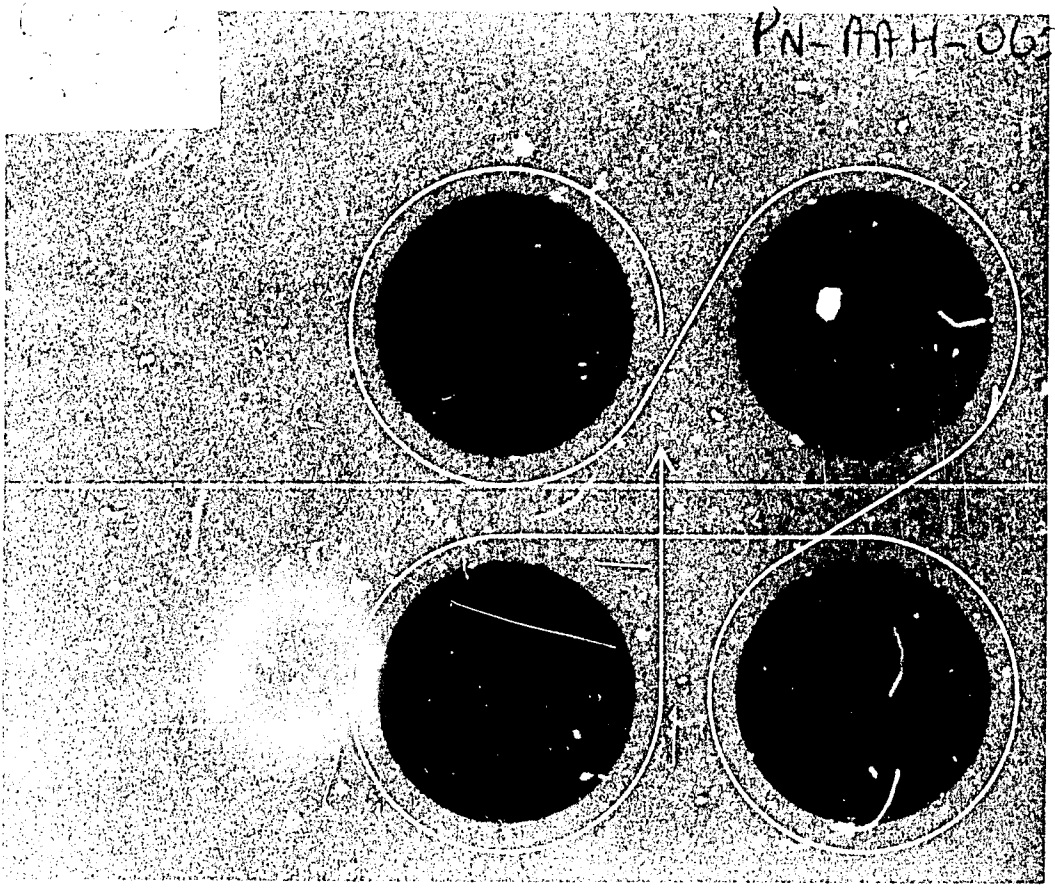
CORNELL INTERNATIONAL AGRICULTURE BULLETIN 37

PN-AAH-062



POTASSIUM FERTILITY IN OXISOLS AND ULTISOLS OF THE HUMID TROPICS

A summary of cooperative projects carried out by
Centro de Pesquisa Agropecuaria dos Cerrados, Planaltina, Brazil
University of Puerto Rico, Rio Piedras, Puerto Rico
Soil Research Institute, Kumasi, Ghana
Yurimaguas Experiment Station, Ministerio de Agricultura, Yurimaguas, Peru
North Carolina State University, Raleigh, North Carolina
Cornell University, Ithaca, New York

NEW YORK STATE COLLEGE OF AGRICULTURE AND LIFE SCIENCES
A STATUTORY COLLEGE OF THE STATE UNIVERSITY
AT CORNELL UNIVERSITY, ITHACA, NEW YORK

With modern methods of travel and communication shrinking the world almost day by day, a progressive university must extend its campus to the four corners of the world. The New York State College of Agriculture and Life Sciences at Cornell University welcomes the privilege of participating in international development — an important role for modern agriculture. Much attention is being given to efforts that will help establish effective agricultural teaching, research, and extension programs in other parts of the world. Scientific agricultural knowledge is exportable.

A strong agriculture will not only provide more food for rapidly growing populations in less-developed countries, but also a firmer base upon which an industrial economy can be built. Such progress is of increasing importance to the goal of world peace.

This is one in a series of publications designed to disseminate information concerned with international agricultural development.

Contents

Summary and recommendations 3
Introduction 5
Forms and levels of soil potassium in highly weathered soils 5
Soil potassium critical levels 6
Potassium response curves 11
Determining appropriate levels for maintenance applications of potassium fertilizer 15
- Crop removal of K 15
- Leaching losses 17
- Release of K by soil minerals 22
- Potassium balance measured in the field 24

Interactions of other nutrients with potassium 25
- Effects of other cations on soil solution K 25
- Effects of other ions on K leaching 27
- Effects of other ions on K uptake 30

The effect of potassium fertilizer on other elements 32
- Direct potassium effects 32
- Other effects 35

Evaluation of nutrient imbalances by foliar analysis 36
Soil testing 38
- Measuring soil potassium 38
- The effect of levels of other ions on the interpretation of K soil test values 40

Literature cited 41
Acknowledgements 45

September 1979

Potassium Fertility in Oxisols and Ultisols of the Humid Tropics*

Edited by K. Dale Ritchey†

SUMMARY AND RECOMMENDATIONS

It is possible to study the fate of potassium fertilizer in highly weathered acid soils of the tropics because low amounts of potassium-fixing and potassium-releasing minerals are present.

Potassium that is not leached or removed from the field in harvested material remains available on the soil exchange complex. On a Dark Red Latosol in central Brazil, leaching began to occur only with the addition of 300 kg/ha K as KCl, which is well above the recommended rate. The potassium content measured in grain crops varied with K status of the soil, from 1.4 percent to 1.9 percent in soybeans and 0.23 percent to 0.39 percent in maize. The amount of K that will be exported from the field as grain is easily calculated, and at least this amount of K must be returned to the soil yearly in order to maintain production. If the stover is also removed, its K content should be taken into account as well. Forages removed from the field may contain 1 percent to 3 percent K on a dry-matter basis.

*This study was supported in part by the United States Agency for International Development under research contracts with North Carolina State University, csd-2806 and ta-c-1236, and with Cornell University, csd-2490, ta-c-1104, and ta-c-1441, and a grant-in-aid to Cornell University from the Potash Institute (Atlanta) and the International Potash Institute (Berne).

†Research Associate, Agronomy Department, New York State College of Agriculture and Life Sciences, Cornell University, Ithaca, N.Y. 14853.

The amount of available K is quite low in these soils, and, therefore, potassium fertilization produces significant results. Yield increases of 100 percent with additions of 125 kg/ha K are typical of responses observed in Central Brazil, the Llanos Orientales of Colombia, and Yurimaguas, Peru. The economic return from investments in potassium fertilizer is often excellent because the cost of potassium fertilizer is relatively low.

It is important to be able to monitor the K status of the soil to know when more fertilizer is needed. Adding more than the crop needs can result in leaching losses or reduced yields when other nutrients are not at optimal levels. The soil critical level, therefore, is defined as that value of K below which yield will increase when potassium fertilizer is added. The critical level for maize on the Dark Red Latosol in Central Brazil was 50 ppm (0.13 meq/100 g soil) K extracted with the North Carolina double-acid extractant from the top 15-cm layer. For the Typic Paleudult studied in Peru, the critical level was 78 ppm (0.20 meq/100 ml soil) in the top 10 cm (by EDTA-modified Olsen extractant). The critical level tends to increase with greater total amounts of exchangeable cations in the soil.

Representative sampling is not always easy because potassium is relatively mobile. After senescence of a row crop such as maize, the potassium present in the stover is washed out of the plant and onto the soil surface by rain. The potassium tends to accumulate in the maize row, the space between the rows being left with a much lower K value. Soil sampling methods must take this into account. Recycling K from the entire root zone onto the soil surface reduces leaching losses. This phenomenon may mask the decrease in K status of the soil as a whole, however, since farmers usually do not sample below the top 10 – 15-cm layer.

If soil levels of magnesium or calcium are low, excessive potassium fertilization can reduce yields. When the soil is deficient in sulfur, the substitution of potassium sulfate for potassium chloride fertilizer is recommended, not only because the sulfate can supply sulfur but because high rates of chloride may actually exacerbate sulfur deficiency. Monitoring nutrient imbalances in the crop by foliar analyses, which can be evaluated with an integrated multinutrient comparison system, appears useful in low CEC soils where more than one nutrient may be out of proportion at the same time. When high rates of fertilizer have been banded too near to the row, damage may occur to seeds or young plants because of the high solubility of potassium chloride fertilizer. Broadcasting corrective doses of K and limiting banded applications of K fertilizer to maintenance doses carefully placed 10 cm beside and 10 cm below the seed will reduce the danger of fertilizer salt injury.

Introduction

The Ultisols and Oxisols occupy extensive areas in the tropics. Favorable rainfall, topography, drainage, and physical characteristics make them suitable for crop production, but low soil fertility, high soil acidity, and deficiencies of phosphorus and some micronutrients have restricted their use. As expanding agricultural activity highlights the sometimes spectacular responses to phosphorus and lime, the importance of potassium fertilization may be overlooked. Hidden deficiencies of this relatively inexpensive nutrient may reduce yields significantly, and these deficiencies will increase with time as low soil reserves are depleted.

The objective of this publication is to summarize results of field research carried out in Brazil, Peru, Puerto Rico, Colombia, and Ghana as it relates to potassium fertilization on Ultisols and Oxisols.

Forms and Levels of Soil Potassium in Highly Weathered Soils

Potassium (K) is present in soils in four forms: *(a)* potassium that occurs as a structural component of such primary minerals as micas and K-feldspars and available only when these minerals are decomposed, *(b)* potassium temporarily trapped between layers of expanding lattice clays such as illite and montmorillonite, *(c)* exchangeable K easily extractable by a neutral salt such as ammonium acetate, and *(d)* a small quantity of soluble K present in the soil solution. The latter two forms are readily available to plants, and they are the ones commonly measured in soil testing. Highly weathered soils of the tropics usually do not contain much of the expanding lattice type of clay minerals and have very small amounts, if any, of primary K minerals capable of decomposing. The extractable potassium is therefore the only important source of K in the soil for growing crops.

Lopes (1975) reviewed 16 publications dealing with potassium response in Brazilian soils. In general, crops responded to potassium fertilizer additions when the extractable K level was less than 0.15 meq/100 g. He analyzed 518 topsoil samples collected from a 600,000-square kilometer area of central Brazil and found that 85 percent of the samples had values of extractable K less than this level. About 40 percent of the samples had less than half of this level.

At the Yurimaguas Experiment Station in the Amazonian jungle of Peru, soil K levels calculated for the top 20 cm ranged from 0.04 to 0.09 meq/100 g (NCSU, 1973). In the Llanos Orientales (eastern plains) of Colombia, mean values of 0.07 meq/100 g K in the surface and 0.035 meq/100 g K in the subsoil were found by Rodriguez (1975). He concluded that levels of K, magnesium (Mg), and particularly iron (Fe) and calcium (Ca) were lower than in most highly weathered soils of the tropics.

Soil Potassium Critical Levels

The critical soil test value can be defined as that level below which yields decline. In general, the critical soil test varies according to the extractant used, the ability of the crop species and variety to obtain potassium from the soil, the particular soil type, and the level of other nutrients present.

The use of Cate-Nelson plots allows rapid determination of approximate critical levels. The graphs are prepared by plotting the relative production of a particular treatment (production relative to another treatment in the same experiment that has sufficient K) against the soil test potassium measured for the treatment. The "Cate-Nelson critical value" can be obtained by graphically dividing the points into groups in which most of the points fall into the lower lefthand quadrant (low relative yields associated with low soil K) and the upper righthand quadrant (relative yields of 80 percent or more indicating little or no response to K).

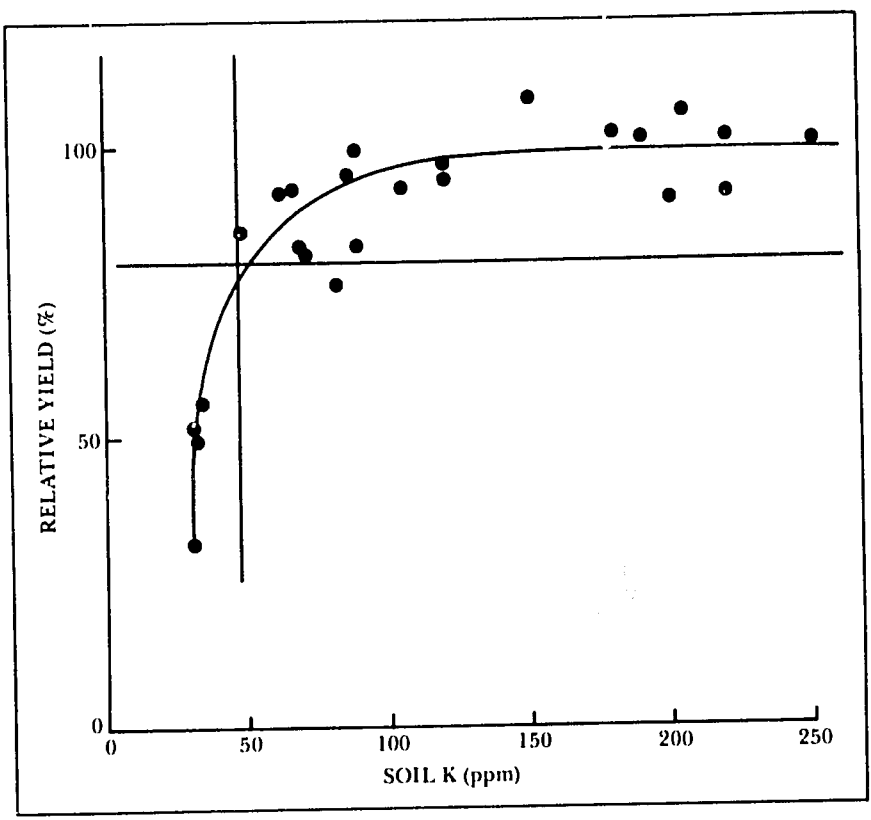


Figure 1. Relative yield per plot (as compared with highest yielding treatment) of Cargill 111 maize as related to double-acid extractable K sampled in the 0–10-cm layer 5 weeks after fertilization on a Dark Red Latosol, CPAC, Planaltina, Brazil.

If phosphorus (P) or another element is present in insufficient quantity to allow the crop to develop well, the amount of potassium present even at low soil test levels may be sufficient to meet the needs of the stunted plant. Additional potassium fertilizer, therefore, would not increase growth, and no response would be measured. Interpreting initial experimentation carried out on highly weathered soils may be difficult because of limitations to crop growth caused by uncorrected deficiencies of other elements.

As mentioned earlier, Lopes (1975) used a critical level value of 0.15 meq/100 g (60 ppm) based on his study of previous Brazilian research. The Cerrado Agricultural Research Center (CPAC) of EMBRAPA uses 50 ppm K (0.13 meq/100 ml) extracted by the NCSU double-acid method (Vettori, 1969) in the surface 15 cm of soil as the level below which remedial applications of K are needed to bring the soil up to acceptable levels. Figures 1 and 2 (maize) and 3 (soybeans) show experimental results collected over three years on a Brazilian Dark Red Latosol whose properties are given in table 1. The critical values are approximately 50 ppm for each year. In a nearby experiment, maize yield increases of 155 percent were obtained on a Red-Yellow Latosol where the original soil level was 0.06 meq/100 g K (23 ppm).

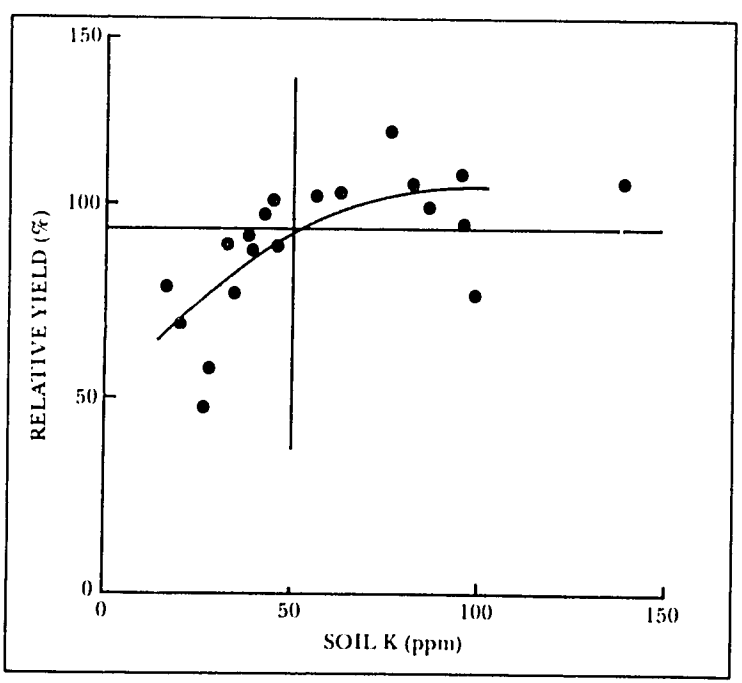


Figure 2. Second year relative yield of Cargill 111 maize (ratio of yield obtained on residual half-plot receiving no fertilization to yield on associated half-plot receiving maintenance potassium) as related to double-acid extractable K measured after first crop. Dark Red Latosol, CPAC, Planaltina, Brazil (Ritchey, de Souza, and Lobato, 1979).

Table 1. Properties of Dark Red Latosol and Red-Yellow Latosol, CPAC, Planaltina, Brazil

Soil designation	*Depth of sample*	*Sand*	*Silt*	*Clay*	*C*	*N*	*Exchangeable cations*				*Total content**		*pH*	
							Ca + Mg	*K*	*Al*	*Σ*	*Ca*	*Mg*	*H_2O*	*KCl*
	cm	*percent*					*me/100g*							
Clayey dystrophic Dark Red Latosol†	0–10	36	19	45	1.8	0.21	0.4	0.10	1.9	2.4	0.2	2.6	4.9	4.2
	10–35	33	19	48	1.2	0.08	0.2	0.05	2.0	2.2	0.2	2.4	4.8	4.3
	35–70	35	18	47	0.9	0.05	0.2	0.03	1.6	1.8	0.2	2.5	4.9	4.2
	70–150	35	18	47	0.7	0.05	0.2	0.01	1.5	1.7	0.2	2.6	5.0	4.4
Clayey dystrophic Red-Yellow Latosol‡	0–15	36	18	46	2.0	0.15	1.0	0.08	1.5	2.6	0.2	0.9	4.7	4.0
	15–37	35	17	48	1.5	0.10	0.6	0.03	1.1	1.7	0.2	0.8	5.0	4.0
	37–70	34	17	49	0.7	0.07	0.9	0.02	0.9	1.8	0.1	0.8	5.0	4.1
	70–140	32	18	50	0.5	0.06	0.6	0.01	0.3	0.9	0.1	0.7	5.2	4.4

*Samples from near potassium experiments. Analyses courtesy of E. Greweling, Cornell University.
†Classified as Typic Haplustox, fine, kaolinitic, isohyperthermic (NCSU, 1973) and as Typic Acrustox (Typic Rhodustox), oxidic, kaolinitic, isothermic (Rodrigues, 1977). Data from Equipe de Pedologia e Fertilidade do Solo, 1966.
‡Classified as Typic Acrustox (Typic Xantustox), clayey, oxidic, kaolinitic, isothermic (Rodrigues, 1977). Data from Rodrigues, 1977.

In work on a Yurimaguas series soil (Typic Paleudult, fine loamy, siliceous, isohyperthermic), table 2, in the Amazon jungle of Peru, Villachica (1978) used the EDTA-modified Olsen extract to characterize plant-available K in the surface 10 cm of the soil. His results supported the use of a 0.2 meq/100 ml critical value as suggested by Hunter (1975). On an Orthoxic Tropohumult in Puerto Rico with 0.61 meq/100 g extractable K, maize showed no response to potassium fertilization (R. H. Fox, 1979: personal communication).

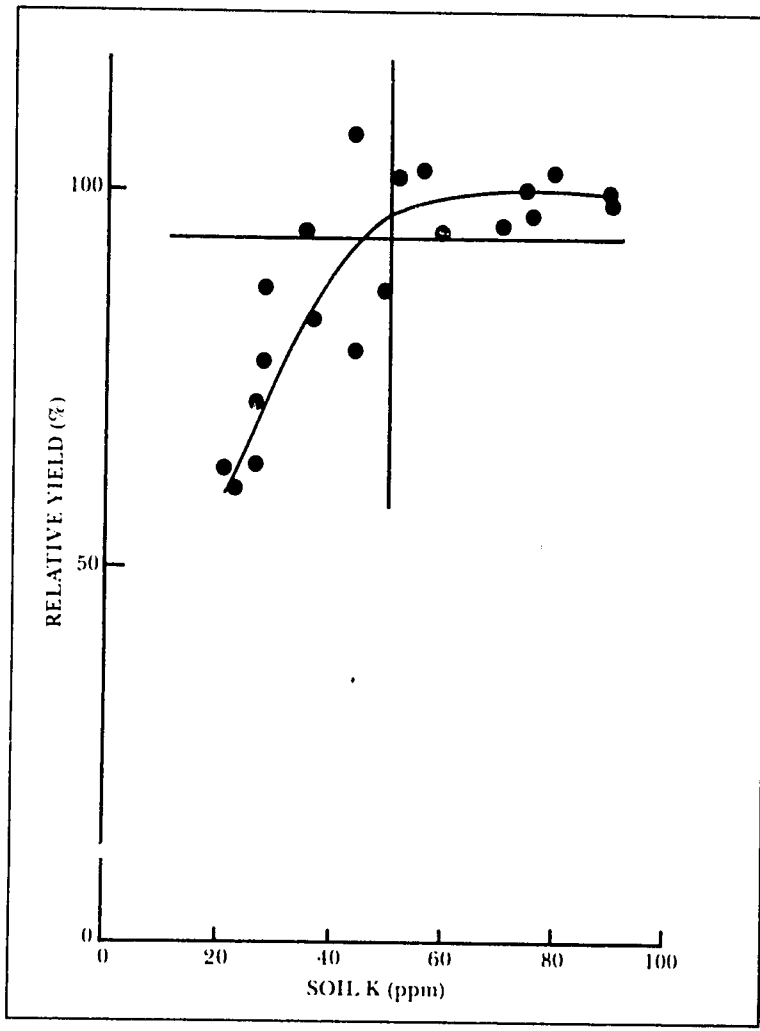


Figure 3. Relative yield per plot (as compared with highest yielding treatment) of Santa Rosa soybeans as related to double-acid extractable K sampled at planting. Subplots sampled had received 0–500 kg/ha K when land was cleared 2 years earlier. Dark Red Latosol, CPAC, Planaltina, Brazil.

The range of critical levels (0.13–0.20 meq/100 g) encountered in these studies supports the conclusions of Boyer (1972) who stated that for tropical agriculture the absolute minimum level of exchangeable potassium was close to 0.10 meq/100 g, but varied from 0.07 to 0.20 meq/100 g depending on the kinds of soil and plants involved.

Table 2. Properties of Peruvian Amazon jungle Yurimaguas series soil (Typic Paleudult, fine loamy, siliceous, isohyperthermic)

Depth	*Clay*	*Sand*	*Silt*	*pH*		*Exchangeable cations*			
				H_2O	*KCl*	*Ca*	*Mg*	*K*	*Na*
cm	*percent*					*meq/100 gm*			
0–5	6.4	80.2	13.5	3.8	3.1	0.84	0.37	0.20	0.03
5–13	10.1	69.6	20.3	3.7	3.5	0.05	0.03	0.04	0.01
13–43	14.9	61.0	24.1	3.9	3.6	0.05	0.03	0.03	0.02
43–77	16.5	57.2	26.2	4.0	3.6	0.03	0.02	0.02	0.01
77–140	24.8	50.6	24.6	4.1	3.5	0.03	0.01	0.03	0.03
140–200	24.1	53.7	22.3	4.4	3.6	0.06	0.03	0.04	0.01

Depth	*Exchangeable acidity (1N KCl)*	*Exchangeable Al (1N KCl)*	*Effective CEC*	*CEC $BaCl_2$–TEA*	*Al saturation*	*Organic C*
cm	*meq/100 gm*				*percent*	
0–5	2.05	1.17	3.49	16.31	33.5	13.4
5–13	2.63	2.14	2.76	10.58	77.5	0.84
13–43	3.11	2.82	3.24	9.77	87.0	0.42
43–77	3.12	2.73	3.20	10.93	85.3	0.29
77–140	4.48	4.19	4.58	12.56	91.5	0.18
140–200	3.80	3.51	3.94	10.18	89.1	0.17

Source: Tyler, 1975.

Potassium Response Curves

Yield response curves can, among other things, show crop production as a function of the amount of the fertilizer element applied or as a function of the soil test value for the element. Such curves give an idea of how much fertilizer will be needed to obtain a desired level of production, assuming that other factors are not limiting.

Maize grain response to K fertilizer grown on a Dark Red Latosol of central Brazil the first year after clearing is shown in figure 4. Maximum yield was obtained with application of 250 kg/ha K; grain production at the 125-kg/ha rate was 89 percent of the maximum. In the second year of the experiment, each plot was split, and one-half received 83 kg/ha K while the other received no additional K. Maize grain yield (fig. 5) from the residual K treatment, which received only the initial application of 125 kg/ha K, was 86 percent of the maximum obtained in the experiment. In the third year, essentially maximum yields of soybean grain were obtained

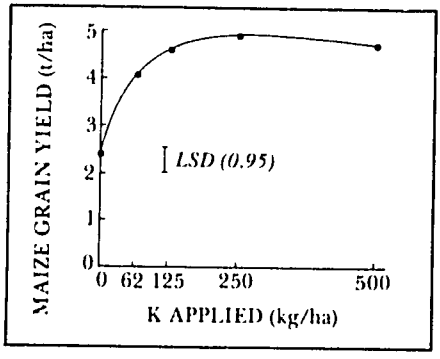


Figure 4. Influence of varying rates of KCl fertilizer (applied broadcast first year after clearing) on yield of Cargill 111 maize grain grown on Dark Red Latosol, CPAC, Planaltina, Brazil (Ritchey, de Souza, and Lobato, 1979).

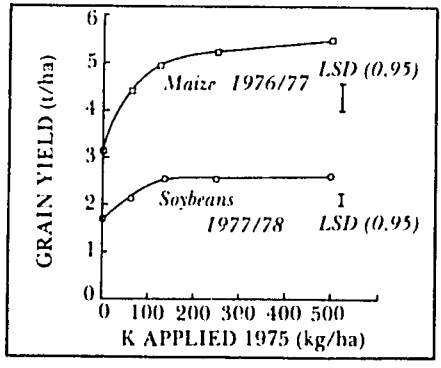


Figure 5. Cargill 111 maize grain yield at 15.5% moisture harvested in 1976/77 and Santa Rosa soybean grain yield at 13% moisture harvested in 1977/78 as a function of the amount of K fertilizer applied in 1975/76. Dark Red Latosol, CPAC, Planaltina, Brazil (CPAC, 1978).

on the same plots, with no additional K after the original 125 kg/ha.

At the Yurimaguas Experiement Station in Peru, rice and maize grown on an old *Andropogon* pasture responded to applied potassium as shown in figures 6 and 7. The major rice increase was obtained with 50 kg/ha K, but maize yields continued to increase with fertilizer applications up to 133 kg/ha K.

Villachica (1978) carried out two crop rotation experiments evaluating responses to five levels of four fertilizer variables in a design where only one treatment was replicated. Potassium fertilizer was applied in amounts ranging from 41 kg/ha to 208 kg/ha per crop. No zero rate was used. The yield of the first crop in the maize-rice rotation is shown in figure 8. Adding K fertilizer at rates greater than 41 kg/ha brought no significant response. The soil K before fertilizing was 0.19 meq/100 g, which is near the critical level for this soil. Similarly, production of soybean grain (fig. 9) did not increase with K fertilizer in excess of 41 kg/ha. The level of extractable soil potassium measured before fertilizing the first crop was 0.13 kg/ha. Adding 41 kg/ha K and incorporating it into 10 cm, if all the K remained on the exchange sites, would have raised the exchangeable K to

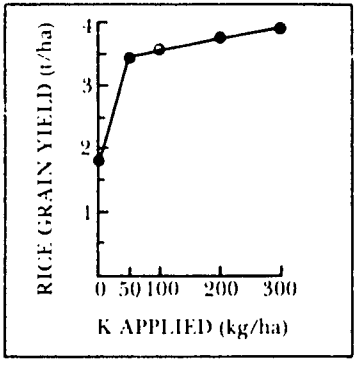


Figure 6. Influence of varying rates of potassium on yields of rice grown on an old *Andropogon* pasture, Typic Paleudult, Yurimaguas, Peru (NCSU, 1975).

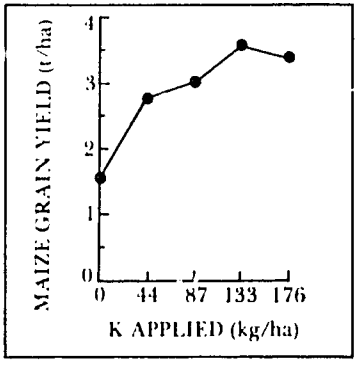


Figure 7. Influence of varying rates of potassium on yield of Cuban Yellow maize grown on an old *Andropogon* pasture, Typic Paleudult, Yurimaguas, Peru (NCSU, 1975).

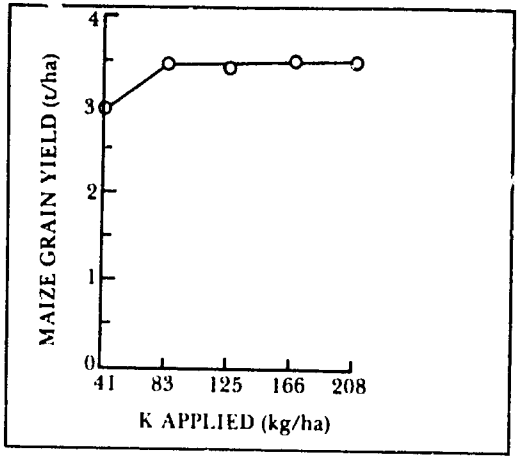


Figure 8. Influence of rates of potassium ranging from 41 to 208 kg/ha on yields of PM-211 maize grown on an old *Andropogon* pasture. Half the K was broadcast at planting and half was sidedressed later. Typic Paleudult, Yurimaguas, Peru (NCSU, 1975).

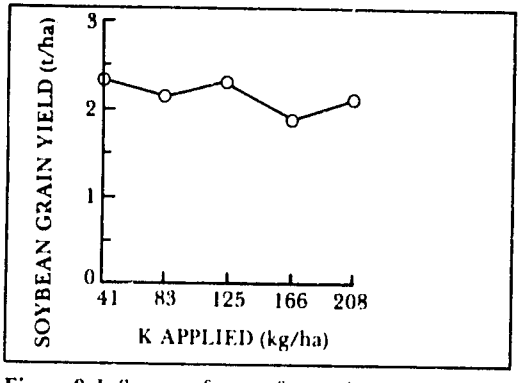


Figure 9. Influence of rates of potassium ranging from 41 to 208 kg/ha on yield of Nacional soybeans grown on an old *Andropogon* pasture. Half the K was broadcast at planting and half was sidedressed later. Typic Paleudult, Yurimaguas, Peru (NCSU, 1975).

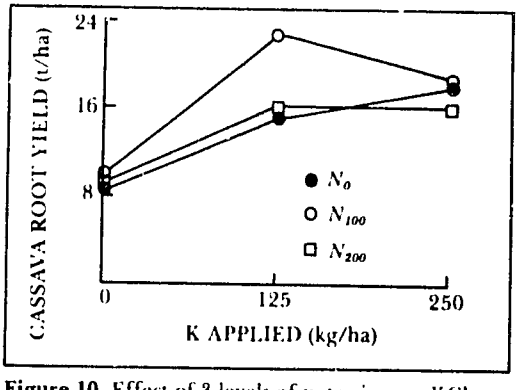


Figure 10. Effect of 3 levels of potassium as KCl on cassava root yields at 0, 100, and 200 kg/ha N on a Typic Haplustox at Tranquero, Llanos Orientales, Colombia (Ngongi, 1976).

0.23 meq/100 g, which is above the critical level. Each succeeding crop in the rotation sequence was fertilized with K at the initial application rate. Rice following maize or soybeans did not show a significant (P = 0.95) response to K, nor did maize following soybeans.

Figure 10 shows cassava root yield data obtained by Ngongi (1976) on a highly weathered acid Oxisol in the eastern plains of Colombia. (Naderman [1973] identified a similar soil as Typic Haplustox, clayey, kaolinitic, isohyperthermic.) The soil properties are given in table 3. Highest yields were obtained at the 100-kg/ha N rate. Application of 125 kg/ha K as KCl resulted in yields of 22.8 t/ha of roots. Applying a total of 250 kg/ha K decreased production at 100 kg/ha N.

Yield responses for three different sources of K are shown in figure 11. Yields tended to improve with increased K to the highest rate of 200 kg/ha K, except for the KCl source where excessive K decreased yields by 1.8 t/ha.

Table 3. Properties of soil used at Tranquero (0–15 cm), Llanos Orientales, Colombia

Soil type	*pH 1:1 H_2O*	*O.M.*	*Soil P**	*SO_4 -S†*	*Extractable cations*				*CEC*	*Al saturation*
					Al^{+++}	*Ca*	*Mg*	*K*		
		%	*ppm*		*(meq/100 g)*					*%*
Virgin	4.9	2.5	1.8	4.5	1.6	0.1	0.05	0.05	6.4	89
Treated‡	4.9	2.4	2.5	—	1.6	0.4	0.08	0.09	6.2	73

Source: Ngongi, 1976.
*Bray II.
†NH_4OAc + HOAc method of Bardsley and Lancaster (1960).
‡After basal application of 0.5 ton lime and 100 kg P_2O_5 per hectare. Lime had 10/1 Ca:Mg ratio.

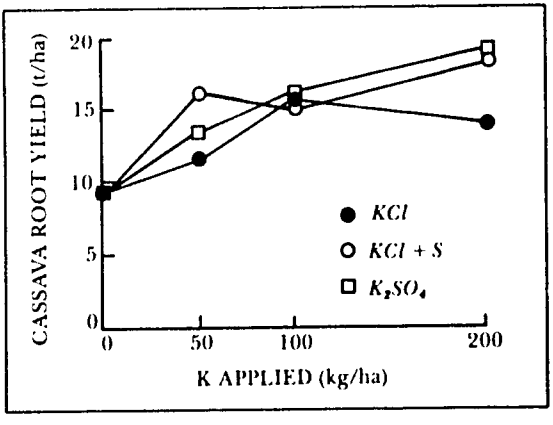


Figure 11. Effect of varying levels of 3 K fertilizer sources on cassava root yields on a Typic Haplustox at Tranquero, Llanos Orientales, Colombia (Ngongi, 1976).

Determining Appropriate Levels for Maintenance Applications of Potassium Fertilizer

To determine the amount of K fertilizer that should be applied for each crop, we need to estimate the amount removed from the field in the crop, the amount dissolved in rain water and leached down through the soil beyond the reach of plant roots, and the amount released from soil mineral reserves. After soil test potassium has been built up to an acceptable level, annual fertilizer applications should, at a minimum, replace the K exported from the field by the crop and lost by leaching. (If a considerable amount of potassium is released each year from mineral K reserves in the soil, annual applications of fertilizer K can be reduced.)

Crop removal of K

The amount of potassium contained in several crops grown under tropical conditions has been studied in both Peru and Brazil (table 4). Field crops commonly remove 50 to 100 kg/ha K when the stover or straw is also harvested. Maize, rice, and sorghum grain do not contain much K, and the K content does not vary significantly with the potassium status of the soil; soybeans, however, contain considerably more K. Stover, in general, is higher in K content than grain and also much more responsive

Table 4. Soil potassium at planting; yield and K content of harvested grain, hay, or roots; yield and K content of crop residual; and total K uptake for several crops on 3 highly weathered soils of the tropics

Soil and treatment	*Soil potassium*	*Product yield*	*Product K content*	*Crop residue yield*	*Crop residue K content*	*Total uptake*
	meq/100 g	*kg/ha*	*%*	*kg/ha*	*%*	*kg/ha*
Typic Paleudult, Yurimaguas, Peru (Source: Seubert, 1975)						
		Rice				
First crop, unfertilized, on burned forest land	0.32*	1,221	0.31	1,846	2.07	42
Second crop						
Unfertilized	0.10	1,938	0.27	2,254	1.91	49
Fertilized with 50-172-40†		2,562	0.27	3,402	1.72	64
		Guinea grass				
Following unfertilized rice on forest land cleared by burning						
Unfertilized		2,111	2.35			50
Fertilized with 50-172-40†		3,460	3.06			108

Table 4. continued

Soil and treatment	*Soil potassium*	*Product yield*	*Product K content*	*Crop residue yield*	*Crop residue K content*	*Total uptake*
	meq/100 g	*kg/ha*	*%*	*kg/ha*	*%*	*kg/ha*
Dark Red Latosol, Planaltina, Brazil						
Brachiaria decumbens *(Source: NCSU, 1974)*						
Second cut after initiation		8,100	1.13			92
Sorghum						
Third crop after clearing 271-70-125†		6,900	0.34	6,496	1.60	127
Maize						
Lime experiment, first crop, 100-130-83† (Source: Gonzalez, 1976)						
0 t/ha lime		2,115	0.40	1,609	.93	23
1 t/ha lime		4,019	0.25	2,593	1.06	38
2 t/ha lime		4,341	0.27	2,906	1.21	47
4 t/ha lime		4,797	0.23	3,093	1.05	44
8 t/ha lime		4,792	0.24	3,252	1.25	52
Phosphorus experiment, first crop (Source: Yost, 1977) 100-560-83†		7,960	0.54	6,070	0.45	71
K experiment, first crop						
200-175-0†	0.08‡	2,328	0.36	2,376	0.28	16
200-175-125	0.23	4,372	0.31	3,685	0.77	40
200-175-500	0.50	4,712	0.39	3,985	1.72	86
Soybean grain						
K experiment, third crop						
No K	0.06‡	1,700	1.45			25§
Residual of 125 kg/ha K	0.12	2,548	1.76			45
Residual of 500 kg/ha K	0.21	2,624	1.92			50
Typic Haplustox, Tranquero, Colombia						
Cassava tubers (Source: Ngongi, 1976)						
Potassium sources × rate experiment						
100-100-0†	0.09	9,500	0.30			29
100-100-50	—	13,800	0.57			79
100-100-100	—	15,800	0.72			114
100-100-200	—	19,100	0.80			153

*Olsen K, 0 – 10 cm, before fertilizer addition.
†Numbers refer to kg/ha of N-P-K applied.
‡Double-acid K, 0 – 15 cm.
§Grain only.

to soil K level. Maize stover grown on Dark Red Latosol the first year after clearing contained 0.28 percent K at low soil K and 1.72 percent K at high soil levels. If rain falls on grain stover after plant senescence, a considerable portion of the K present will wash out of the dead tissues back onto the field. Forages contain high amounts of K, and if the yearly production is removed as hay or silage, a great deal of K can be exported from the field. Although the K content of cassava roots is not extremely high, the large quantity of tubers produced means that a significant amount of K will be lost when they are harvested.

Leaching losses

The amount of K lost by leaching is affected by several factors. The ability of highly weathered tropical soils to retain cations (cation exchange capacity or CEC), measured at the actual pH of the soil in the field, is rather limited. The sum of KCl-extractable cations in the unlimed soils studied is about 2 meq/100 g. When enough lime is incorporated into the top 20-cm layer to raise the pH to 5.5 (thus eliminating most of the harmful effects of soil acidity), the sum of KCl-extractable cations increases to about 4 or 5 meq/100 g.

If a normal-sized application of 100 kg/ha potassium is broadcast over the soil surface and incorporated to a depth of 20 cm, the total K added will be about 0.12 meq/100 g. This amount can be retained without much difficulty. It is quite common, however, to apply K in 5- or 10-cm wide bands, for example, alongside maize rows as they are being planted. In this case, a moderate rate of potassium, about 80 kg/ha, in a band 8 cm wide every 80 cm would add the equivalent of 1.0 meq/100 g K to the soil affected by the band, and this amount cannot be easily retained. A fair proportion will remain in the soil solution and thus be apt to move down through the soil when it rains. The more the rainfall, the deeper the K will be moved. If the plant roots extend to only 20 or 30 cm because of a physical or soil acidity barrier, potassium moved deeper than this will be lost. One reason for the focus on overcoming restrictions on rooting depth is to be able to recover potential leaching losses of valuable soluble plant nutrients like potassium and nitrogen. Figure 12 shows that varying rates of K fertilizer broadcast applied at planting leave different amounts of potassium at various soil depths when measured at the end of one growing season. On a Dark Red Latosol in central Brazil with rates of up to 125 kg/ha K, the loss of K due to leaching below 30 cm was not significant. Additions of 250 and 500 kg/ha K caused leaching to 60 and 90 cm, respectively. Some of the losses observed with the application of 500 kg/ha K broadcast would also occur directly under the band if 50 kg/ha were applied in a band along a maize row.

The data presented in table 5 illustrate the leaching of K in a Typic Paleudult under Peruvian jungle conditions. After felling the jungle vegetation, burning, and adding about 0.17 meq/100 g K as fertilizer, the top 10 cm showed 0.58 meq/100 g K, which is quite a high value for these soils. After 15 months the 0 – 10-cm soil K value dropped to 0.13 meq/100

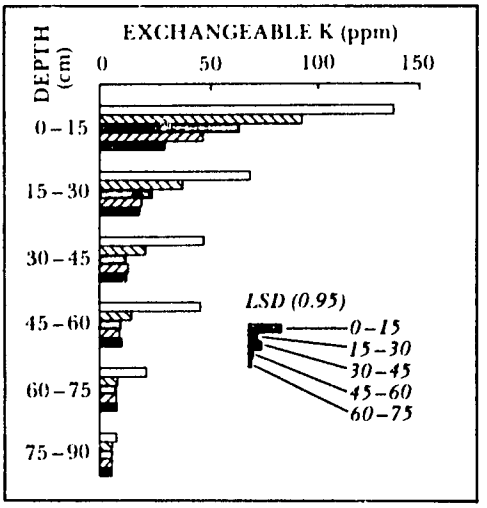


Figure 12. Exchangeable potassium measured at varying depths in Dark Red Latosol after first crop, for 5 levels of potassium chloride fertilization, CPAC, Planaltina, Brazil (de Souza et al., 1979).

Table 5. Potassium retained in top 10 cm of soil* before cropping, after cropping, and with varying K treatments on a Typic Paleudult, Yurimaguas, Peru

Source of K	*Treatment with K fertilizer*		*Treatment without K fertilizer*	
	kg/ha			
First and second crops				
Soil K measured before first crop	338		338	
Contribution from fertilizer	160		0	
Amount removed by first crop (rice)	−96		−84	
Amount removed by second crop (maize)	−53		−53	
Total	349		201	
Soil K measured after second crop		111		111
Amount assumed lost by leaching	238		90	
Third crop				
Soil K measured after second crop	111		111	
Contribution from fertilizer	80		0	
Amount removed by third crop (soybeans)	−12		−12	
Total	179		99	
Soil K measured after third crop		117		76
Amount assumed lost by leaching	62		23	

Source: Villachica, 1978.

*Calculated by measuring Olsen-EDTA extractable K found in top 10 cm — with or without potassium fertilizer — before cropping, after 1 crop each of rice and maize, and after crop of soybeans and comparing these values with total amount of K added in fertilizer and harvested in crops.

g K in the residual potassium treatment and to 0.20 in the treatment receiving 80 kg/ha maintenance fertilizer per crop. Taking into account the 161 kg/ha and 149 kg/ha K taken up by the three harvested crops, the 0–10-cm layer lost 300 kg/ha K in the maintenance fertilized treatment and 113 kg/ha K in the residual K treatment over the 15-month period. Whether later crops would have roots deep enough to recover some of this leached potassium depends on the presence of chemical or physical barriers to root penetration for each species. Other data from these same soils indicate that the potassium probably leaches quite deep.

Figure 13 shows that within one month after burning, soil potassium down to the 30–50-cm depth was as much as three times higher than its preclearing value. Six months later, the subsurface K level had returned to its original value. Apparently, the potassium that had been added to the soil by the process of clearing and burning was leached out quite rapidly. The nitrate and ammonium nitrogen levels in the soil tended to follow a similar pattern, some K possibly having moved in the nitrate form.

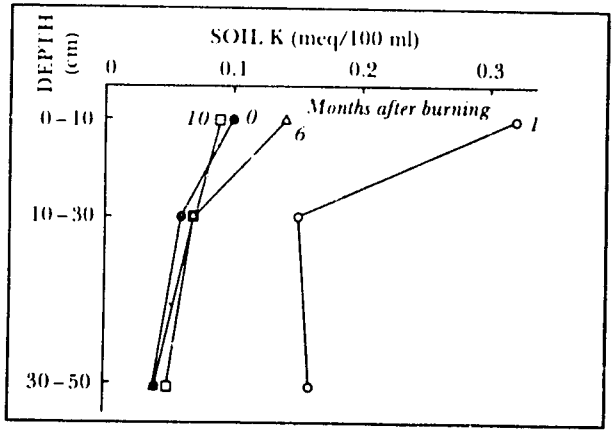


Figure 13. Extractable K measured before burning and at 1, 6, and 10 months after burning and clearing 17-year-old jungle vegetation on a Typic Paleudult at Yurimaguas, Peru (Seubert, 1975).

According to the data in table 6, which takes into account the K harvested in the first rice crop, about 185 kg/ha of soil K was lost in the top 50 cm during the six months after clearing. The magnitude of loss decreased as the level of exchangeable K diminished; little or no leaching loss occurred between the sixth and tenth months. In fact, a small net increase in K appeared in the system, although it was probably not statistically meaningful because of the variability in measurements.

Growing plants contain large amounts of potassium and thus provide a mechanism for minimizing leaching losses. To produce fruit containing 50 to 200 kg/ha K, bananas and plantains may take up as much as 800 kg/ha K (de Geus, 1967). As the vegetative parts of cassava plants begin to die, total potassium content declines (fig. 14). On the 226th day after emergence, the plants contained 310 kg/ha K; but by the 315th day, the

Table 6. Olsen-EDTA extractable K in 0–50-cm layer measured 0, 1, 6, and 10 months after burning for first 2 rice crops on a Typic Paleudult, Yurimaguas, Peru*

Source of K	*Soil K*	
	kg/ha	
Soil K measured before clearing†	117	
Soil K measured after burning†		368
Net increase due to treatment‡	251	
First rice crop		
Soil K measured before planting†	368	
Amount removed by crop	−42	
Total	326	
Soil K measured 6 months after burning†		141
Amount assumed lost by leaching	185	
Second rice crop		
Soil K measured before planting†	141	
Amount removed by crop§	−49	
Total	92	
Soil K measured 10 months after burning (1 month before harvest)†		129
Net increase	37	

Source: Seubert, 1975.

*Changes in K in 0–50-cm layer calculated from changes in soil content and amounts removed by the 2 crops. Rice crops followed continuous rice-cropping system (tilled, unfertilized treatment).
†CV of 18%, 14%, and 37% for 0–10 cm, 10–30 cm, and 30–50 cm, respectively.
‡Increase primarily due to rain washing potassium from dead vegetation; K contained in ashes added 38 kg/ha K (CV of 47%).
§CV of 31%.

total was only 223 kg/ha K, and of this, 87 kg/ha was present in dry leaves and petioles. K, which is not chemically bound in plant tissues, can be easily washed out from senescent material by rainwater and thus returned to the surface of the soil.

The beneficial role of the maize plant in reducing leaching losses is illustrated by the soil test K values observed for the 125-kg/ha K treatments on the clayey Red-Yellow Latosol (table 7). The stunted, nitrogen-deficient plants that received 125 kg/ha K without nitrogen did not take up much potassium. The extra potassium remained in the soil, subject to leaching. A pulse of K was observed in the 15–30-cm layer at midseason. In the postharvest sampling, this pulse had moved to the 60–75-cm layer, where it was shown as a 10-ppm increase in K observed between the two times of measurement. In contrast, the healthy plants that received 125 kg/ha K along with sufficient nitrogen took up more of the potassium during the growing season, and at maturity the rain redeposited part of this K on the soil surface. Less K was lost through leaching.

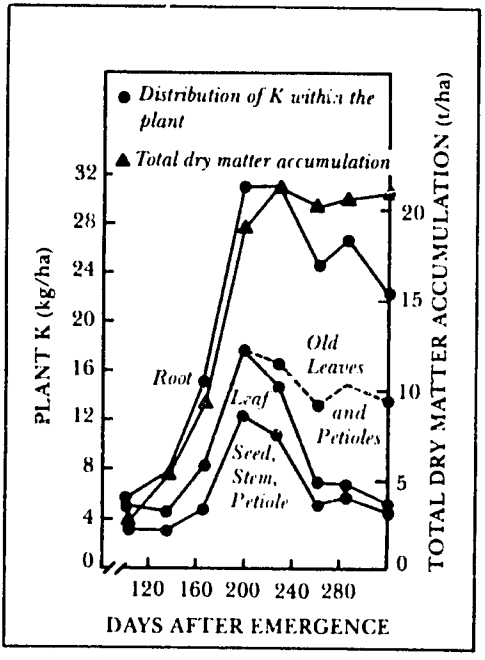


Figure 14. Distribution among cassava plant parts of potassium uptake, measured at Turrialba, Costa Rica. Data from Oelsligle and McCollum (NCSU, 1975).

Table 7. Changes in soil potassium ppm* at various soil depths for 3 different fertilizer treatments on a Red-Yellow Latosol, CPAC, Planaltina, Brazil

	Fertilizer K applied (kg/ha)†		
Depth	*0*	*125*	*125-N*
cm	*ppm*		
0–15	+6	+12	+8
15–30	−5	−6	−32
30–45	−1	−6	−1
45–60	0	+1	−6
60–75	−2	+5	+10
75–90	0	0	+1

Source: Ritchey et al., 1977.

*Calculated by subtracting postharvest value from midseason value, first year of cultivation.
†Fertilizer treatments of 0, 125 kg/ha K as KCl broadcast plus nitrogen, and 125 kg/ha K without nitrogen.

Release of K by soil minerals

According to data summarized by Black (1968), the average total K content of all farmland in the U.S. is 8,000 ppm, whereas the more weathered soils of the southeastern U.S. Coastal Plain have less than 3,000 ppm. Rodriguez (1975) studied levels of total potassium in soils of the Llanos Orientales of Colombia and obtained values ranging from 700 ppm to 5,000 ppm, the majority falling between 1,500 and 2,000. Weaver (1975) analyzed soils from six locations in the Cerrado vegetation area of Central Brazil and found values of total K of 664 to 8,053 ppm in the clay fraction of the surface 15 cm.

Values for total K measured in soil samples collected at the CPAC Cerrado research center near Brasilia are shown in Table 8. In the clay fraction of the loamy-textured Red-Yellow Latosol, 4,000 ppm K were detected; on the clayey Dark Red and Red-Yellow Latosols, as little as 144 ppm K were found. Weaver (1975) suggested that the relatively high amount of mica he observed in several soils of Central Brazil may have originated from parent material with a high initial content of dioctahedral mica. A portion of this material may have persisted during soil development, perhaps by the same process reported by LeRoux (1973), who attributed the presence of mica in some South African Oxisols to peripheral chloritization (replacement of interlayer K around the edges of the particle by aluminum-hydroxy polymers) which protected the original mica core.

Less than one-third of the medium-textured Red-Yellow Latosol sample was clay. If the resistant K minerals were present in the finer sizes, as suggested by Rich (1972), the total K on a whole-soil basis might be significantly less than in the clay fraction reported, as indeed is the case for whole-soil sample numbers 11 and 12 analyzed by Kronberg (1977).

The rate of decomposition of the K-containing minerals determines the amount of K available to any one crop. This rate is controlled by several factors, including the concentration of K in the soil solution and the nature and fineness of the soil minerals.

One way to evaluate the amount of K made available under normal agricultural conditions is to measure the potassium content of crops produced on sites where K fertilizer has not been added and to compare this figure with the measured decrease in extractable K. To date, data from field experiments carried out on the Peruvian Typic Paleudult and Brazilian Dark Red Latosol indicate that, within the errors of measurement, the potassium removed from the soil under field conditions can all be accounted for by decreases in the extractable K measured. Thus the hypothesis is supported that little K is being released from nonexchangeable sources. Rodriguez (1975) found very little change in native extractable soil potassium after up to 11 wetting and drying cycles of 26 days each for the 18 soils of the Colombian Llanos that he studied.

In exhaustive greenhouse cropping of two Dark Red Latosols collected at CPAC, the amount of K contained in five consecutive maize crops was equal to 100 percent of the decrease in exchangeable K for the cerradão-

phase sample and 240 percent for the cerrado-phase sample (João Mielniczuk, 1979: personal communication). It is not known whether K released under the very low soil potassium levels associated with exhaustive cropping is a significant source of K for crops grown under agronomically feasible conditions (i.e., semiintensive agriculture with other expensive inputs). It has been suggested that K-mineral breakdown may become appreciable only at soil solution concentrations so low that they are inadequate to sustain normal agriculture.

Table 8. Total and exchangeable K measured for several soils of CPAC, Planaltina, Brazil

Soil and sample number		*Depth*	*Soil Potassium*	
			Total	*Exchangeable*
		cm	*ppm*	
Clayey Dark Red Latosol, CPAC*		0–15	285	27
		15–30	279	20
		30–45	288	16
		45–60	294	12
Clayey Red-Yellow Latosol, Plateau, CPAC*		0–15	144	31
		15–30	134	23
		30–45	155	12
		45–60	173	8
Clayey Dark Red Latosol, CPAC†	16	0–15	250	
	17	15–30	170	
	4	0–15	330	
	6	15–30	250	
Clayey Dark Red Latosol, cerradão phase, CPAC‡	2		641	78
Clayey Dark Red Latosol, cerrado phase, CPAC‡	1		1,196	47
Medium-textured Red-Yellow Latosol, CPAC‡	5		2,037	47
Medium-textured Red-Yellow Latosol, CPAC	17	0–20	4,000	23
<2μm (clay fraction)§	19	100–120	3,500	4
Medium-textured Red-Yellow Latosol, CPAC†	11	0–15	1,080	
	12	15–30	900	
Low Humic Gley (Aeric Tropaquept) CPAC†	3	0–15	580	
	2	15–30	500	

*Analysis by HF digestion. Dark Red and Red-Yellow Latosol samples taken from near the K experiments reported in this bulletin.
†Analysis by X-ray fluorescence (fusion, ignited samples). Samples 16 and 17 from near K experiment. Samples 4 and 6 from near zinc x lime experiment reported in this bulletin (Kronberg, 1977).
‡João Mielniczuk (Faculdade de Agronomia, Univ. Federal do Rio Grande do Sul, Porto Alegre) 1979: personal communication.
§Weaver (1975). Total K values were back-calculated from the percentage mica data which Weaver reported as 10 times the K_2O found by HF-H_2SO_4 digestion.
(Exchangeable K values courtesy of M. G. Cline.)

Potassium balance measured in the field

Working on a newly cleared Dark Red Latosol, de Souza et al. (1979) prepared a potassium "balance sheet" to see if changes in soil K could be accounted for by the amounts of potassium added and removed. The amount of K removed by the grain and stover of the maize crop and the increases in K levels found in the soil were calculated for five levels of K fertilizer application. The results shown in table 9 indicate that, within experimental error, practically all the potassium was accounted for by leaching, plant uptake, and changes in extractable K in the soil.

With this data, we are better able to make recommendations for the amounts of K fertilizer that should be applied annually. CPAC recommends that corrective applications of 83 kg/ha K and 42 kg/ha K be made for soil test values of 0–25 ppm and 25–50 ppm, respectively. In addition, each crop should receive a maintenance application of 25 kg/ha K banded.

These recommendations are supported by the results of the first three years of cropping on the Dark Red Latosol at CPAC. Application of a total of 125 kg/ha K maintained production at near-maximum levels, as shown in figures 4 and 5.

Table 9. Percentage of recovery of potassium* on a Dark Red Latosol, CPAC, Planaltina, Brazil

At planting		*At harvest*		
Fertilizer K added	*K originally present in soil, 0–90 cm*	*K remaining in soil, 0–90 cm*	*K removed by maize crop*	*Calculated K recovery*
kg/ha				*%*
0	140±7	127±14	16±7	102±13
62	132±12	155±16	29±4	95±7
125	136±7	188±24	40±7	87±9
249	138±22	275±28	76±15	91±4
498	151±37	498±94	86±27	90±9

Source: de Souza et al., 1979.

*Calculated by comparing K originally present in soil at 0–90 cm and K added as fertilizer, with K present in soil after harvest and K contained in maize grain and stover.

Interactions of Other Nutrients with Potassium

Knowing the effects of other nutrient ions on potassium nutrition is important not only for maximizing the efficiency of K use, but also for understanding how levels of other ions will change K fertilizer recommendations to be given to farmers.

Nutrient imbalances affecting K nutrition originate in the amount and distribution of ions on the exchange complex, but their effects occur at several stages. The concentration and activity of K in soil solution is determined both by the amount of K on the soil complex and by the other ions present. The ability of the plant root to take K up from the solution depends not only on the amount in the solution but also on the amount and type of other ions present. Aluminum and manganese, which are often present in significant concentrations in acid soils, can seriously affect the healthy operation and growth of crop roots and interfere with K uptake. Rubidium (Rb^+), sodium (Na^+), and ammonium (NH_4^+), which have the same charge as and are similar in size to the potassium ion, apparently compete with K^+ at the root surface; it is not clear whether the divalent ions calcium and magnesium can compete as effectively.

Inside the plant, the amounts of other ions affect the efficiency with which K acts and the amounts of K needed for maximum production. The addition of a nutrient element previously present in quantities insufficient for maximum growth can increase the demand for potassium. Increases in K requirements resulting from heavier applications of N, P, or micronutrient fertilizers are not uncommon in the tropics.

Effects of other cations on soil solution K

Rodriguez (1975) found that adding lime equivalent to twice the exchangeable Al present in 14 soils of the Colombian Llanos Orientales did not, in general, significantly change the amount of extractable potassium even after 11 wetting and drying cycles of 26 days each.

Goedert, Corey, and Syers (1975), working on Oxisols and Ultisols of southern Brazil, found that liming decreased the amount of potassium in solution while maintaining approximately the same level of exchangeable K. The buffering capacity for potassium increased. They concluded that although liming would decrease potassium susceptibility to leaching, it might also reduce solution potassium to levels where plants might suffer K deficiencies.

Gonzalez (1976) studied the soil solution of a Dark Red Latosol which had received lime rates of 0, 1, 2, 4, and 8 t/ha incorporated to 15 or 30 cm. Figure 15 shows the relationship between exchangeable Ca + Mg and the ratio of soil solution K to exchangeable K sampled during tasseling of the first maize crop. Soil solution potassium values averaged about 0.63 meq/liter for the samples that measured 0.33 to 1.15 meq/100 g Ca + Mg. These values correspond to aluminum saturations ranging from 31 percent to 75 percent. In the group of samples with 4 percent to 5 percent aluminum saturation (Ca + Mg between 2 and 3 meq/100 g), the solution

K dropped to 0.34 meq/liter; and for Ca + Mg levels over 4 meq/100 g, the solution K remained practically unchanged at 0.32 meq/liter. It is not clear whether further increases in exchangeable Ca + Mg would have significantly reduced the solution K.

Additional liming above the pH at which all the aluminum has been neutralized would increase the effective cation exchange capacity (CEC) by deprotonation of pH-dependent sites; it is not known if this treatment would have the same effect on K in soil solution as the reactions in which CEC was increased by removing aluminum. Goedert, Corey, and Syers point out that where organic matter is the main source of cation exchange capacity, the increase in K-buffering capacity as CEC is increased by liming should not be as rapid as where neutralization of Al is involved.

In some temperate-region soils, certain clay minerals "fix" potassium, particularly when high rates of lime are applied. This detrimental aspect of liming can be eliminated from consideration for most of the highly weathered soils of the tropics because the clays responsible are not present.

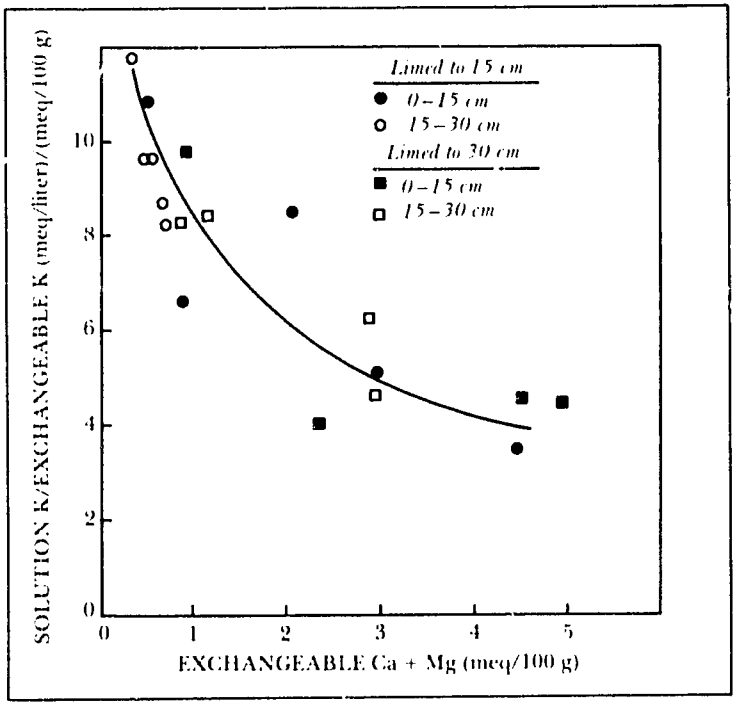


Figure 15. Ratio between K measured in soil solution and exchangeable K found on soil complex as affected by level of exchangeable Ca + Mg on soil complex for rates of 0, 1, 2, 4, and 8 t/ha lime incorporated to 15 or 30 cm. Depth of sample (0–15 cm or 15–30 cm) or depth of lime incorporation had no apparent effect on location of curve. Samples collected at maize tasseling stage of first crop after clearing on a Dark Red Latosol, Planaltina, Brazil (Calculated from Gonzalez, 1976).

Effects of other ions on K leaching

Liming should reduce the potential for loss of K by leaching. It increases the cation exchange capacity by raising the pH and thus provides more exchange sites for retention of K. Moreover, liming precipitates exchangeable aluminum and thus facilitates retention because K can compete more successfully with the calcium ions that remain on the exchange complex than with the aluminum that was originally there. Mielniczuk (1977) showed that the K-buffering capacity of a Dark Red Latosol at CPAC increased greatly when limed to pH 6.0.

In 1972, a lime × zinc experiment was established on a virgin Dark Red Latosol; limed with 7.5, 15, and 22.5 t/ha lime (with a $CaCO_3$ equivalent of 100 percent); fertilized (the blanket fertilizer application included 83 kg/ha K); and planted to maize. After harvest of the first crop, the experiment was planted to Star grass which was irrigated during the dry season but received only a minimum of maintenance fertilizer. Samples in 1976 indicated no significant effect of the lime rates on soil K distribution to 90 cm (table 10).

In many experiments where the lime rate is varied, the total yield and therefore the uptake of K from the field may be affected by the lime treatment. As the lime rate is decreased, the yield also declines, and therefore more unused potassium remains in the soil system. This residual K complicates the interpretation of soil K distribution, unless the observations are limited to a range of lime rates that has little effect on yield or K uptake.

Table 11 shows how lime applied at five rates to a Dark Red Latosol affected the distribution of K after five crops of maize and one of sorghum. Yields increased greatly with the first lime increments, but yields

Table 10. Average extractable soil K* as a function of various rates of lime on a Dark Red Latosol, CPAC, Planaltina, Brazil

Depth	*Lime applied (t/ha)*			*LSD (0.95)*
	7.5	*15*	*22.5*	
cm	*ppm*			
0–15	8.3	7.8	9.8	0.9
15–30	8.0	7.7	7.0	1.9
30–45	6.3	5.3	5.3	1.8
45–60	4.2	4.2	4.0	1.5
60–75	3.5	3.5	3.0	1.4
75–90	3.2	2.8	3.5	2.3
Mean	5.6	5.2	5.4	

*Sampled November 1976, 4 years after lime was applied in 1972 in a lime × zinc experiment. Average of 3 zinc rates and 2 replications.

did not differ significantly between the 4- and 8-t/ha rates. The experiment received from 83 kg/ha to 125 kg/ha K per crop. At the lower lime rates, lime had an obvious negative effect on total K present in the profile; this effect was due principally to the greater amount of K removed in the grain and stover of the larger crops that resulted from liming. Total production from the 4- and 8-ton rates were practically equal, and the distribution of K was also similar. If lime has any effects on leaching, one might expect a doubling of the lime rate to 8,000 kg/ha to cause some change in K distribution in the profile. The absence of this change suggests that, under the conditions studied, lime did not adversely affect leaching. In fact, the greater depth of rooting that may be associated with increased liming (Bouldin, 1979) may have improved the overall efficiency of K use.

Calcium or magnesium applied in forms other than carbonates or oxides may cause more leaching of potassium because these two elements increase the number of cations competing for space on the soil exchange complex without significantly raising the pH. There would also be a greater number of mobile anions which, when leached, will remove a cation. Fig. 16 shows the effects of gypsum (calcium sulfate) applications made on a Dark Red Latosol to ameliorate acid conditions in subsurface layers. In addition to the desired downward movement of calcium, marked leaching of magnesium and potassium also occurred.

Similarly, Villachica (1978) reported that adding 18 kg/ha Mg as magnesium sulfate (equivalent to 0.15 meq/100 g in the surface 10 cm) to a Typic Paleudult had a depressing effect on extractable K (K = 0.16 –

Table 11. Extractable soil K* at 8 depths as a function of various rates of lime applied to a Dark Red Latosol, CPAC, Planaltina, Brazil

Depth	*Lime incorporated 0–15 cm (t/ha)*					*LSD (0.95)*
	0	*1*	*2*	*4*	*8*	
cm	*ppm*					
0–15	20	22	22	18	22	5
15–30	20	19	16	13	11	6
30–45	12	10	9	8	8	4
45–60	12	8	7	6	6	2
60–75	11	10	7	6	5	3
75–90	13	9	6	6	6	3
90–105	17	11	7	6	6	3
105–120	25	12	8	7	6	5
Mean	16	13	10	9	9	
Average grain yield in kg/ha	2,220	3,280	3,480	3,900	3,920	

*Sampled June 1977, 5 years after lime was applied in a rates × depth of incorporation experiment. Average of 5 replications.

0.021 Mg, significant at 0.95). He suggested that the two cations may compete for sites on the exchange complex.

It can be concluded that liming will probably decrease potassium leaching losses because it raises the exchange capacity of the soil, lowers the concentration of K in the soil solution, and may increase the crop uptake of K by reducing aluminum toxicity. On the other hand, adding calcium or magnesium sulfate would heighten competition for exchange sites and increase the level of K in the soil solution subject to leaching. If the calcium sulfate additions result in deeper plant roots, however, the potassium losses may be recuperated.

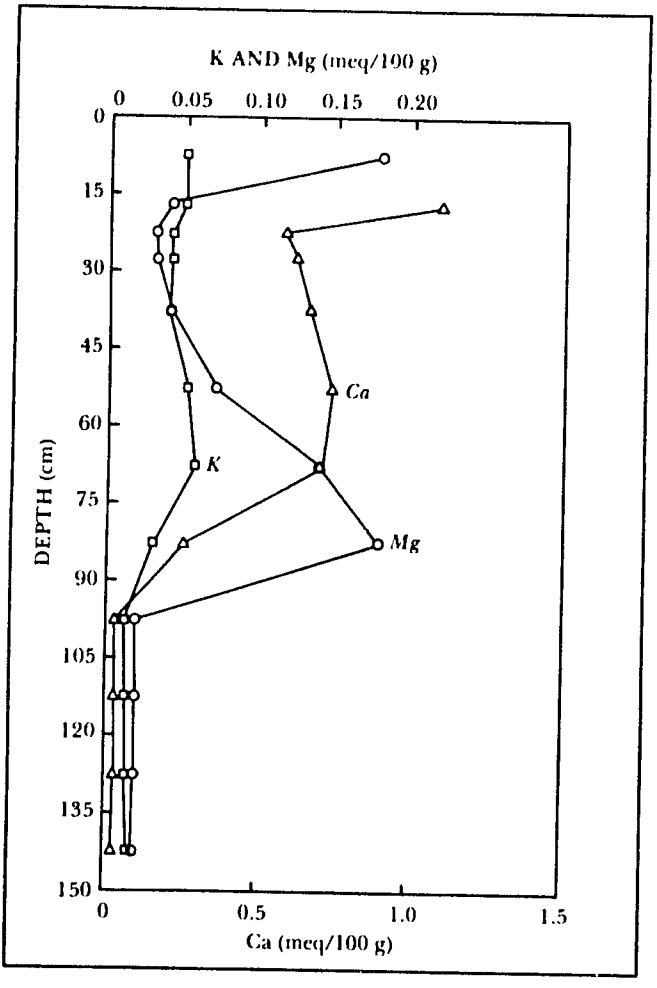


Figure 16. Laboratory distribution of K, Mg, and Ca with depth, following incorporation of 1400 kg/ha Ca as gypsum in 0–15-cm layer of a Dark Red Latosol and leaching with 1500 mm water (Ritchey, de Souza, and Lobato, 1978).

Effects of other ions on K uptake

Many laboratory studies have focused on the mechanisms of K uptake by the root and the effects of competing ions. Hiatt and Leggett (1974) and Barber (1968) have reviewed the sometimes confusing literature.

There is some measure of agreement that monovalent ions (Na^+, Rb^+, and NH_4^+) can compete with K^+ at the root surface. When the level of Ca^{++} is quite low, additions of calcium will increase K uptake, apparently by improving the structural integrity of root membranes (Mengel, 1968). Competitive effects of higher concentrations of Ca^{++} and Mg^{++} are less easily demonstrated. Although several groups have proposed using the soil solution activity ratio $K/\sqrt{(Ca + Mg)}$ to evaluate availability of K to plants, Barber (1968) states that little evidence is available to indicate that the ratio can determine K adsorption by roots.

In the liming study carried out on a Dark Red Latosol, Gonzalez (1976) found that calcitic lime rates varying from 0 to 8,000 kg/ha had no effect on K content of ear leaves, grain, or stover in three continuous crops of maize, despite a 50 percent decrease in soil solution K (table 4).

In the previously mentioned lime × zinc experiment that received 7.5, 15, and 22.5 t/ha lime, lime rates had no significant effect on the percent-

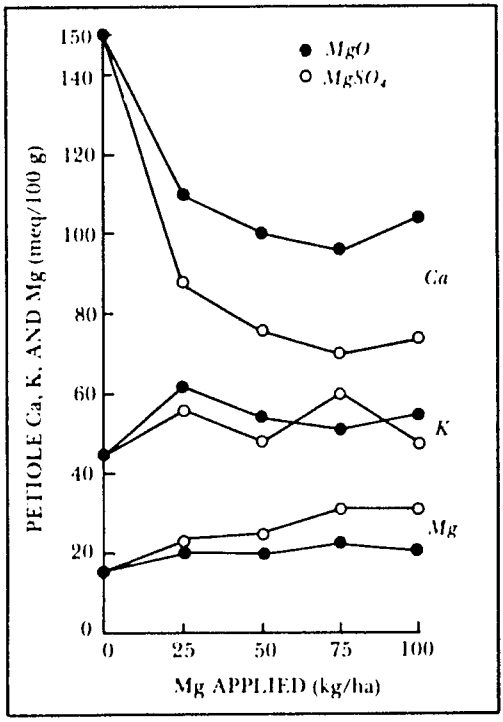


Figure 17. Influence of rates and sources of magnesium on mineral content of cassava petioles 14 weeks after planting at Tranquero, Colombia. MgO source had 16% Mg and 29% Ca (Ngongi, 1976).

age of K in the maize grain harvested, although at the high lime rate, stover K content was significantly different at 0.90 probability from the lower lime treatments. The high lime rates markedly reduced grain yield, at least partially because of an induced zinc deficiency. Applying more zinc increased the yield (NCSU, 1973).

Varying the percentage of calcitic and dolomitic lime applied to a Dark Red Latosol to obtain soil Mg/K ratios ranging from 0.45 to 4.8 did not affect the K content of soybean grain, but potassium content of the soybean leaves decreased at the high magnesium rate (significant at 0.90). This difference cannot be attributed to a dilution effect because the grain yield was also slightly lower with the high magnesium treatment.

The data in figure 17 obtained in the Llanos Orientales of Colombia by Ngongi (1976) indicate that increasing the rate of Mg applied to a Typic Haplustox did not consistently affect the K content of the cassava petioles. Leaf blade and root K were not affected either. Yields were significantly increased by Mg, particularly where magnesium sulfate was the source (fig. 18). The maximum yield of 25.4 t/ha was obtained with 50 kg/ha Mg as sulfate. Yields fell off with further increases up to 100 kg/ha Mg, possibly because of Ca deficiency (fig. 17) or excess sulfur affecting phosphorus intake.

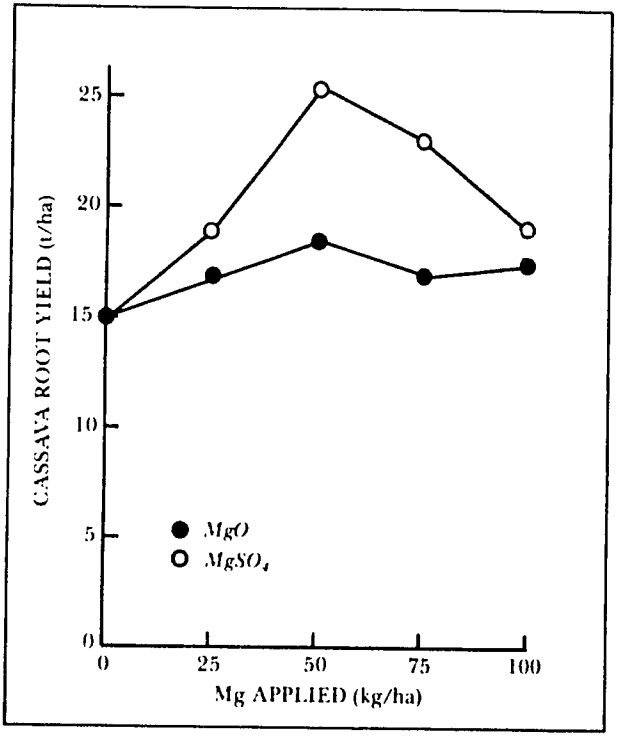


Figure 18. Influence of rates and sources of magnesium on cassava root yields 38 weeks after planting at Tranquero, Colombia (Ngongi, 1976).

The Effect of Potassium Fertilizer on Other Elements

Direct potassium effects

It has long been known that excessive applications of potassium can induce magnesium deficiencies. Unusually high rates of K applied to the Dark Red Latosol reduced Mg content in maize ear leaves (fig. 19).

When 125 kg/ha K fertilizer was applied to a Dark Red Latosol limed to pH 5.2 with low-magnesium limestone, maize stover contained only 0.07 percent Mg. Forage with less than 0.10 percent Mg is considered unsafe because it is one of the factors which causes "hypomagnesemia", a fatal condition in lactating cows characterized by low levels of magnesium in the blood. The K fertilizer treatment resulted in soil K values of 104 ppm in samples collected one month after application. Figure 19 shows that this level of K has lowered the Mg content of the ear leaves of maize growing on soil with adequate magnesium levels. This finding suggests that if less K fertilizer had been applied to the inadequate Mg plots, the Mg content of the maize stover might have been higher.

Villachica (1978) applied 18 kg/ha Mg as magnesium sulfate and 63 kg/ha K as KCl soon after clearing a Typic Paleudult soil which originally had a Mg/K ratio of 1.94. This treatment caused the soil Mg/K ratio to decline to 1.49, which is below the lower limit of about 2 which Boyer (1978) mentions for several tropical crops. After crops of soybeans, rice, and maize were harvested, the soil Mg decreased to 0.07 meq/100 ml, but the soil K increased to 0.27 meq/100 ml because split K applications totaling 125 kg/ha had been applied to each crop. The Mg/K ratio decreased to 0.26. A significant negative effect of K fertilizer rate on Mg accumulation in the soybean grain was observed in the treatments where

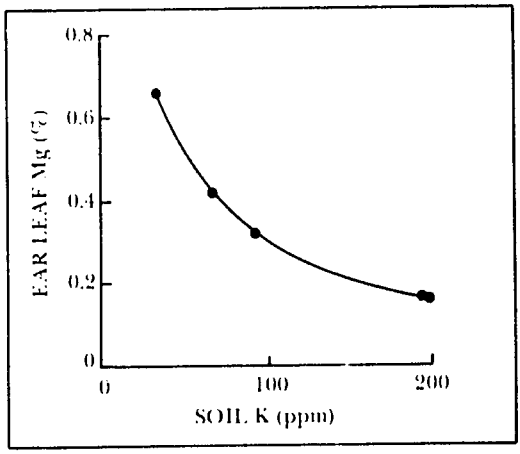


Figure 19. Magnesium content of maize ear leaves at silking as a function of extractable soil K sampled in the 0–10-cm layer 5 weeks after planting on a Dark Red Latosol, CPAC, Planaltina, Brazil. Three tons of lime containing 345 kg/ha Mg were incorporated 6 weeks before planting.

K was varied. Although the relationship between soybean grain yields and exchangeable K was not significant, soil K saturation and yields had a significant negative relationship. The relationship between exchangeable Mg/K and yield was highly significant. It can be concluded that the application of excess K exacerbated the low Mg situation. Rice, the second crop, was not significantly affected by the K-Mg imbalance. Yields of the third crop (maize), however, showed a highly significant relation to the exchangeable Mg/K ratio, although exchangeable K and K saturation effects were not significant. Goedert of CPAC (1978; personal communication) considered soybeans more sensitive to Mg deficiencies than maize.

In a similar experiment, increasing K rates applied to rice following maize caused a significant decline in Mg accumulation, and there was a significant negative K-Mg fertilizer interaction. These relationships support the thesis that K was interfering with Mg nutrition. Calcium accumulation was also adversely affected by K fertilization.

For the first soybean crop, Villachica (1978) proposed that, to avoid yield depression, the soil exchangeable Mg/K ratio should be more than a critical value of 1.2, and exchangeable Mg should be more than a critical value of 0.2 meq/100 ml. For the maize crop following soybeans and rice, he proposed a soil exchangeable Mg/K ratio of 1.2 and an exchangeable Mg value of 0.38 meq/100 mg. These values are consistent with the results of other research work he cited: potato yields on a Spodosol declined when the soil Mg/K was less than 0.8 and soil Mg was 3.0 meq/100 g or below (Hossner and Doll, 1970). Maize yields on Ultisols of Nigeria declined if soil Mg/K was less than 0.8–1.0 when exchangeable Mg was below 0.4 meq/100 g (Lombin and Fayemi, 1978).

Wade (1978) discusses the effect of nutrient imbalance in peanut production on a Typic Paleudult in the Peruvian jungle. His data support the idea that K additions may lower yields by causing a decrease in the plant Ca/K ratio and a resulting decline in shelling percentage (fig. 20). Shelling

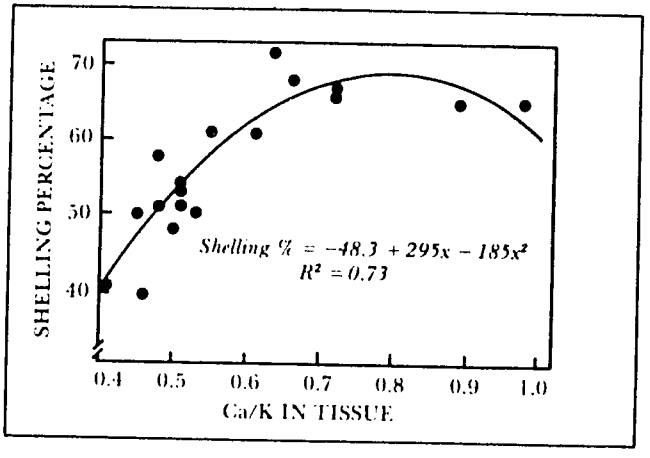


Figure 20. Relationship of shelling percentage of peanuts to Ca/K concentration ratio in whole plant tissue, Typic Paleudult, Yurimaguas, Peru (Wade, 1978).

percentages of less than 60 percent were associated with Ca/K ratios of 0.53 or less. Figure 21, based on data given by Wade, shows that the low Ca/K ratio was caused by high K rates as well as by low Ca. In about half the cases where shelling percentage was less than 60 percent, the tissue Ca was 1.3 percent or more (which at K less than 2.5 percent was adequate); but because of higher K, the Ca/K ratio fell below the critical value, and therefore the shelling percentage was adversely affected.

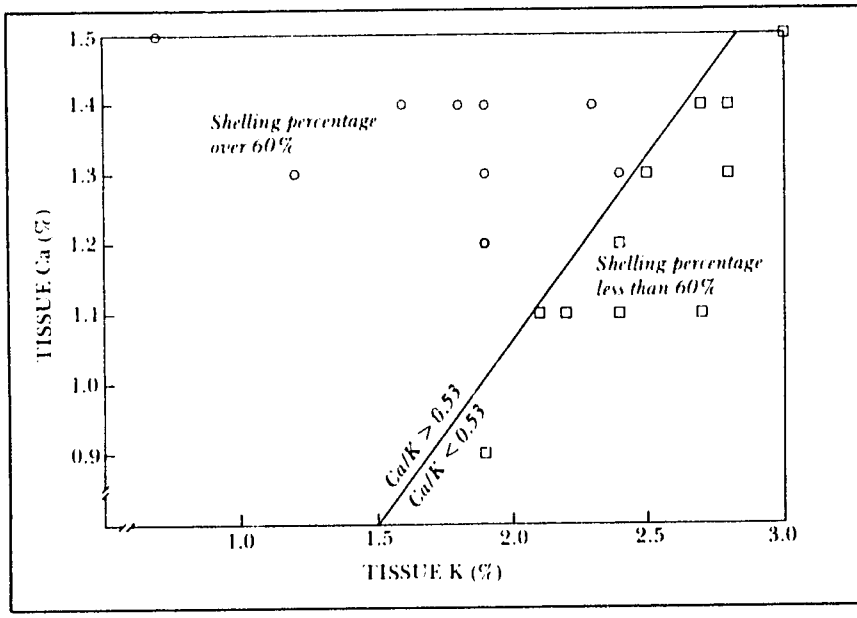


Figure 21. Distribution of Ca/K tissue ratios in peanut plants. For Ca/K ratios greater than 0.53, shelling percentage is uniformly over 60%. Low shelling percentage is associated with Ca/K ratios less than 0.53, which can be caused by low Ca values or by high K values (Wade, 1978).

Ngongi (1976) showed several instances where root yield in cassava was reduced with relatively heavy applications of K fertilizer. As shown in Figure 10, the 100 kg/ha N rate was apparently the most productive, and maximum yield was obtained with application of 125 kg/ha K at this N rate. Application of 250 kg/ha K caused a yield decline of 1.8 t/ha. The content of Mg in the cassava petioles decreased significantly with K fertilization (fig. 22). The K/Mg ratio was even more affected because petiole K increased with higher rates of K fertilizer. The calcium level surprisingly increased with higher K rates. To evaluate the situation in the soil, calculations were made assuming that all fertilizer was uniformly incorporated throughout the top 15-cm soil layer and assuming that all the added fertilizer cations were present on the exchange complex. Obviously, these assumptions are not met because the K and part of the

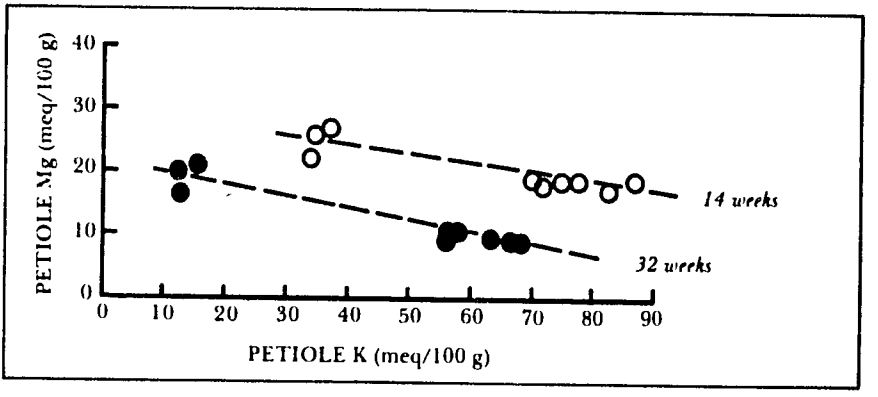


Figure 22. Magnesium content as affected by K content of cassava petioles sampled at 14 and 32 weeks after planting. Increasing K fertilizer applications from 0 to 125 and from 125 to 250 kg/ha raised K in the petiole and decreased Mg (Ngongi, 1976).

phosphorus fertilizer were applied in bands; but the resulting nutrient ratios may still be useful in understanding the balance of nutrients available to the cassava plants. According to these soil calculations, the high K brought the soil Mg/K ratio down to 0.29, which is below the critical value.

Figure 11 illustrates another such case where 200 kg/ha K as potassium chloride (KCl) reduced yield about 1.6 t/ha compared with 100 kg/ha as KCl. According to the soil calculations mentioned above, the ratio of soil Mg to soil K would have been less than 0.4, which is quite low, but because yield decreased only in the KCl treatment, sulfur may have been involved. Tranquero soil had 4.5 ppm sulfur (by ammonium acetate–acetic acid extract), and cassava plants receiving no S fertilizer showed apparent S deficiency (small yellowish-green leaves) during the dry season, recuperating when the rains began. Where potassium sulfate or KCl + S fertilizer was applied, the S content of the leaf blades was increased relative to the KCl source. Raising the rate of KCl fertilizer increased chloride and decreased S; this response may indicate competition between chloride and sulphate.

Other effects

Yield reductions that occur when high rates of potassium are applied may be related to factors other than imbalances caused by excess K. The anion that accompanies the potassium is usually chloride, although sulfate is also commonly used. When potassium chloride is applied in bands at planting, it often comes into contact with or is located near the seed. Water that the seedling needs to grow is held by the fertilizer in a form unavailable to the young plant, and this can result in injury and death. This problem is more serious in soils with a low water-holding capacity and obviously is exacerbated if rainfall is deficient during the germination period. Placing the fertilizer band 5 cm beside and 5 cm below the seeds is recommended for reducing the danger of injury from salt effects. On a

Dark Red Latosol, a carefully placed band application of 125 kg/ha K as KCl did not reduce maize stands even though the maize was planted during a ten-day dry period (Ritchey and Lobato, 1977). Planting equipment available to the farmer, however, is often not designed or adjusted to attain separation between fertilizer and seed.

Broadcast application of the potassium fertilizer practically eliminates the danger of salt effects on seedlings. Moreover, in the highly weathered soils of the tropics, the absence of expanding lattice clays eliminates the potential for permanent K retention, and there is no need for banding to reduce this problem. Broadcasting is usually somewhat less convenient, however, especially when limited tillage is being practiced, with row crops being planted and fertilized in one operation.

When high rates of K have reduced yields, another nutrient, often magnesium, has usually been in short supply. In some cases, the anion accompanying the potassium apparently exacerbated an existing shortage, as illustrated by the possible chloride-sulfate interaction in cassava in Colombia. Advantage can be taken of the need for an anion to accompany the potassium in the fertilizer. Where soil sulfur is low and little sulfate in other forms is being added, using potassium sulfate rather than potassium chloride is a good way to provide both sulfur and potassium. At Huhunya in Ghana, when potassium sulfate was substituted for potassium chloride, cassava yields increased from 12,000 kg/ha to 17,400 kg/ha. The leaf color in the sulfur plots was dark green, but the KCl plants had yellowish-green leaves typical of S-deficient plants.

Applying more potassium fertilizer than is needed is expensive, inefficient, and can reduce yields through salt effects if bands are placed too close to the seed or through deficiencies of other nutrients if the K or associated anion interacts competitively with an element not present at optimum level.

Evaluation of Nutrient Imbalances by Foliar Analysis

Sumner (1977) has proposed wider use of the Diagnosis and Recommendation Integrated System (DRIS) for evaluating nutritional needs of plants. The system makes simultaneous nutrient comparisons based on ratios among several plant nutrient contents. Indices for each nutrient are prepared by calculating the ratio between a given nutrient element and each of the other elements. The ratios in the plants under study are then compared with the "ideal" ratios measured in a high-production population; a negative value results if the element is relatively deficient and a positive value results if the element is relatively abundant. The magnitude depends on the degree of the imbalance, but it is also inversely proportional to the CV (coefficient of variation) of the original data used in establishing the ideal high-yield standard; thus, it takes natural variability into account. The individual values are then simultaneously evaluated to produce an index which reflects the degree of deficiency or sufficiency for each element in relation to all of the other measured elements. Ranking

the indices shows the one that is most deficient. Knowing which elements are most out of balance is particularly useful for highly weathered soils where many nutrients are in low supply and where large changes in the cations present on the exchange complex may be induced by liming when the soil is brought under cultivation.

DRIS evaluations (based on nutrient-level criteria from high-yielding maize crops in the midwestern U.S.A.) prepared for a maize crop planted the first year after clearing a Brazilian Dark Red Latosol are presented in table 12. Before foliar analyses were complete, the researchers decided to apply more phosphorous fertilizer to the field for the second year of the experiment because the soil test value was low. The DRIS indices apparently reflected the nutritional situation rather well. Potassium was indicated as the element most deficient in the 0- and 62-kg/ha K treatments. At the high K levels, phosphorus was indicated as most deficient, followed by Mg. The K rank changed to the "least deficient" position.

Table 12. DRIS (Diagnosis and Recommendation Integrated System) indices for 5 nutrients analyzed in maize ear leaves grown first year after clearing Dark Red Latosol, CPAC, Planaltina, Brazil*

Amount applied		*Nutrient and index, ranked in order of decreasing necessity*				
K	*Mg*					
kg/ha						
0	345	K (−99)	P (−16)	Ca (24)	N (31)	Mg (52)
62	345	K (−23)	P (−13)	Ca (9)	N (12)	Mg (17)
125	345	P (−14)	K (−5)	Mg (5)	Ca (6)	N (7)
250	345	P (−18)	Mg (−11)	Ca (−1)	N (12)	K (19)
500	345	P (−12)	Mg (−12)	Ca (−4)	N (10)	K (19)
125	7	Mg (−49)	P (−10)	K (6)	N (18)	Ca (36)
125	27	Mg (−38)	P (−11)	K (9)	N (17)	Ca (24)
125	97	Mg (−22)	P (−10)	K (−1)	N (13)	Ca (20)
125	345	P (−14)	K (−5)	Ca (6)	N (7)	Mg (8)

*Varying proportions of calcitic and dolmitic lime were used to raise pH to about 5.1.

Soil Testing

Measuring soil potassium

A small soil sample is mixed with an extracting solution designed to remove the potassium that is readily available to plants and so obtain an indication of the K status of a field. Extractants used include neutral normal ammonium acetate, which measures the exchangeable K; the North Carolina double-acid extractant [0.05 *N* HCl + 0.025 *N* H_2SO_4 (Mehlich)], which is more convenient than exchangeable for routine laboratory analysis; and the modified Olsen extract (0.5 *M* $NaHCO_3$ + 0.01 *M* EDTA) used for the data reported for Peru. Most of the values for the Brazilian research reported in this bulletin are double-acid extractant values. De Souza et al. (1979) found an excellent linear relationship ($Y = 2.8 + 1.24x$; $r = 0.99$) between exchangeable and double-acid extractable K (fig. 23).

The distribution of K in the soil tends to be variable. If the land has already been row-cropped, fertilizer potassium originally applied uniformly to the crop may be locally redistributed in the field after harvest in such a way as to make soil sampling difficult. This problem is illustrated in figure 24 where the amount of potassium present in soil samples taken from between rows of corn after harvest is compared with the amount found within the row. Apparently, a proportion of the potassium present in the growing maize plant is washed out of the dead leaves after the plant matures. The rain deposits much of this potassium in the soil at the base of the plant, the K thereby being concentrated in the row. Soil samples should be taken from both the row and inter-row areas so as to obtain a sample that is representive of the actual K present. A similar problem of uneven K distribution in the field might occur where maintenance applications of potassium and other fertilizer elements have been applied in a band along the row at planting.

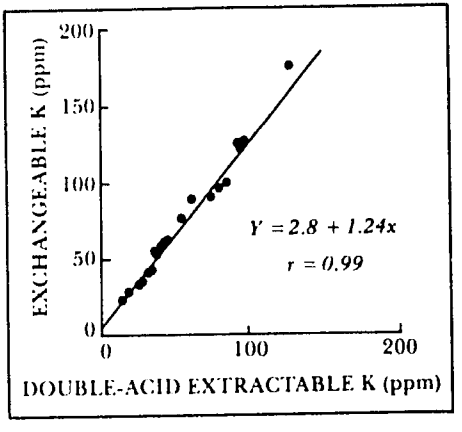


Figure 23. Relationship between neutral 1.0 *N* ammonium acetate (exchangeable) K and double-acid (0.05 *N* HCl + 0.025 *N* H_2SO_4) extractable potassium on the 0–15-cm layer of a Dark Red Latosol (de Souza et al., 1979).

The "recycling" effect caused by rainwater returning K from dead leaves to the surface of the field is quite beneficial because it reduces K leaching losses and reduces exportation of K from the field if the stover is harvested. On the other hand, soil sampling only to 15-cm depth in such a field may present an inaccurate picture of the true K fertility in the soil profile as a whole.

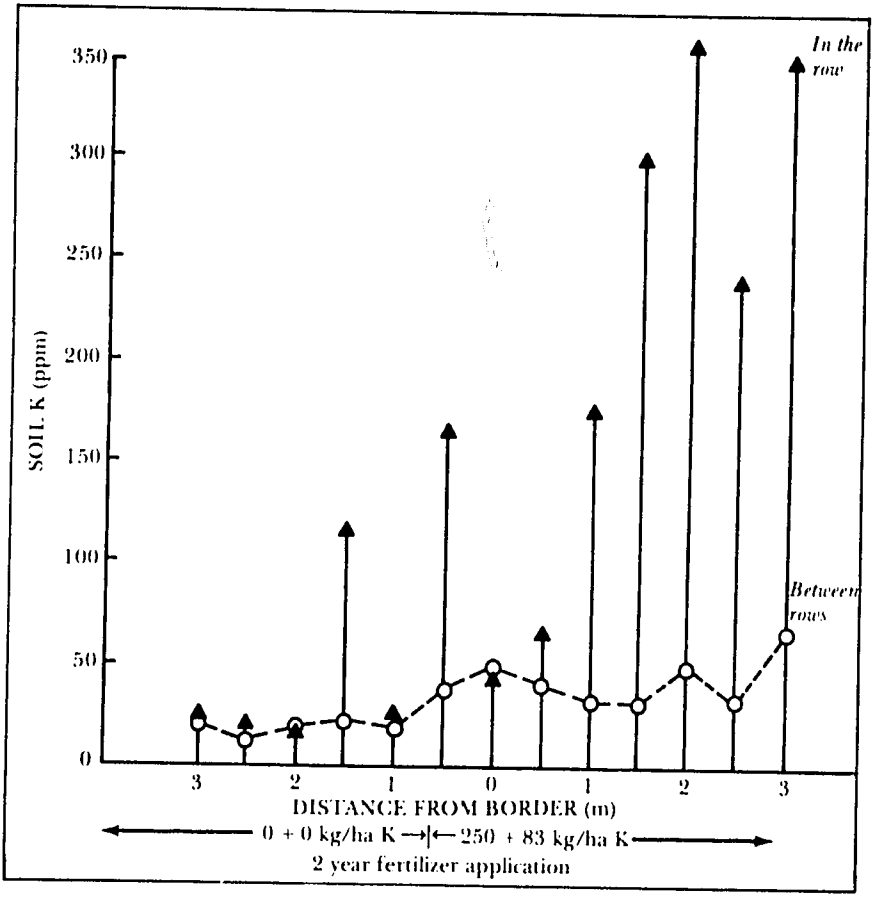


Figure 24. Double-acid extractable K at 0 – 15-cm depth measured within maize row and halfway between maize rows after harvest of second-year crop on a Dark Red Latosol, CPAC, Planaltina, Brazil. Composites of 2 subsamples were collected at 50-cm intervals beginning 3 m within plot that received no K fertilizer for 2 years, crossing plot boundary, and continuing 3 m into adjacent plot, which received 250 kg/ha K the first year and 83 kg/ha the second year (Ritchey et al., 1977).

Effect of levels of other ions on the interpretation of K soil test values

Whether or not the levels of other cations have an effect on potassium uptake will influence the criteria used in interpreting K soil test values.

McLean (1977) presented a good summary of two commonly used concepts: "sufficiency levels of available nutrients" (SLAN), and "basic cation saturation ratios" (BCSR). The sufficiency level approach was developed in situations where only one nutrient was deficient; the lower the soil test value for this nutrient, the greater the increase in yield resulting from fertilization with the missing element. This approach largely ignores the levels of other ions.

The basic cation saturation approach "implies that for optimum growth of crops both a best ratio of basic cations and a best total base saturation exist in a soil" (McLean, 1977, p. 46). It tries to take into account *(a)* the interactions that occur among cations in influencing what proportion of a particular cation will be present in the soil solution and what proportion will be present on the exchange complex, and *(b)* the results of interactions among cations in the soil solution as they affect nutrient uptake by the root. McLean explained that the BCSR "seems to work best in highly weathered soils of low pH requiring relatively major adjustments in fertility" (p. 50), and cited the following "ideal saturation" nutrient ranges given by Graham (1959): 65 – 85 percent Ca, 6 – 12 percent Mg, and 2 – 5 percent K. But McLean also noted that other researchers have stated that crop yields may not be greatly affected by variation in these saturations beyond the ranges given.

McLean concluded that in perhaps a majority of cases a combination of the two concepts works best. An example is the recommendation system used for Alabama presented by Cope and Rouse (1973). The critical soil K level for cotton response is 55 ppm in sandy soils (less than 5 meq/100 g CEC), 85 ppm in medium-textured soils (5 – 10 meq/100 g CEC), and 120 ppm for fine-textured soils (CEC over 10 meq/100 g). Thus the minimum requirement of exchangeable potassium becomes greater with the general increase in the level of the other cations. Boyer (1972) concludes that, depending on the tropical crop and the soil, a minimum level of 0.10 meq/100 g K (range of 0.07 to 0.20 meq/100 g K) should be present, along with a relative minimum level of 2 to 3 percent of the sum of the exchangeable bases. Thus 0.15 meq/100 g (59 ppm) K would be required for a soil with CEC equal to 5.0 meq/100 g.

In the very highly weathered soils of the tropics, the effective CEC with farmer levels of liming often does not exceed 5 meq/100 g. The responses to K are more directly related to low absolute amounts of K rather than to competing effects; thus, research on the these soils has placed more emphasis on the level of exchangeable K than on a ratio of potassium to total CEC or another similar ratio.

As agriculture intensifies, higher liming rates are likely, and total cation exchange capacity may increase to levels over 5.0 meq/100 g, with the potassium critical level also being raised. Boyer (1978) mentions optimal soil cation ratio ranges of 3 to 4 for Mg/K (but up to 50 for some species), 4 to 17 for Ca/K, and 15 to 35 (or higher for some species) for (Ca + Mg)/K.

Depending on the species involved, levels of 0.5 to 6.5 meq/100 g Mg, 2.2 mg/100 g Ca, or 4.6 meq/100 g Ca + Mg could cause nutrient imbalances at a K level of 50 ppm (0.13 meq/100 g). Such levels of Ca and Mg could easily result from modest lime application of 4 to 8 t/ha.

Little published information is available showing clearcut evidence that increases in Ca and/or Mg cause declines in yield or K content of crops, but some borderline cases of imbalance may have been observed in the soils studied, as previously discussed. The higher requirements implied by these ratios may actually be related to increased crop demand for K associated with increases in maximum potential yield resulting from the generally higher nutrient level of the soil.

LITERATURE CITED

Barber, S. A.
1968. Mechanism of potassium absorption by plants. *In* The role of potassium in agriculture (V. J. Kilmer, S. E. Younts, and N. C. Brady, eds.), pp. 293–319. Amer. Soc. Agron., Madison, WI.

Black, C. A.
1968. Soil–plant relationships. John Wiley and Sons, Inc., NY.

Bouldin, D. R.
1979. The influence of subsoil acidity on crop yield potential. Cornell Intnatl. Agr. Bul. 34.

Boyer, J.
1972. Soil potassium. *In* Soils of the humid tropics, pp. 102–35. Natl. Acad. Sci., Washington, DC.
1978. Le calcium et le magnesium dans les sols des regions tropicales humides et sub-humides. Initiations-Documentations Techniques No. 35. O.R.S.T.O.M., Paris.

Centro de Pesquísa Agropecuária dos Cerrados (CPAC)
1978. Relatório Técnico Anual 1976–77. Empresa Brasiliera de Pesquísa Agropecuária. Brasília D.F., Brasil.

Cope, J. T., Jr., and Rouse, R. D.
1973. Interpretation of soil test results. *In* Soil testing and plant analysis (L. M. Walsh and J. D. Beaton, eds.), pp. 35–54. Soil Sci. Soc. Amer., Madison, WI.

de Geus, J. G.
1967. Fertilizer guide for tropical and subtropical farming. Centre d'Etude de L'Azote, Zurich.

de Souza, D. M. G.; Ritchey, K. D.; Lobato, E.; and Goedert, W.
1979. Potássio em solo de cerrado II. Equilíbrio no solo. R. bras. Ci. Solo. In press.

Equipe de Pedologia e Fertilidade do Solo
1966. Levantamento Semidetalhado dos Solos de Areas do Ministerio do Agricultura do Distrito Federal. Boletim Tecnico No. 8. Escritório de Pesquisas e Experimentação, Ministério da Agricultura, Brasil.

Goedert, W. J.; Corey, R. B.; and Syers, J. K.
1975. The effects on potassium equilibria in soils of Rio Grande do Sul, Brazil. Soil Sci. 120:107–11.

Gonzalez, E.
1976. Effect of depth of lime incorporation on the growth of corn in Oxisols of Central Brazil. Thesis for degree of Ph.D., N. Carolina State Univ., Raleigh. 125 pp.

Graham, E. R.
1959. An explanation of theory and methods of soil testing. Mo. Agr. Exp. Sta. Bul. 734.

Hiatt, A. J., and Leggett, J. E.
1974. Ionic interactions and antagonisms in plants. *In* The plant root and its environment (E. W. Carson, ed.), pp. 101–34. University Press of Virginia, Charlottesville.

Hossner, L. R., and Doll, E. C.
1970. Magnesium fertilization of potatoes as related to liming and potassium. Soil Sci. Soc. Amer. Proc 34:772–74.

Hunter, A. H.
1975. Laboratory and greenhouse techniques for nutrient survey studies to determine the soil amendments required for optimum plant growth. Mimeo. Rept., Dept. of Soil Science, N. Carolina State Univ., Raleigh.

Kronberg, B. I.
1977. The geochemistry of some Brazilian soils and geochemical considerations for agriculture on highly leached soils. Thesis for degree of Ph.D., Dept. of Geology, Univ. of Western Ontario, London, Ontario, Canada.

Le Roux, J.
1973. Quantitative clay mineralogical analysis of Natal Oxisols. Soil Sci. 115:137–44.

Lombin, L. G., and Fayemi, A. A.
1978. Prospects of magnesium deficiency in soils of western Nigeria as assessed under field conditions. Trop. Agr. (Trinidad) 55:157–66.

Lopes, A. S.
1975. A survey of the fertility status of soils under "cerrado" vegetation in Brazil. Thesis for degree of Ph.D., N. Carolina State Univ., Raleigh. 138 pp.

McLean, E. O.
1977. Contrasting concepts in soil test interpretation: Sufficiency levels of available nutrients vs. basic cation saturation ratios. *In* Soil testing: Correlating and interpreting the analytical results (M. Stelly, ed.), pp. 39–54. ASA Spec. Publ. No. 54. Amer. Soc. Agron., Madison, WI.

Mengel, K.
1968. Exchangeable cations of plant roots and potassium absorption by the plant. *In* The role of potassium in agriculture (V. J. Kilmer, S. E. Younts, and N. C. Brady, eds.), pp. 311–19. Amer. Soc. Agron., Madison, WI.

Mielniczuk, J.
1977. Formas de potássio em solos do Brasil. R. bras. Ci. Solo 1:55–61.

Naderman, G. C.
1973. Yellowing of rice (*Oryza sativa* L.) as related to root development and mineral nutrition in soils of the Eastern Plains of Colombia. Thesis for degree of Ph.D., Cornell Univ., Ithaca, NY.

Ngongi, A. G. N.
1976. Influence of some mineral nutrients on growth, composition, and yield of Cassava (*Manihot esculenta* Crantz). Thesis for degree of Ph.D., Cornell Univ., Ithaca, NY.

North Carolina State University
1973. Research on tropical soils. Annual progress report to USAID.
1974. Research on tropical soils. Annual progress report to USAID.
1975. Research on tropical soils. Annual progress report to USAID.

Rich, C. I.
1972. Potassium in soil minerals. *In* Potassium in soil, pp. 15–31. Proc., 9th Colloq., Intnatl. Potash Inst.

Ritchey, K.; de Souza, D. M. G.; Goedert, W.; and Lobato, E.
1977. Potassium fertilization in soils of tropical America: Campos Cerrados. Presented at Quinta Coloquio de Suelos: Potasio y Micronutrientes en la agricultura colombiana, Bogota, Septiembre 26–30, 1977.

Ritchey, K. D.; de Souza, D. M. G.; and Lobato, E.
1978. Downward calcium movement as a method of increasing rooting depth and drought resistance in tropical savannah Oxisols. 11th Cong. Intnatl. Soil Sci. Soc., Trans., Vol. 1 (Abstracts).
1979. Potássio em solo de Cerrado I. Resposta à adubação potássica. R. bras. Ci. Solo. In press.

Ritchey, K. D., and Lobato, E.
1977. Effects of fertilizing with potassium and magnesium in maize growing on an Oxisol of the Federal District of Cerrados, Brazil. Subj. 9, Cereal Crops, 32nd Suite, Potash Review, No. 2.

Rodriques, T. E.
1977. Mineralogia e gênese de uma sequência de solos dos Cerrados, No Distrito Federal. Thesis for degree of M.S., Univ. Fed. do Rio Grande do Sul, Porto Alegre, Brazil. 101 pp.

Rodriguez P., M. S.
1975. Calcium, magnesium, and potassium status in some soils of the Eastern Plains of Colombia. Thesis for degree of M.S., Cornell Univ., Ithaca, NY. 177 pp.

Seubert, C. E.
1975. Effects of land clearing methods on crop performance and changes in soil properties in an Ultisol of the Amazon Jungle of Peru. Thesis for degree of M.S., N. Carolina State Univ., Raleigh. 152 pp.

Sumner, M. E.
1977. Effect of corn leaf sampled on N, P, K, Ca, and Mg content and calculated DRIS indices. Commun. Soil Sci. Plant Anal. 8:269–80.

Tyler, E. J.
1975. Genesis of the soils within a detailed soil survey area in the Upper Amazon basin, Yurimaguas, Peru. Thesis for degree of Ph.D., N. Carolina State Univ., Raleigh. 165 pp.

Vettori, L.
1969. Métodos de análise de solo. Boletim técnico no. 7. Escritório de Pesquisas e Experimentação, Ministério da Agricultura, Brasil.

Villachica, J. H.
1978. Maintenance of soil fertility under continuous cropping in an Ultisol of the Amazon Jungle of Peru. Thesis for degree of Ph.D., N. Carolina State Univ., Raleigh. 269 pp.

Wade, M. K.
1978. Soil management practices for increased crop production for small farms of the Amazon Jungle of Peru. Thesis for degree of Ph.D., N. Carolina State Univ., Raleigh. 243 pp.

Weaver, R. M.
1975. Quartz presence in relationship to gibbsite stability in some highly weathered soils of Brazil. Clays and Clay Minerals 23:431–36.

Yost, R. S.
1977. Effect of rate and placement on availability and residual value of P in an Oxisol of Central Brazil. Thesis for degree of Ph.D., N. Carolina State Univ., Raleigh. 160 pp.

ACKNOWLEDGEMENTS

Several of the active researchers are identified in the literature citations. However, among the many additional people instrumental in planning, initiating and executing these studies, we especially thank Elmar Wagner, Wenceslau Goedert, and Edson Lobato of Centro de Pesquisa Agropecuaria dos Cerrados; Henry Obeng, Charles Ofori, and Peter Kwakye of the Soil Research Institute; Jose Vicente-Chandler and Mario Perez-Escolar of the University of Puerto Rico; Carlos Valverde of the Ministerio de Agricultura de Peru; John Malcolm of USAID; Charles McCants, Pedro Sanchez, and John Nicholaides of North Carolina State University; and Matthew Drosdoff and Marlin Cline of Cornell University. The interests of Cornell and North Carolina State Universities were ably represented by the field project leaders, Richard Fox in Puerto Rico, George Naderman and Dale Ritchey in Brazil, Amos Ngongi in Ghana, and Dale Bandy in Peru.

The New York State College of Agriculture and Life Sciences provides equal program and employment opportunities.