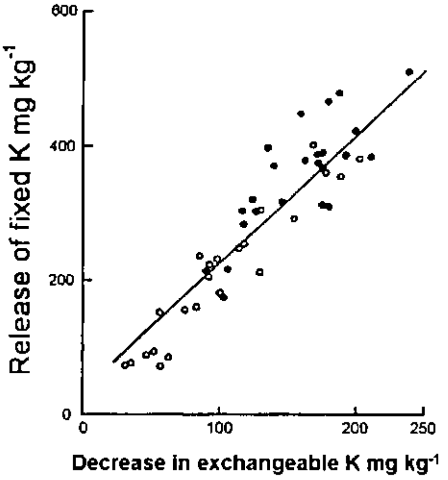

Fig. 12. Release of fixed (non-exchangeable) K related to decrease in exchangeable K. O, arable soils; ●, grass soils (see legend to Fig. 9) (adapted from Johnston and Mitchell, 1974).

Figures 10, 11 and 12 show different ways of using data from exhaustive cropping experiments on K release from one soil type with a wide range of K_{exch} from past cropping and manuring. Similar relationships were not so strong when data from three different soils were combined (Figures 13 and 14) but nevertheless there was a relationship. Arnold and Close (1961) also found a good relationship (r = +0.84) between the release of non-exchangeable K and initial K_{exch} up to 500 mg kg^{-1} for 20 different soils from the UK. Although Arnold and Close (1961) considered the correlation was too poor for the trend to be a useful guide, the good correlations found for the Agdell soils (Figures 11 and 12) suggest that it may be worthwhile to reconsider the use to which such a relationship could be put.

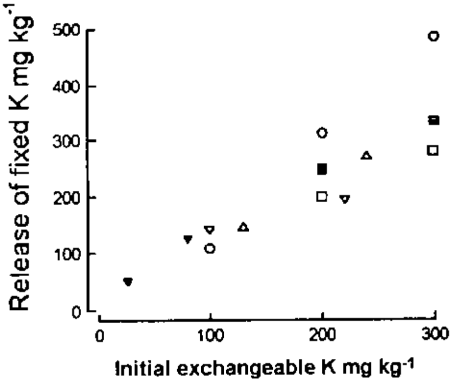

Fig. 13. Release of fixed (non-exchangeable) K related to initial exchangeable K on a silty clay loam, a sandy clay loam and a sandy loam soil.

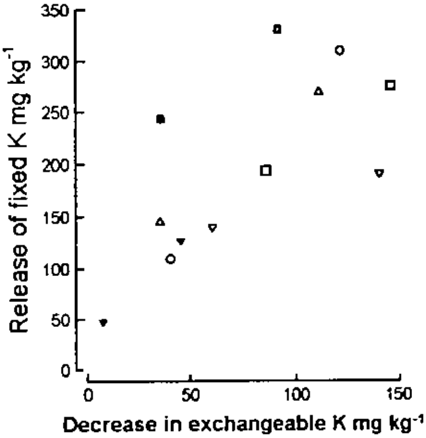

Fig. 14. Release of fixed (non-exchangeable) K related to decrease in exchangeable K on a silty clay loam, a sandy clay loam and a sandy loam soil.

Improving potassium recommendations for farmers

Giving good recommendations for K applications depends on both the response of crops to soil derived K and possible increases in yield at each level of K_{exch}. Both are likely to depend on the relationship between K_{exch} and fixed K.

A large number of experiments on a wide range of soils in the UK related the response of potatoes to K fertilizers to K_{exch} ranging from 30 to 500 mg kg^{-1} (Eagle, 1967). Including an estimate of the release of non-exchangeable K (fixed), determined using a cation exchange method, with that for K_{exch} greatly improved the relationship (from $r = -0.23^{*}$ to $r = -0.53^{***}$). This led Eagle (1967) to suggest that potatoes acquired much of their K requirements from non-exchangeable forms.

It is probable that the reason for such an observation arises because potatoes tend to have small, generally shallow root systems, in comparison to say, cereals. Such limited root systems may not fully explore the soil volume and thus may not have access to all the available K_{exch}. Therefore, crops with such root systems will be dependent on the release of fixed K as well as K_{exch} from the limited amount of soil explored by the roots.

Other factors besides inefficient root systems can limit the availability of K to plants. Poor soil structure can certainly affect the response of crops to nutrients (Johnston, 1994). Other soil factors include soil depth and stoniness, weed competition and soil borne diseases.

The effect of such factors on the K nutrition of crops must influence the reliability of K recommendations for crops. Some of the factors, like soil depth and stoniness and climate, can rarely be altered but the certainty and reliability of K recommendations could be improved if the amount and availability of the fixed K was known. From such knowledge, especially if it was based on a well established ratio of K_{exch} to fixed K, modifying factors for K recommendations on different soil types could be developed. Such modifying factors would not alter current K recommendations nor the amount of K to be applied which should at least replace offtake in some developed countries. In some of these countries there is a wealth of background information, much of it derived from very many field experiments, and advisors often have adequate knowledge about soil types and K responses on which to modify K recommendations. Rather the farmer would have greater certainty that the recommendations were reliable when crops could not make full use of K_{exch} due to external factors which limited root growth. These factors would include not only the soil factors listed above but others like droughtiness, water logging and aerial pathogens leading to a decrease in photosynthate production and translocation to the roots.

Many countries do not have the benefit of accumulated knowledge on soil K reserves and crop responses to K. It is where this information is lacking that there is the greatest need to be as specific as possible about K recommendations and such recommendations can be improved if there is knowledge about the size and availability of the fixed K pool. In many of the poorer, developing countries reliable K recommendations are vital because too little K has a yield and hence financial penalty whilst recommending too much is a luxury poor farmers cannot afford.

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Session 6

Posters

Potassium fertilization of potatoes in north India*

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Introduction

In north India, potatoes are grown on 0.88 Mha of alluvial soils as an irrigated autumn/winter crop under subtropical short day conditions. This region lies between 27° to 31° N latitude and 75° to 88° E longitude. The mean tuber yield on farmer's fields is 165 q ha^{-1}. Unbalanced fertilization heavily in favour of nitrogen (N) is one of the major reasons responsible for the small yields. Therefore, multilocational replicated trials were done on farmer's field to study the effects of combinations of levels of N and potassium (K) on tuber yield and quality.

Materials and methods

Field trials were conducted on farmer's fields at six locations in Jalandhar district, 31° N latitude and 75° E longitude, 237 m above sea level. The soils were Typic Ustochrepts. Soil pH ranged from 6.1 to 7.6, organic carbon from 0.13 to 0.66% (mean 0.32), CEC from 5 to 10 $cmol_c\ kg^{-1}$ (mean 7), available N (Subbiah and Asija, 1956) from 106 to 282 kg ha^{-1} (mean 192), Olsen-P from 12 to 26 kg ha^{-1} (mean 16) and exchangeable K (pH 7, 1 N NH_4OAc) from 100 to 206 kg ha^{-1} (mean 141). In the irrigation water, the pH ranged from 7.3 to 8.3, EC from 0.34 to 0.91 dS m^{-1} (mean 0.50) and the K content from 4.3 to 9.2 mg l^{-1} (mean 5.6).

The treatments tested consisted of combinations of three levels each of N (80, 160, 240 kg ha^{-1} as urea) and K (0, 75 and 150 kg ha^{-1} K_2O as muriate of potash) along with one control. All 10 treatments received 100 kg ha^{-1} P_2O_5. Potato tubers, cv. Kufri Jyoti, were planted at a spacing of 20 cm in rows 60 cm apart in the first week of October, 1996 and harvested in the last week of January, 1997. Plot size was 4.2 x 3.0 m. Most of the vines were killed by a severe frost seven weeks before harvest. Harvested tuber samples were analyzed for quality and weight loss in the four weeks after harvest.

Results and discussion

Tuber yield

The mean response, average of the six locations, to 80, 160 and 240 kg ha^{-1} N was 56, 76 and 81 q ha^{-1}, tubers, respectively, and to 75 and 150 kg ha^{-1} K_2O was 26 and 40 q ha^{-1} tubers (Table 1). The response to K depended on the level of N. The response to 75 kg ha^{-1} K_2O was 11, 38 and 29 q ha^{-1} with 80, 160 and 240 kg ha^{-1} N, respectively, while the corresponding response to 150 kg ha^{-1} K_2O was 21, 48

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* Keywords: potassium, potato, tuber yield, quality, India.

and 49 q ha^{-1}. The interaction between N and K was significant. For optimum tuber yield, potatoes required 160 kg ha^{-1} N plus 150 kg ha^{-1} K_2O. In the Indo-Gangetic plains, similar optimum levels of N and K were reported for potatoes grown on soils low in available N and K (Singh and Grewal, 1985).

The better response to the larger amount of K in this study may be attributed to the severe frost which occurred during the growing period because K imparts resistance to frost injury (Grewal and Singh, 1980). Potassium fertilization significantly increased the yield of marketable size tubers at the cost of small and medium size tubers (Table 2). The mean increase in the yield of large size tubers was 14% with a corresponding decrease in the proportion of small and medium size tubers. Increase in total yield and the yield of large size tubers may be attributed to the stimulating effect of K on photosynthesis, phloem loading and translocation as well as synthesis of large molecular weight substances within storage organs (Beringer, 1978) contributing to rapid bulking of the tubers.

Table 1. Effect of nitrogen and potassium on tuber yield of potatoes (q ha^{-1}) in north India.

K_2O (kg ha^{-1})	N (kg ha^{-1}) 0	80	160	240	Mean*
0	93	138	141	148	142
75	-	149	179	177	168
150	-	159	189	197	182
Mean	-	149	169	174	-
LSD (0.05%)		N=7, K=7, NxK=12.			

* Mean excluding control (0).

Table 2. Percentage of different size grade tubers in the harvested produce as influenced by nitrogen and potassium fertilization.

K_2O (kg ha^{-1})	Tuber size	N (kg ha^{-1}) 0	80	160	240	Mean*
0	L	7	19	21	23	21
	M	65	61	60	60	60
	S	28	20	19	17	19
75	L	-	21	25	32	26
	M	-	64	62	57	61
	S	-	15	13	11	13
150	L	-	24	30	33	29
	M	-	61	58	55	58
	S	-	15	12	12	13

L = Large (>75 g); M = Medium (25-75 g); S = Small (<25 g).

* Yield of the control excluded from the mean.

Quality of tubers

Increasing levels of N significantly decreased the specific gravity of the tubers and tended to decrease tuber dry matter, while increasing levels of K significantly decreased both specific gravity and dry matter (Table 3). Potassium fertilization tended to increase the vitamin C content of the tubers and decrease the reducing sugars. The N, K effects and their interaction on the quality of the tubers were not significant. These results are supported by the observations of Singh *et al.* (1995).

Table 3. Effect of levels of nitrogen and potassium on the quality of tubers at harvest.

Main effects	Dry matter %	Sp. gravity	Vitamin C (mg 100 g^{-1} tuber)	Reducing sugars (mg 100 g^{-1} tuber)
Control	18.9	1.071	10.78	471
N (kg ha^{-1})				
80	18.1	1.069	11.33	412
160	17.7	1.067	10.82	448
240	17.5	1.064	10.93	445
K (kg ha^{-1} K_2O)				
0	18.3	1.069	10.97	456
75	17.7	1.067	11.12	433
150	17.3	1.064	11.00	416
CD (5%)				
N	NS	0.002	NS	NS
K	0.56	0.002	NS	NS

Weight loss from tubers after harvest

During four weeks of storage after harvest at room temperature (15-19°C), tuber weight loss ranged from 1.48 to 2.09%. Application of 150 kg ha^{-1} K_2O significantly decreased the weight loss (Table 4) but N tended to increase it. The NxK interaction effect on weight loss was not significant. The role of K in osmoregulation in cell sap and in the maintenance of the ultra structure of cell membranes (Beringer, 1978) might be responsible for reduced weight loss from tubers grown with sufficient K.

Table 4. Effect of levels of nitrogen and potassium on weight loss (%) from tubers at room temperature storage after harvest.

Main effects	Weight loss (%) Weeks after harvest			
	1	2	3	4
Control	0.69	0.85	1.26	1.63
N (kg ha^{-1})				
80	0.69	0.96	1.27	1.68
160	0.78	1.06	1.40	1.83
240	0.75	1.05	1.40	1.80
K (kg ha^{-1} K_2O)				
0	0.79	1.13	1.48	1.94
75	0.71	0.97	1.31	1.70
150	0.73	0.97	1.28	1.66
CD (5%)				
N	NS	NS	NS	NS
K	NS	NS	NS	0.20

Economics of potassium fertilization

The economics of N and K fertilization were calculated as net returns (price of increased yield minus additional cost of fertilization). For these calculations, the prevailing wholesale market prices were used, namely: Rs. 1000 t^{-1} tubers, Rs. 7.3 kg^{-1} N and Rs. 6.55 kg^{-1} K_2O.

The maximum net return was given by 240 kg N + 150 kg K_2O ha^{-1}, closely followed by 160 kg N + 150 kg K_2O ha^{-1} (Table 5). All the combinations of N and K fertilization tested were profitable, with the benefit : cost ratio (BCR) ranging from 3.2 to 4.7. The mean BCR for N and K on a single nutrient basis was 6.9 and 4.6 respectively.

Table 5. Net returns and benefit : cost ratio (BCR) of nitrogen and potassium fertilization of potatoes.

	Net return (Rs ha^{-1}) N (kg ha^{-1})		
K_2O (kg ha^{-1})	80	160	240
0	4207 (7.2)	4215 (3.6)	4622 (2.6)
75	5062 (4.7)	7769 (4.6)	7277 (3.2)
150	5816 (3.7)	8524 (3.9)	9031 (3.3)

Values in parenthesis are BCR.

From the results, it may be concluded that K fertilization together with N was essential to increase tuber yield and profitability of the potato crop grown in north India. It also improved the nutritive quality of tubers and reduced the weight loss after harvesting.

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Long-term changes of the potassium status of soils as affected by the clay mineralogy*

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The content and mineralogical composition of the fine silt and clay fractions and the potassium (K) status of the soil were measured in samples taken from long-term field experiments on soddy-podzolic soils in some regions of Russia and Belarus. The content of illite in the clay fraction tended to increase in soils treated with K fertilizers. For example, the illite in the clay fraction of samples taken from the arable layer (0-30 cm) of a sandy soil from Belarus increased from 25% to 34%.

As a result of the long-term application of K fertilizer, the content of the most mobile forms of soil K increased greatly. For example, the a_{K+} value of the K treatments was, on average, 2.5 times larger than that of the K_0 (without K) treatments, the content of easily exchangeable K was 2.3 times larger, the content of exchangeable K was 1.9 times and the content of non-exchangeable K 1.3 times larger than the K_0 treatments. The uptake of K by ryegrass in a pot experiment using soils from the field experiments was, on average, 3.0 times greater from the K treated soil than from the K_0 soil.

Potassium fixation capacity tended to decrease in loamy soils treated with K fertilizers. On the basis of a laboratory experiment with loamy soils under flow conditions, the K fertilized soils had higher values of the zero-order desorption rate coefficient compared with soils not treated with K fertilizers. In loamy soils, the content of non-exchangeable, exchangeable and easily exchangeable K as well as the a_{K+} and PBC^K values were found to be strongly correlated to the content of fine silt and to the proportion of expandable clays in the clay fraction. In sandy soils, no correlation was found between K status characteristics and the soil properties measured, i.e. content of clay and fine silt fraction, proportion of any individual clay mineral or organic carbon content. It is suggested that in coarse-grained soils K status characteristics were controlled mainly by illites and hydro-thermally changed K feldspars in sand and coarse silt sized particles.

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* **Keywords**: potassium fertilizers, soil potassium.

Influence of potassium fertilization and liming on maize, wheat and soybeans

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Introduction

The Eastern Croatia province occupies about 20% of the territory of Croatia and has 30% of its arable land. However, this one province produces about 50% of Croatia's maize, nearly 60% of its wheat and nearly 90% of its soybean production. Recently, plant nutrient problems have been found (Kovacevic *et al.*, 1988, 1990, 1993; Kovacevic and Vukadinovic, 1992a, 1992b), especially in maize and soybean crops grown on some K deficient gleysols, Zn deficient calcareous soils and P deficient acid soils.

Materials and methods

Two problem soils (A and B) with different properties were choosen to test the response of the main arable crops in Croatia to ameliorative fertilization.

Soil A was a drained, silty clay loam gleysol developed on calcareous loess. The organic matter content was 2.4%, pH (1 N KCl) was 7.3, and the clay, silt and sand contents were 35.2, 62.0 and 2.7%, respectively. The clay fraction consisted of vermiculite/chlorite (30%), smectite (30%), mixed layer minerals (20%), illite (15%) and kaolinite (5%). The experiment tested four amounts of potassium (K) in a randomized block design with four replicates. The K to be applied was divided into two equal amounts, one was broadcast prior to ploughing and the other after ploughing in 1986. The experiment had two blocks so that maize and soybeans were both grown each year and they rotated on each block. Gross plot area was 294 m^2. Phosphorus (P) (120 kg P_2O_5 ha^{-1}) and nitrogen (N) (240 and 125 kg N ha^{-1} for maize and soybeans, respectively) were applied to all plots. In the second and the third year of the experiment, all plots received 150 kg K_2O ha^{-1}.

Soil B was a planosol (pH in 1 N KCl was 4.2). This soil was choosen because it gave consistently small yields of maize, which were smaller than those of wheat. In the autumn of 1986, a field experiment tested four amounts of calcite (liming material containing about 50% CaO) and P (superphosphate containing 18% P_2O_5). There were two blocks, one for wheat, one for maize grown in rotation and within each block, each treatment was replicated four times. The plot size for the calcite and superphosphate applications were 1166 m^2 and 294 m^2, respectively.

The soils were characterized (Table 1) by sampling by auger to 30 cm depth from the four replicates of the control treatment of both experiments. The soil was extracted using NH_4-acetate-EDTA (Lakanen and Ervio, 1971) and the elements determined by the ICP technique. In earlier investigations, the soils were extracted either with 1 N NH_4-acetate (Whiteside, 1979) or AL-extract (Egner *et al.*, 1960). See Table 4 for some earlier data obtained by these methods.

Plant leaf samples were taken at the beginning of the silking stage of maize (25 ear-leaves) and immediately before anthesis of soybean (about 50 of the uppermost full-developed third-leaf). After drying and grinding, plant samples were digested by wet-ashing with concentrated sulphuric acid containing Se as a catalyst. Potassium, calcium (Ca) and magnesium (Mg) concentrations in the plant samples were determined by an AAS procedure.

Table 1. Some chemical properties of the top 30 cm layer of a drained gleysol (A) and planosol (B).

	A	B		A	B
pH in H_2O	8.07	5.47			
pH in 1N KCl	7.19	4.24			
mg kg^{-1} of air-dried soil (NH_4 acetate-EDTA extraction*)					
Phosphorus (P)	60	36	Cadmium (Cd)	0.19	0.03
Potassium (K)	116	243	Lead (Pb)	5.08	2.89
Magnesium (Mg)	1404	195	Cobalt (Co)	0.21	0.90
Calcium (Ca)	48000	1120	Aluminium (Al)	44.0	210.0
Sulphur (S)	62	26	Strontium (Sr)	59.4	2.1
Iron (Fe)	305	263	Barium (Ba)	71.7	35.6
Manganese (Mn)	57	101	Sodium (Na)	173.0	29.0
Copper (Cu)	5.2	1.9	Mercury (Hg)	0.0	0.0
Zinc (Zn)	0.6	2.5	Arsenic (As)	0.0	0.0
Boron (B)	1.0	0.0	Molybdenum (Mo)	0.0	0.0
Nickel (Ni)	0.74	0.86	Selenium (Se)	0.0	0.0
Chromium (Cr)	0.27	0.0			

* Lakanen and Ervio (1971); 0.0 indicates less than the detection limit using the ICP procedure.

Results and discussion

The application of K to the drained gleysol considerably increased the grain yields of both maize and soybeans. However, liming the planosol to increase its pH value to neutral decreased both maize and wheat yields (Table 2). These responses could be explained by comparing the soil data given in Table 1.

Table 2. Response of crops to soil improvement by potassium and lime.

Crop	Soil A: kg ha^{-1} K (autumn 1986)				Soil B: t ha^{-1} calcite (spring 1987)			
	125	835	1580	2220	0	10	20	32
	Grain yield (t ha^{-1} on 14% moisture basis)							
	3-year average (1987-1989)				4-year average (1987-1990)			
Maize	1.93	5.39	6.64	7.64	4.54	4.35	4.27	4.10
Wheat					7.15	6.98	6.81	6.70
Soybeans	1.29	2.17	2.45	2.61				

Potassium deficiency and an excess of plant available Ca and Mg are the main reasons for the appearance of K deficiency in maize and soybeans. Normalization of the K soil status was made by the large applications of KCl (Soil A, Table 2). Without K, both crops were extremely K deficient and had an excess of Mg and Ca. The K, Ca and Mg status was only acceptable when very large amounts of K were applied (Table 3).

Table 3. Grain yields and nutritional status of maize and soybean leaves in the first season, 1987.

Treatment	Grain yield (t ha^{-1})	Concentrations (% in dry matter)			
		P	K	Ca	Mg
Maize yields and leaf composition at silking stage (Kovacevic and Vukadinovic, 1992a)					
Control	1.75		0.64	1.43	2.03
835 kg ha^{-1} K	7.76		1.43	1.38	1.39
2220 kg ha^{-1} K	8.88		1.86	1.33	1.14
LSD 1%	0.87		0.14	0.17	0.21
Soybean yields and leaf composition before anthesis (Kovacevic and Vukadinovic, 1992a)					
Control	1.28		0.57	1.44	1.60
835 kg ha^{-1} K	2.70		1.90	1.64	0.95
2220 kg ha^{-1} K	2.55		2.28	1.49	0.78
LSD 1%	0.36		0.27	0.31	0.27
Maize yields and leaf composition at silking stage (Kovacevic *et al.*, 1990b)					
a) control	4.86	0.245	2.27	0.57	0.250
b) 10 t ha^{-1} calcite	4.51				
c) 32 t ha^{-1} calcite	4.75	0.233	2.32	0.53	0.223
c) 1350 kg ha^{-1} P_2O_5	3.91	0.275	2.47	0.55	0.218
d) 32 t ha^{-1} calcite plus 1350 kg ha^{-1} P_2O_5	4.08	0.253	2.11	0.54	0.220
LSD 1%	0.36				

Similar results were found on a calcareous loamy chernozem developed on loess substrate in Fejer county, Hungary when 1500 kg ha^{-1} K_2O were applied (Kadar *et al.*, 1991). A comparison of the results of the two experimental fields, one situated in Hungary and the other in Croatia, was made by Kadar *et al.* (1997).

In general, liming acid soils is usually recommended for their improvement. Based on our experience with two field trials, maize, soybean and barley grain yields were increased by liming, but only by 10% or less. Conversely, wheat yields were not increased by liming or P; they were 7.21 t ha^{-1} on the control and 7.22 to 7.49 t ha^{-1} with the lime and P treatments (Kovacevic *et al.*, 1993). However, on a planosol, lime application decreased the yield of maize and wheat (Table 2), but these decreases cannot be explained by soil test data (Tables 1 and 4) or by leaf analysis (Table 3). The soil analysis (Kadar, 1995; Kadar *et al.*, 1994) showed very low levels of toxic metals in the two soils, suggesting that this was not the cause of the small yields. Madjaric (1985) also discussed the effect of various soil parameters on wheat yields under the conditions of East Croatia.

Table 4. Treatment effects on selected soil chemical properties.

Treatment	pH		mg kg^{-1} of soil				
			1N NH_4-acetate			AL-extraction	
	H_2O	KCl	K	Ca	Mg	P_2O_5	K_2O
Soil A: drained gleysol (Kovacevic and Vukadinovic, 1992a)							
a) control	8.07	7.19	70	15060	1450		
b) with 835 kg ha^{-1} K	8.24	7.28	89	18270	1560		
c) with 2220 kg ha^{-1} K	8.10	7.30	130	17530	1460		
LSD 1%	0.28	0.17	15	2640	330		
Soil B: planosol (Kovacevic *et al.*, 1990b)							
a) control	5.47	4.24				177	220
b) with calcite (32 t ha^{-1})	7.61	7.00				205	215
c) with 1350 kg ha^{-1} P_2O_5	5.20	4.20				468	262
d) with calcite and P_2O_5	7.27	6.21				338	224

Conclusions

Ameliorative fertilization with K on a drained gleysol improved maize and soybean yields and their K and Mg content. However, soil and plant tests could not explain why maize and wheat yields were decreased by liming the acid soil. Neither has it been possible to explain the considerably smaller maize grain yields compared to those of wheat on the acid soil.

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Potassium status of the soils of the Eastern Croatia*

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Introduction

In general, the potassium (K) status of the soils of Croatia is considered to be satisfactory. However, soil tests indicate K deficiency in soils in areas of the former Zupanja, Beli Manstir, Nova Gradiska and Slav. Brod communes. The soil K resources and the efficiency of K fertilizers in Croatia were reviewed by Kovacevic and Basic (1997). About 80% of the total arable land in Croatia is farmed by private farmers (peasant holdings) but, it is estimated that soil tests have been done on less than 5% of these soils. As the strategy for agriculture development in Croatia (MAF, 1995) is based on private family farm production, inclusion of these soils in routine soil testing is essential for the improvement of soil and crop management practices, especially fertilization. Growth retardation and chlorosis of maize and soybean plants were observed when these crops were grown on some drained gleysols in the lowlands of the Sava River (local name Posavina) in Eastern Croatia. The alkaline soil reaction, low levels of plant available K and high levels of magnesium (Mg), as well as the large clay content, are all connected with the problem of K nutrition in these soils.

Materials and methods

During the period from 1970 to 1989, routine soil testing using the AL-method (Egner *et al.*, 1960) was done on the arable soils which were then the property of the state farms (in total 128,451 ha). A bulked soil sample (usually from 25 individual samples) was taken with an auger to either 25 or 30 cm of depth to represent an area of 3-5 ha of arable land. Soil testing was done in the laboratories of University Agricultural Faculties (Osijek and Zagreb) and in the laboratories of the former state farms (Vukovar, Osijek, Pozega and Zupanja). The results were treated mainly as internal data of each state farm and were brought together only by personal communication. As the state farms were organized at the communes level, the old administrative divisions of Eastern Croatia (until end of 1992) were used for this study.

Potassium was tested on four experimental fields in the lowlands of the Sava River on K deficient soils in Gundinci, Cerna, Stari Mikanovci and Crnac polje. The treatments, designated as FE-1, FE-2, FE-3 and FE-4, respectively, were replicated

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* **Keywords**: Croatia, potassium, soil.

four times. The rates of K, kg K_2O ha^{-1}, applied as 60% muriate of potash, were 1105 (FE-1), 990 (FE-2), 2670 (FE-3) and 2550 (FE-4) in the period from 1984 to 1990.

Results and discussion

Routine testing of soil samples for pH, plant available phosphorus (P) and K, and humus content, began routinely in Eastern Croatia (Slavonia and Baranya regions) in the middle of the 1960s. For that purpose, temporary laboratories were established in the Department of Soil Science, Agricultural Institute, Osijek; Department of Agricultural Chemistry, Faculty of Agriculture, Osijek; and in the IPK Scientific Agricultural Center, Osijek. The results of this routine soil testing were published in a few articles, while two are especially important with data on soil properties in our region (Janekovic, 1971; Janekovic and Pichler-Sajler, 1976).

According to the internal data of the former large state farms (agrocombinates), soils from nearly 130,000 ha (23%) of the arable land in the Eastern Croatia were analyzed by routine soil test procedures until 1990. Soils with less than 100 mg kg^{-1} plant available K were found on only 16% of the area. 23% of soils were moderate (100 to 150 mg K_2O kg^{-1}), 30% were satisfactory (150 to 200 mg K_2O kg^{-1}), 19% were classified as good (200 to 250 mg K_2O kg^{-1}) while 12% were very good (more than 250 mg K_2O kg^{-1}) (Table 1).

In Eastern Croatia, 294,198 ha or about 53% of the arable land is owned by small farmers. These small private farms occupy about 75% of the total arable land (in Croatia as a whole 1,109,000 ha, while the remaining 25%, 373,000 ha, is managed by the former state farms). In general, the K status of this arable land belonging to small private farms is unknown because only 4% of the land has been included in routine soil testing. Based on the results of soil tests, the application of the more K became the usual fertilization practice for the former state farms Belje (commune B. Manastir), Jasinje (commune Sl. Brod) and Zupanja (commune Zupanja), especially during the 1980s. For this reason, we presume that the levels of plant available K were increased compared with their earlier status. Also, the application of straight K fertilizer was made as a part of balanced fertilization, especially in Belje and Zupanja state farms. However, recently, fertilizer consumption in Croatia decreased because of the economic difficulties caused by war and the global economy of the states in transition. For example, in the period 1986-1990, annual fertilizer consumption in Croatia was 568,438 t, while in the next 5 years it was 40% less, 343,301 t (Kovacevic and Basic, 1997).

Some gleysols situated in the lowlands of the Sava River are vertic and plastic, with a small air capacity when wet, together with only a small amount of plant available K. Finding K deficiency symptoms in maize and soybeans, as well as low grain yields, was the reason for conducting the four field experiments with increased K fertilization as discussed by Bertic *et al.* (1989), Katusic *et al.* (1988), Kovacevic (1993, 1994), Kovacevic and Grgic (1995), Kovacevic *et al.* (1990a, 1990b), Kovacevic and Vukadinovic (1992), Richter *et al.* (1990).

Table 1. Proportion of arable soils with different levels of readily soluble potassium (AL-method) in Eastern Croatia.

Commune	Percentage of soils in each K class (mg K_2O kg^{-1})					Area sampled (ha)	Total arable land (ha) in 1989
	<100	100-150	150-200	200-250	>250		
B. Manastir	49	17	15	8	11	18250	55262
Vukovar	0	15	38	34	13	11500	43302
Zupanja	43	44	13	0	0	14809	38603
Osijek	0	5	34	35	26	24858	47130
D. Miholjac	7	17	38	18	20	12288	27002
Sl. Brod	25	41	23	7	4	12805	48781
N. Gradiska	9	38	40	9	4	7560	38170
Nasice	0	24	37	30	9	11480	37930
P. Slatina	8	30	37	20	5	12768	33099
Sl. Pozega	0	25	54	18	3	2133	42590
Other*							146910
Total (ha)	20552	29544	38535	24406	15414	128451	558779
Croatia							1482000

* For the remaining four communes Djakovo, Orahovica, Valpovo and Vinkovci, there are no accurate data.

The soils used for the experiments described here were heavy clay soils with more than 35% of the less than 0.002 mm fraction and 10% or less of the fraction above 0.20 mm.

The soils also contained large amounts of smectite, illite and vermiculite. For example, vermiculite + chlorite was about 30% of total clay minerals for all three soils with the same proportion of smectite in the soil of the FE-1 and FE-3 treatments. Kaolinite was from 5 to 10% of the clay minerals. The soils were moderately supplied with K and rich in Mg (Table 2), the share of $CaCl_2$-extractable Mg being between 3 and 7% of the total Mg, while the AL-method extracted about 15% of total Mg (Richter *et al.*, 1990). The physical and chemical characteristics of these soils probably account for the small yields and the seasonal variability. Also, specific soil management practices are required for these soils (Vidacek, 1982; Bicanic, 1989; Basic *et al.*, 1996). Vukadinovic *et al.* (1988) found strong K fixation of these soils (Table 3). For example, of an addition of 1000 mg K (as KCl solution) to 1000 g of soil, 70% was fixed in FE-1, 76% in FE-2 and 81% in FE-3.

Table 2. Total and extractable K, Mg (AL-method; Egner *et al.*, 1960) and Ca (KCl extraction) content in surface soil layer (0-30 cm) of the three field experiments (Richter *et al.*, 1990).

	mg kg^{-1}						
	Total			Extractable			pH
	K	Mg	Ca	K	Mg	Ca	(KCl)
FE-1	13710	7000	13710	70	1250	8680	7.15
FE-2	17640	6520	11320	110	950	6450	6.77
FE-3	12810	13250	68490	70	2000	6030	7.19

Table 3. Soil characteristics for the four field experiments (control treatment and depth of soil from 0 to 30 cm): intensity of K fixation (Vukadinovic *et al.*, 1988).

Fertilization*	Potassium fixation (%) in the soil of the field experiments			
mg K kg^{-1}	FE-1	FE-2	FE-3	FE-4
0	control	control	control	control
500	77.3	86.8	91.9	94.4
1000	70.0	76.0	80.9	88.1

* In the form of KCl (25 ml of solution containing different levels of potassium was added to 10 g of soil).

There was a close relationship between plant available K and K fixation ($r = 0.82^{++}$). Soil samples from the Crnac polje area (FE-4) fixed both P and K. For example, following addition of 1000 mg of either P or K to 1000 g of soil, 71% of the added P and 88% of the added K was fixed. Also, Likoder (pers. comm.)

estimated that about 11,000 ha of Nova Gradiska area (about 7000 ha soils of former state farms and about 4000 ha soil of small private farmers) have similar nutritional problems.

In general, grain yields of maize and soybean were increased greatly by the application of large amounts of K (Table 4). The ear-leaf K and Mg status (% in dry matter at the beginning of the silking stage: averages of four experiments) were: 0.64% K and 1.82% Mg (standard fertilization), 1.60% K and 1.11% Mg (with the largest amount of K). Thus, the imbalance between K and Mg (Johannson and Hahlin, 1977) appears to be related to the small grain yields in the control treatment.

Table 4. Response of crops (grain yields: t ha^{-1} on 14% moisture basis) to the highest rate of potassium fertilization in the field experiments (FE): the first year of testing (Kovacevic and Basic, 1997).

Crop	Treatment	Grain yield (t ha^{-1})			
		FE-1	FE-2	FE-3	FE-4
Maize	Control	4.98	2.48	1.75	3.81
	K*	8.96	7.62	8.88	7.13
	LSD 1%	1.30	1.03	0.87	0.78
Soybean	Control	1.59	2.40	1.28	2.13
	K*	2.18	2.83	2.55	2.82
	LSD 1%	0.24	0.36	0.36	0.66
Wheat	Control	4.77			
	K*	5.05			
	LSD 1%	ns			

* kg K_2O ha^{-1}: 1105 (FE-1), 990 (FE-2), 2670 (FE-3) and 2550 (FE-4).

Conclusions

The quantity of K in soils of the Eastern Croatia differ greatly, ranging from low to a very good supply for the main arable crops according to the analysis of 25% of the arable land area (nearly 130,000 ha). About 16% was poorly supplied with plant available K. However, this testing was mainly focused on the former large state farms, but they cover only 47% of the total arable land in the region. The chemical properties of the soils, including their K status, of farms owned by small farmers, is practically unknown because less than 5% have been tested. Potassium application especially affected maize and soybean yields under K deficient conditions.

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Dynamics of available potassium fractions of different soil types in the Hungarian long-term fertilization experiments*

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Introduction

The availability and movement of plant nutrients to roots are mainly controlled by the concentration of the nutrient in the soil solution. In the case of potassium (K), there is an equilibrium between K in the soil solution and the easily and slowly or non-exchangeable forms of K in the soil. The availability of nutrients is mainly affected by the extent of the root system, soil moisture, clay and humus content and soil pH amongst other factors (van Diest, 1978; Mengel, 1982). Even with a knowledge of these soil properties, it is rather complicated to calculate the precise K requirement of crops through the whole of the growing period.

In addition, the K supplying power of soils varies considerably and thus, the effectiveness of K fertilization is also variable. For studying K availability and the soil supplying capacity for K and its dynamics, several laboratory, chemical and biological methods (e.g. pot experiments) are suggested (Quémener, 1979; Grimme and Németh, 1979; Sárdi and Debreczeni, 1992). Among these, the electro-ultrafiltration (EUF) procedure allows an assessment of nutrient desorption in an electric field (Németh, 1976).

In Hungary, soils are significantly different in their clay content and type of clay minerals. A nation-wide survey of clay mineralogy of soils has been made by Stefanovits and Dombovàriné (1994) in order to improve K fertilizer recommendations.

The National Long-Term Fertilization Trials in Hungary (NLFT) have been continued at nine experimental sites on different soil types. The aim was to study the effects of increasing amounts of fertilizer on soil nutrient status as well as on soil properties. Two crop rotations were tested. The K supplying power of soils was also studied in pot experiments (biological testing). The results of these experiments are reported in another paper.

Materials and methods

Soil samples from the 0-20 cm layer were taken from experiment II (winter wheat-corn rotation) at the nine National Long-Term Fertilization Trials, in the last year of the fourth rotation. Selected treatments for this study were:

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* **Keywords**: plant available potassium, EUF, exchangeable K, pot experiment, ryegrass, long-term trial.

1. Unfertilized control, code 000
2. N_5P_3 (N 250, P_2O_5 150 kg ha^{-1} $year^{-1}$), code 530
3. $N_5P_3K_1$ (N 250, P_2O_5 150, K_2O 100 kg ha^{-1} $year^{-1}$), code 531
4. $N_5P_3K_2$ (N 250, P_2O_5 150, K_2O 200 kg ha^{-1} $year^{-1}$), code 532

The main characteristics of the experimental soils were:

Experiment	Soil type	% clay	pH (KCl)	Humus %
1. Bicsérd (BI)	Luvic phaeosem	33	5.6	1.9
2. Iregszemcse (IR)	Calcaric phaeosem	22	7.4	2.4
3. Hajdúböszörmény (HB)	Luvic phaeosem	35	6.1	3.5
4. Karcag (KA)	Luvic chernozem	37	4.7	2.7
5. Keszthely (KE)	Eutric cambisol	24	6.3	1.7
6. Kompolt (KO)	Haplic phaeosem	41	3.9	2.6
7. Mosonmagyaróvár (MO)	Calcaric fluvisol	12	7.4	1.7
8. Nagyhörcsök (NH)	Calcaric phaeosem	23	7.2	2.7
9. Putnok (PU)	Ochric phaeosem	28	4.6	2.0

The exchangeable K content of the soils was determined using the AL-method (Egner *et al*., 1960) using a soil:extractant ratio of 1:20 and 2 hours shaking and the K content in the extract was determined by flame photometry. Potassium supplying capacity of soils was studied by the electro-ultrafiltration (EUF) method as follows: at 20°C first for 5 minutes and 50 V then in 10-15-20-25-30 minute time intervals at 200 V and for another 5 minutes at 400 V and 80°C. Clay mineralogy of soils was determined by X-ray diffraction.

Results

The exchangeable K content of the experimental soils, as determined by the AL-method, are summarized in Table 1.

Table 1. AL-extractable potassium (a) (AL-K_2O, mg kg^{-1}) and amounts of potassium per unit clay content (b) mg K_2O g^{-1} clay.

Soils	Code number of treatments							
	000		530		531		532	
	a	b	a	b	a	b	a	b
BI	174	(0.53)	167	(0.51)	251	(0.76)	364	(1.10)
IR	156	(0.71)	185	(0.84)	215	(0.98)	359	(1.63)
HB	165	(0.47)	123	(0.35)	195	(0.56)	183	(0.52)
KA	170	(0.46)	180	(0.49)	259	(0.70)	485	(1.31)
KE	164	(0.68)	170	(0.71)	263	(1.09)	336	(1.40)
KO	166	(0.40)	187	(0.46)	264	(0.64)	304	(0.74)
MO	215	(1.79)	197	(1.64)	193	(1.61)	207	(1.73)
NH	137	(0.60)	151	(0.66)	209	(0.91)	282	(1.23)
PU	217	(0.77)	175	(0.62)	296	(1.06)	318	(1.14)

The potassium fractions obtained for the different time intervals, temperatures and voltages in the EUF extracts are summarized in Table 2. Based on these values, it was possible to model the K supplying power of the soil and the K dynamics as well as the time dependent K equilibrium. The proportions of the different clay minerals based on the determinations of Stefanovits-Dombováriné (1994) are shown in Table 3.

Table 2. Summary of the amounts of potassium extracted by the EUF method after 16 years of N_5P_3, $N_5P_3K_1$ and $N_5P_3K_2$ treatments (codes 530, 531 and 532 respectively) in long-term experiments in Hungary.

Soil	K (mg K_2O kg^{-1})											
	AL-extracted			K extracted by the EUF method at								
				50 V			200 V			400 V		
	530	531	532	530	531	532	530	531	532	530	531	532
BI	167	251	364	6	12	18	38	58	69	35	64	87
IR	185	215	359	6	8	20	28	30	40	34	68	47
HB	123	195	183	8	8	8	28	30	40	34	68	47
KA	180	259	485	10	18	30	52	74	116	50	73	138
KE	170	263	336	7	10	20	28	44	76	24	60	48
KO	187	264	304	10	15	18	46	67	80	44	58	82
MO	197	193	207	10	13	16	41	39	48	50	44	39
NH	151	209	282	6	12	14	24	36	54	38	48	80
PU	175	296	318	8	20	22	40	74	82	36	66	70

Discussion

The amounts of K determined in the AL-extract of the soils from the NLFT plots after 16 years without K fertilization were related to the clay content and quantity of K per unit of clay (Table 1). The application of K increased both AL-extractable K and the amount of K per unit of clay. The AL-extractable K content of soils with treatment K_2 was twice that in soils without K.

It should be noted that the K supplying capacity of the MO calcaric fluvisol, which had the smallest clay content, was unexpectedly large. Soil water conditions are favourable at this site (River Lajta has a beneficial influence on it) as well as clay mineralogy with a large illite content (Table 3) favouring the release of K to the soil solution.

Another soil to be mentioned is the Luvic phaeosem (at HB), which had least exchangeable K when 200 kg K_2O ha^{-1} was applied. The possible explanation for this may be that this soil has a high clay content and an unusually high K fixation capacity (smectite content 47% of the clay).

Table 3. Clay mineralogy of the soils from the experimental sites (0-30 cm soil layer) (Stefanovits-Dombováriné, 1994).

Soil	Illites	Kaolinites	Chlorites	Smectites	Vermicu-lites	Illite-smectite	Illite-chlorite	Illite-vermiculite
BI	45	-	19	17	6	10	3	-
IR	50	-	30	8	-	10	2	-
HB	29	-	7	47	6	5	3	3
KA	56	-	17	7	3	11	5	1
KE	59	10	13	6	-	9	3	-
KO	27	20	-	37	-	10	6	-
MO	48	-	28	16	-	7	-	-
NH	No data							
PU	33	14	-	27	-	24	-	2

The amounts of the K fractions obtained by EUF may give more detailed information on K supplying characteristics of soils in the long-term (results are summarized in Table 2). The amount of K desorbed in the first 5 minutes was large for most soils and then decreased in the successive fractions.

The amounts of K determined in the EUF fractions were different for the soils with or without K fertilization. The greatest rates of K supply were observed for the acidic soils (KA, KO and PU, respectively). Results were related to clay content and the amounts of the dominant clay minerals (Table 3). By contrast, in the MO and HB soils, relatively small differences were obtained between treatment effects in the amounts of K, being independent of K fertilization. The smallest quantities of K were removed at 400 V and 80°C compared to the values obtained for the other soils.

From the results of these experiments, it was concluded that the EUF procedure allowed a good assessment of soil K status and supply characteristics of the different soil types. However, further investigations are needed for some soils (such as MO and HB soils), for a better understanding of.the relationships between long-term K fertilization and soil K status.

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