FERTILITY MAINTENANCE AND LIMING OF CASSAVA

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Introduction

Cassava is generally grown by poor farmers living in marginal areas with adverse climatic and soil conditions. The crop is very suitable for these conditions because of its exceptional tolerance to drought and to acid, infertile soils. It is often grown on sloping land because of its minimal requirement for land preparation, and its ability to produce reasonably good yields on eroded and degraded soils where other crops would fail. It has been shown, however, that growing cassava on slopes can result in severe erosion, with high soil and nutrient losses. Thus cassava cultivation on slopes requires adequate cultural and soil conservation practices that minimize erosion.

Cassava is well adapted to poor or degraded soils because of its tolerance to low pH, high levels of exchangeable aluminium (Al) and low concentrations of phosphorus (P) in the soil solution. Studying the effect of pH on the growth of several crops grown in flowing nutrient solution, Islam *et al.* (1980) reported that cassava and ginger (*Zingiber officinale*) were more tolerant of low pH (<4) than tomatoes (*Lycopersicon esculentum*), wheat (*Triticum aestivum* L.) or maize (*Zea mays* L.). CIAT (1978) and Howeler (1991a) also reported that cassava and cowpeas (*Vigna unguiculata*) were more tolerant of acid soils with high levels of exchangeable Al, and were much less responsive to lime applications than common beans (*Phaseolus vulgaris*), rice (*Oryza sativa*), maize and sorghum (*Sorghum vulgaris*).

Long-term effect of cassava production on soil productivity

When cassava is grown continuously on the same soil without adequate fertilizer or manure inputs, soil productivity may decline due to nutrient depletion and soil loss by erosion. Sittibusaya (1993) reported that cassava yields in unfertilised plots declined from 26-30 t ha^{-1} to 10-12 t ha^{-1} after 20-30 years of cassava cultivation. Similar or even faster yield declines have been observed for other annual crops (Ofori, 1973; Nguyen Tu Siem, 1992).

Cong Doan Sat and Deturck (1998) compared the effect of long-term cultivation of cassava with that of natural forest, rubber, cashew and sugarcane grown on similar soils in southern Vietnam. Cassava cultivation resulted in the lowest levels of soil organic C, total N and exchangeable K and Mg, and an intermediate level of P because of some P fertilizer applications. Cassava cultivation also resulted in the lowest clay content, soil aggregate stability and water retention, as well as intermediate bulk density and infiltration rates. Compared to native forest, grasslands or perennial plantation crops, long-term cassava cultivation has a negative impact on soil productivity, especially when grown on slopes with inadequate management and no fertilizer. This is also true, however, for other annual food crops, which all require frequent land preparation, resulting in erosion and more rapid decomposition of OM. Moreover, fertilizer inputs may not compensate for nutrient removal in harvested products, or losses by leaching and erosion.

When cassava was grown for eight consecutive years without fertilizers in Quilichao, Colombia, root yields declined from 22 t ha^{-1} in the first year to 13 t ha^{-1} in the last year (**Figure 1**). With application of only N or P, yields declined from 27 and 29 t ha^{-1} in the first year to 20 and 15 t ha^{-1}, respectively, in the last year. This yield decline was due to the increasing intensity of K deficiency. When only K was applied (150 kg K$_2$O ha^{-1}) yields could be maintained at about 30 t ha^{-1}, while with the annual application of 100 kg N, 200 kg P$_2$O$_5$ and 150 kg K$_2$O ha^{-1}, yields

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actually increased from about 32 to nearly 40 t ha^{-1}. Without K application the exchangeable K content of the soil decreased in 2-3 years from 0.2 to about 0.1 meq 100 g^{-1} and remained at that level for the following five crop cycles. With application of 150 kg K$_2$O ha^{-1}, the soil K level remained constant at about 0.2 meq 100 g^{-1}, while with applications of 300 kg K$_2$O ha^{-1} it increased gradually to 0.45 meq 100 g^{-1}. Thus, high yields and adequate levels of K could be maintained with annual applications of 150 kg K$_2$O ha^{-1} (Howeler and Cadavid, 1990; Howeler, 1991b).

On mineral soils in Malaysia, very high cassava yields of about 50 t ha^{-1} were maintained for nine years with annual applications of 112 kg N, 156 kg P$_2$O$_5$ and 187 kg K$_2$O ha^{-1}, but without fertilizers yields declined from 32 t ha^{-1} in the first year to about 20 t ha^{-1} in the ninth year (Chan, 1980; Howeler, 1992). This was also attributed mainly to increasing K deficiency. In Kerala, India, continuous cropping for ten years also resulted in declining yields when no K was applied, while annual applications of 100 kg K$_2$O ha^{-1} maintained high yields of 20-30 t ha^{-1} (Kabeerathumma *et al*., 1990).

Figure 2 shows similar results for a long-term (>20 yr) fertility trial conducted in Khon Kaen, Thailand. Without K application yields declined from 28 t ha^{-1} in the first year to 10 t ha^{-1} in the second, and then slowly declined to about 5 t ha^{-1} during the subsequent 17 cropping cycles. With application of NK or NPK, yields could be maintained at a level of 20 t ha^{-1} for the entire period. **Figure 2** also shows that when plant tops were re-incorporated into the soil, the yield decline without fertilizer application was much slower. After 19 years the yield was still about 10 t ha^{-1}, i.e. twice as high as when all plant parts were removed. Thus, when plant tops were returned to the soil, yields of about 10 t ha^{-1} could be maintained, even in a very poor soil and without any application of fertilizers. With adequate fertilization high yields of at least 20 t ha^{-1} could be maintained for 19 years of continuous cropping.

Diagnosis of nutritional problems

If plant growth is not optimal and/or yields are low, and if other causes such as insects and diseases, drought, shade or cold have been ruled out, plants may be suffering from nutritional deficiencies and/or toxicities. Before effective remedial measures can be taken, it is essential to diagnose the problem correctly. This can be done in several ways, but the best diagnosis is usually obtained from a combination of different methods:

1. Observation of deficiency and toxicity symptoms
Cassava plants do not readily translocate nutrients from the lower to the upper leaves; instead, when certain nutrients are in deficient supply, plants respond by slowing the growth rate, producing fewer and smaller leaves and sometimes shorter internodes. Leaf life is also reduced. As nutrients are not readily mobilised to the growing point, symptoms for NPK deficiencies, normally found in the lower leaves, tend to be less pronounced in cassava than in other crops. For that reason farmers may not be aware that plant growth is reduced because of nutritional deficiencies. Oftentimes, the initial diagnosis based on deficiency or toxicity symptoms needs to be confirmed by soil or plant tissue analyses or from experiments. Nevertheless, visual identification is a quick, easy method to diagnose many nutritional problems. Symptoms have been described and colour photos have been included in several publications (Lozano *et al*., 1981; Asher *et al*., 1980; Howeler, 1981; 1989; 1996a; 1996b; Howeler and Fernandez, 1985). The symptoms of nutrient deficiencies and toxicities are summarised in **Table 1**.

2. Soil analysis
This method is advantageous in that problems can be detected before planting and, if necessary, lime and/or nutrients can be applied before plant growth is affected by the problem. Soil analyses are particularly useful for detecting P, K, Ca, Mg and Zn deficiencies, while soil pH will indicate whether Al and/or Mn toxicity or micronutrient deficiencies are likely to occur. Analysis for OM content is not very reliable in predicting N responses as high-OM soils may still produce a significant N response if N mineralization is slow, especially in very acid soils.

Soil analyses usually determine the amount of available or exchangeable nutrient as this part of the total soil nutrient is best correlated with plant uptake. These "available" fractions are usually determined by shaking the soil sample with certain extracting solutions and determining the amount of nutrient in the extract. Different laboratories may use different extracting agents as there is no one method that is optimal for all soil types; thus results from one lab may differ from those of another. In interpreting the results, therefore, it is important to consider the methodology used.

Representative soil samples should be taken in areas that appear to be uniform in terms of plant growth and previous management. About 10-20 subsamples are taken in zigzag fashion across the whole area. These subsamples are thoroughly mixed together and then about 300-500 g are air dried or dried at about $65^{o}C$ in a forced-air oven. This combined sample is then ground fine, screened and sent to the lab for analysis.
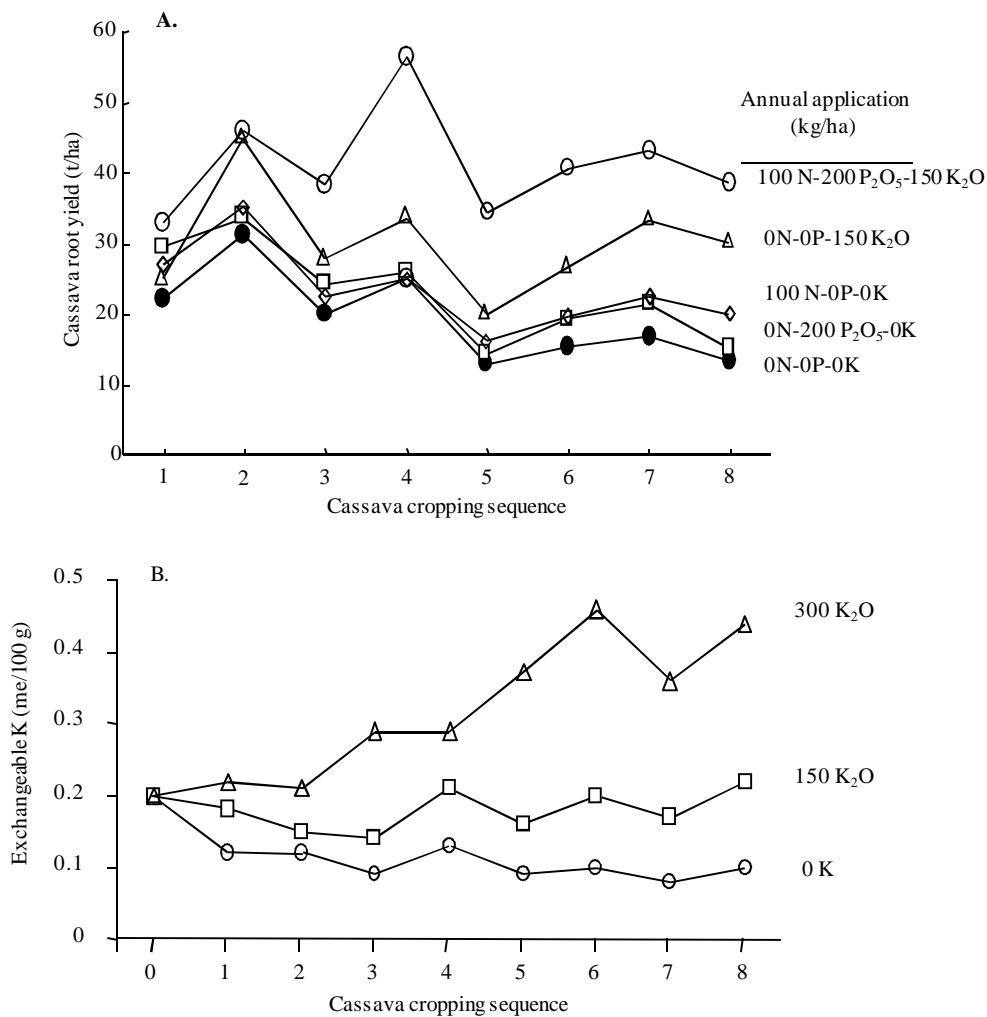

Figure 1. *Effect of various levels of annual applications of N, P and K on cassava root yield (A), and on the exchangeable K content of the soil (B) during eight consecutive cropping cycles in a long-term NPK trial conducted at CIAT-Quilichao, Colombia (**Source:** Howeler and Cadavid, 1990).*
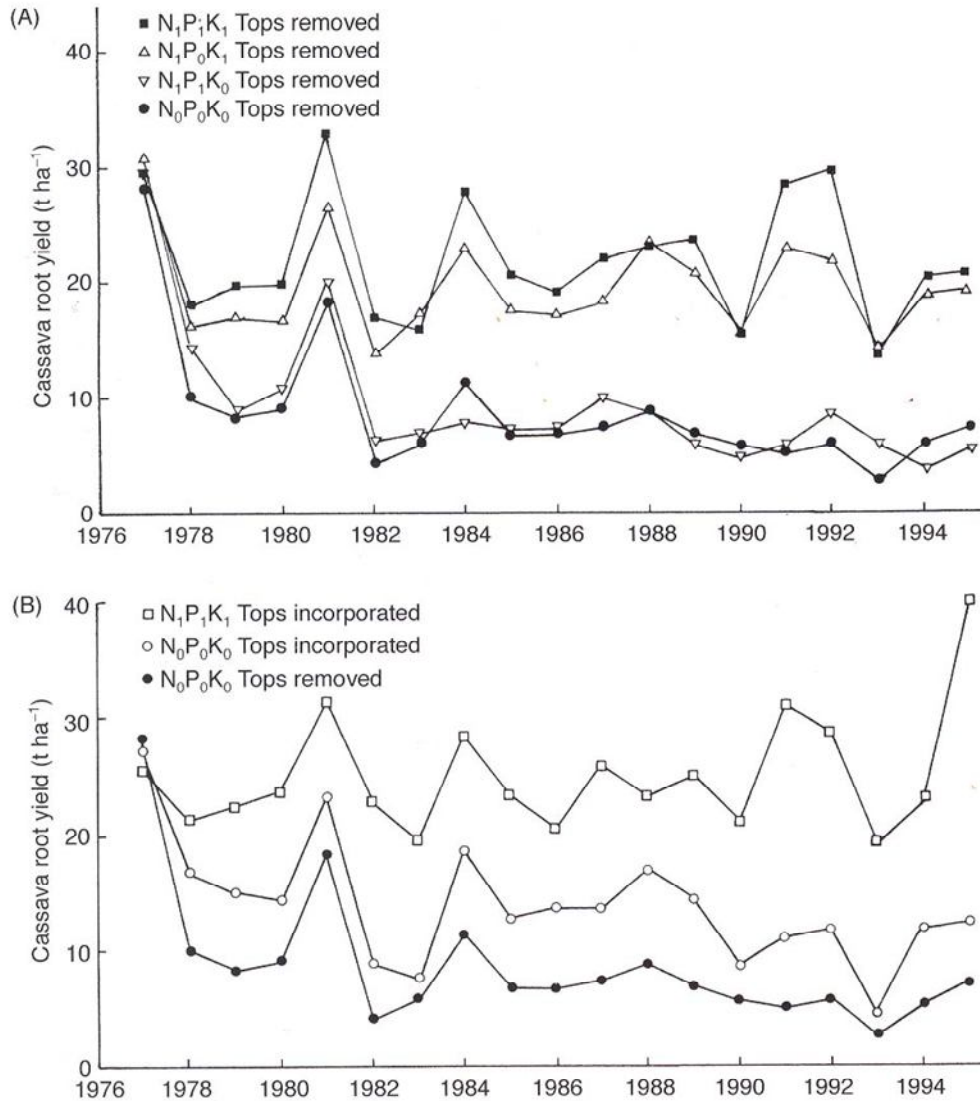
*Figure 2. Effect of annual applications of various combinations of N, P and K (A) and crop residue management (B) on cassava yield during 19 consecutive crops grown in Khon Kaen, Thailand, from 1977-1995) (**Source:** Howeler, 2000).*

Results of the soil analysis can be compared with published data obtained from correlation studies, which indicate either the "critical level" of the nutrient, as determined with a specific extracting agent or the nutrient ranges according to the particular nutritional conditions of the crop. **Table 2** gives the ranges corresponding to the nutritional requirements of cassava as determined with specific methodologies.

Table 1. Symptoms of nutrient deficiencies and toxicities in cassava.

Deficiencies	Symptoms
Nitrogen (N)	• Reduced plant growth • In some cvs., uniform chlorosis of leaves, starting with lower leaves, but soon spreading throughout the plant
Phosphorus (P)	• Reduced plant growth, thin stems, short petioles; sometimes pendant leaves • Under severe conditions 1-2 lower leaves turn yellow to orange, become flaccid and necrotic; may fall off • In some cvs. lower leaves turn purplish/brown
Potassium (K)	• Reduced plant growth with excessive branching, resulting in prostrate plant type • Small, sometimes chlorotic upper leaves; thick stems with short internodes • Under severe conditions premature lignification of upper stems with very short internodes, resulting in zigzag growth of upper stems • In some cvs. purple spotting, yellowing and border necrosis of lower leaves • In other cvs. upward curling of lower leaf borders, similar to drought stress symptoms
Calcium (Ca) (rare in the field)	• Reduced root and shoot growth • Chlorosis, deformation and border necrosis of youngest leaves with leaf tips or margins bending downwards
Magnesium (Mg) (often seen in field)	• Marked intervenal chlorosis or yellowing in lower leaves • Slight reduction in plant height
Sulphur (S) (similar to N deficiency; seldom seen in field)	• Uniform chlorosis of upper leaves, which soon spreads throughout the plant
Boron (B)	• Reduced plant height, short internodes, short petioles and small deformed upper leaves • Purple-grey spotting of mature leaves in middle part of plant • Under severe conditions gummy exudate on stem or petioles (almost never seen in field) • Suppressed lateral development of fibrous roots
Copper (Cu) (mainly in peat soils)	• Deformation and uniform chlorosis of upper leaves, with leaf tips and margins bending up- or downward • Petioles of fully expanded leaves long and bending down • Reduced root growth
Iron (Fe) (mainly in calcareous soils)	• Uniform chlorosis of upper leaves and petioles; under severe conditions leaves turn white with border chlorosis of youngest leaves • Reduced plant growth; young leaves small, but not deformed
Manganese (Mn) (mainly in sandy and high pH soils)	• Intervenal chlorosis or yellowing of upper or middle leaves; uniform chorosis under severe conditions • Reduced plant growth; young leaves small, but not deformed.
Zinc (Zn) (often seen in high pH or calcareous soils; also in acid soils)	• Intervenal yellow or white spots on young leaves • Leaves become small, narrow and chlorotic in growing point; necrotic spotting on lower leaves as well • Leaf lobes turn outward away from stem • Reduced plant growth; under severe conditions, death of young plants

Toxicities	Symptoms
Aluminium (Al) (only in very acid mineral soils)	• Reduced root and shoot growth • Under very severe conditions yellowing of lower leaves
Boron (B) (only observed after excessive B application)	• Necrotic spotting of lower leaves, especially along leaf margins
Manganese (Mn) (mainly in acid soils and when plant growth stagnates)	• Yellowing or oranging of lower leaves with purple-brown spots along veins • Leaves become flaccid and drop off

Deficiencies	Symptoms
Salinity (observed only in saline/ alkaline soils)	▪ Uniform yellowing of leaves, starting at bottom of plant but soon spreading throughout ▪ Symptoms very similar to Fe deficiency ▪ Under severe conditions border necrosis of lower leaves, poor plant growth and death of young plants

Table 2. Approximate classification of soil chemical characteristics according to the nutritional requirements of cassava. (Source: Howeler, 1996a, b)

Soil parameter	Very low	Low	Medium	High	Very high
pH[1]	<3.5	3.5-4.5	4.5-7	7-8	>8
Organic matter[2] (%)	<1.0	1.0-2.0	2.0-4.0	>4.0	
Al saturation[3] (%)			<75	75-85	>85
Salinity (mS cm^{-1})			<0.5	0.5-1.0	>1.0
Na saturation (%)			<2	2-10	>10
P[4] (μg g^{-1})	<2	2-4	4-15	>15	
K[4] (meq 100 g^{-1})	<0.10	0.10-0.15	0.15-0.25	>0.25	
Ca[4] (meq 100 g^{-1})	<0.25	0.25-1.0	1.0-5.0	>5.0	
Mg[4] (meq 100 g^{-1})	<0.2	0.2-0.4	0.4-1.0	>1.0	
S[4] (μg g^{-1})	<20	20-40	40-70	>70	
B[5] (μg g^{-1})	<0.2	0.2-0.5	0.5-1.0	1-2	>2
Cu[5] (μg g^{-1})	<0.1	0.1-0.3	0.3-1.0	1-5	>5
Mn[5] (μg g^{-1})	<5	5-10	10-100	100-250	>250
Fe[5] (μg g^{-1})	<1	1-10	10-100	>100	
Zn[5] (μg g^{-1})	<0.5	0.5-1.0	1.0-5.0	5-50	>50

[1] pH in H_2O.
[2] OM = Walkley and Black method.
[3] Al saturation = 100 x Al(Al+Ca+Mg+K) in meq 100 g^{-1}.
[4] P in Bray II; K, Ca, Mg and Na in 1N NH_4-acetate; S in Ca phosphate.
[5] B in hot water; and Cu, Mn, Fe and Zn in 0.05 N HCl+0.025 N H_2SO_4.

These data were determined from many fertilizer experiments conducted in Colombia and in various Asian countries by relating the relative yield in the absence of N, P or K fertilizers (yield without the nutrient over the highest yield obtained with the nutrient) with the OM, available P and exchangeable K content of the soil, respectively. **Figure 3** gives an example from nine locations in four Asian countries. A line was drawn visually through the points to show the relationship and to estimate the "critical level" of the nutrient or soil parameter. This critical level is interpreted as the concentration of the nutrient in the soil or plant tissue above which there is no further significant response to application of the nutrient (usually defined as corresponding to 95% of maximum yield). Critical levels are 3.2% for OM, 7 μg g^{-1} for P (Bray II) and 0.14 meq 100 g^{-1} for exchangeable K. The critical levels for P and K are close to those reported earlier in the literature (Table 9.8). Those for available soil-P reported for cassava (4-10 μg g^{-1}) are much lower than for most other crops (10-18 μg g^{-1}), indicating that cassava will grow well in soils that are low in P and where other crops would suffer from P deficiency. This is due to the effective association between cassava roots and vesicular-arbuscular mycorrhizae (VAM) occurring naturally in the soil (Howeler, 1990).

The critical levels for exchangeable K for cassava (0.08-0.18 meq K 100 g^{-1}) (**Table 2**) are also lower than for most other crops (0.16-0.51 meq K 100 g^{-1}), indicating that despite the crop's relatively high K requirement, it will still grow well on soils with only intermediate levels of K.

As mentioned above, there is seldom a good relationship between the relative response to N and the soil OM content (Howeler, 1995). Using data from 56 NPK trials conducted in Brazil from 1950-1983 (Gomes, 1998) (see Appendix Table 1), the critical level determined for OM was only 1.3%, considerably lower than the 3.1% determined in Asia (Howeler, 1998).

3. Plant tissue analysis

Analysis of plant tissue indicates the actual nutritional status of the plants. The total amount of a certain nutrient is determined, resulting in data that are fairly similar among different laboratories. These analyses are particularly useful for diagnosing N and secondary or micronutrient deficiencies.

Given that nutrient concentrations vary among different tissues, it is imperative to use an "indicator" tissue, the nutrient concentration of which is best related to plant growth or yield. For cassava, the best "indicator" tissue is the blade of the youngest fully expanded leaf (YFEL), i.e. normally about the 4th-5th leaf from the top. Blades without petioles are analysed as nutrient concentrations are quite different in these two tissues (**Table 3**). Nutrient concentrations also change during the growth cycle, depending on the rate of plant growth (Howeler and Cadavid, 1983; CIAT, 1985a,b). As they tend to stabilise after about 4 months, leaf samples should be taken at about 4 MAP.

About 20 leaf blades (without petioles) are collected from a plot or uniform area in the field and combined into one sample (Howeler, 1983). If leaves are dusty or have received chemical sprays, they should be washed gently and rinsed in distilled or deionized water. To prevent continued respiration with consequent loss of DM, leaves should be dried as soon as possible at 60-80°C for 24-48 h. If no oven is available, leaves should be dried as quickly as possible in the sun, preferably in a hot, but well-ventilated area, and away from dust. After drying, samples are finely ground in a lab mill. For Cu analysis samples should be passed through a stainless steel sieve. For Fe analysis the dry leaves should be ground with an agate mortar and pestle. Samples are normally collected in paper bags to facilitate drying, but for analysis of B, plastic bags should be used. Once ground and sieved, samples are stored in plastic vials until analysis.

To diagnose nutritional problems, the results are compared with the nutrient ranges corresponding to the various nutritional states of the plant (**Table 4**), or with critical levels reported in the literature. While the numbers may vary somewhat given the different varieties, soil and climatic conditions (Howeler, 1983), the data in these tables can be used as a general guide for interpreting plant tissue analyses.

4. Greenhouse and field experiments

If analysis of soil or plant tissue is not possible, one can also diagnose nutritional problems by planting cassava in pot experiments using the soil in question, or directly in the field. To diagnose nutrient deficiencies in a particular soil in either pot or field experiments, it is recommended to use the "missing element" technique, where all nutrients are applied to all treatments at rates that are expected to be non-limiting, while one nutrient is missing in each treatment (i.e. -N, -P, -K etc.). Treatments with the poorest growth or yield indicate the element that is most deficient.

For pot experiments it is recommended not to sterilise or fumigate the soil, in order not to kill the native mycorrhizae. Rooted plant shoots rather than stakes should be used as the stakes have high nutrient reserves and their use would therefore delay responses to nutrient additions. In pot experiments cassava plants are generally harvested 3-4 MAP, and dry weights of top growth are used as indicators of nutrient response.
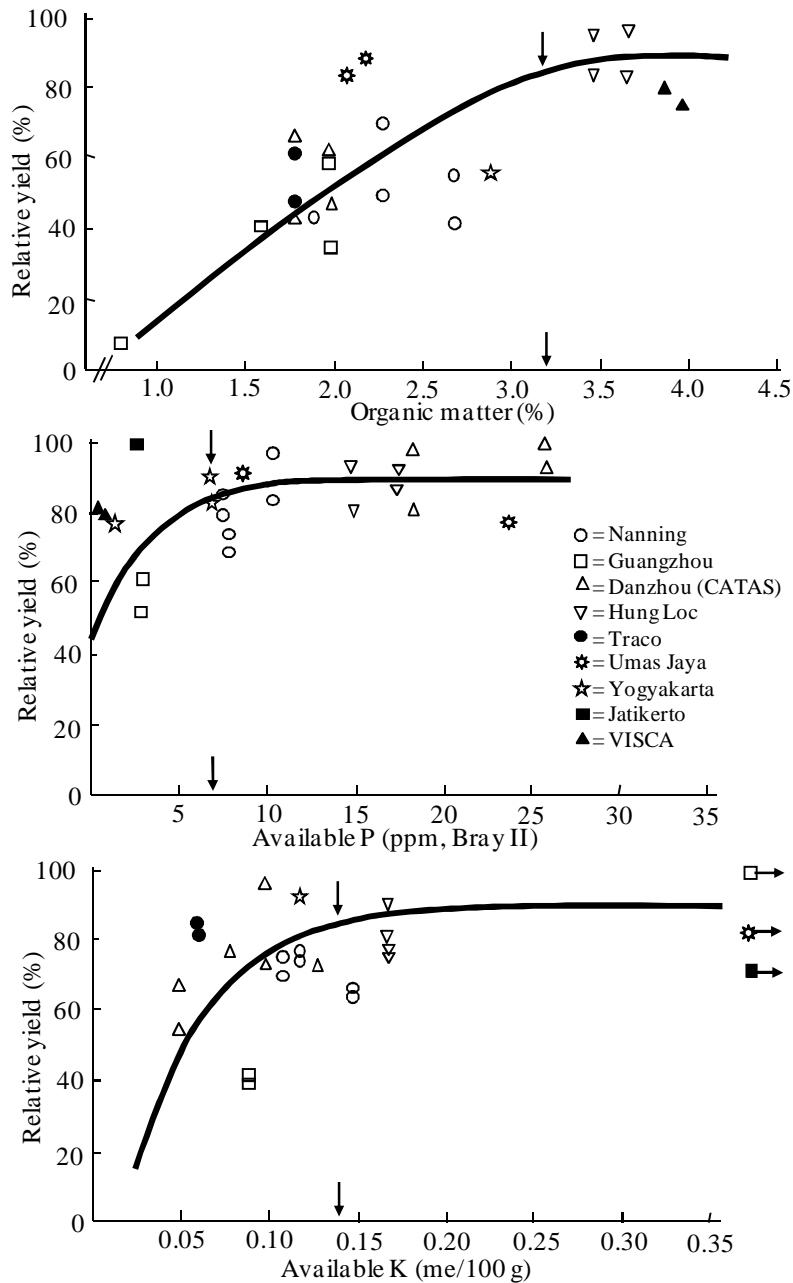
*Figure 3. Relation between the relative yield of cassava (i.e. the yield without the nutrient as a percent of the highest yield with the nutrient) and the OM, available P and exchangeable K contents of the soil in nine long-term NPK trials conducted in Asia from 1993-1996 (**Source:** Howeler, 1998).*

Correcting nutritional problems

Chemical fertilizers

While cassava performs better than most crops on infertile soils, the crop is highly responsive to fertilizer applications. High yields can be obtained and maintained only when adequate amounts of fertilizers and/or manures are applied. Thousands of fertilizer experiments conducted by FAO worldwide indicate that cassava is as responsive to fertilizer applications as other crops, with

yield increases of 49% (West Africa) to 110% (Latin America) vs. increases of 43% (yams and rice in West Africa) to 102% (rice in Latin America) for other crops. In West Africa (Ghana) cassava responded mainly to K; in Latin America (Brazil) to P; and in Asia (Indonesia and Thailand) to N (Richards, 1979; Hagens and Sittibusaya, 1990).

Table 3. Nutrient concentration in various plant parts of fertilised and unfertilised cassava cv. M Ven 77 at 3-4 MAP in Carimagua, Colombia (*Source*: Howeler, 1985a).

	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B
			(%)						($\mu g\ g^{-1}$)		
Unfertilised											
Leaf blades											
Upper	4.57	0.34	1.29	0.68	0.25	0.29	198	128	49	9.9	26
Middle	3.66	0.25	1.18	1.08	0.27	0.25	267	185	66	8.7	37
Lower	3.31	0.21	1.09	1.48	0.25	0.25	335	191	89	7.6	42
Fallen[1]	2.31	0.13	0.50	1.69	0.25	0.22	4850	209	121	9.4	39
Petioles											
Upper	1.50	0.17	1.60	1.32	0.37	0.10	79	172	40	4.4	16
Middle	0.70	0.10	1.32	2.20	0.43	0.10	76	304	72	2.9	15
Lower	0.63	0.09	1.35	2.69	0.45	0.13	92	361	110	2.8	15
Fallen	0.54	0.05	0.54	3.52	0.41	0.13	271	429	94	2.5	18
Stems											
Upper	1.64	0.20	1.22	1.53	0.32	0.19	133	115	36	9.7	14
Middle	1.03	0.18	0.87	1.45	0.30	0.16	74	103	39	8.9	13
Lower	0.78	0.21	0.81	1.19	0.32	0.16	184	95	54	7.9	10
Roots											
Rootlets[1]	1.52	0.15	1.02	0.77	0.38	0.16	5985	191	165	-	10
Thickened roots	0.42	0.10	0.71	0.13	0.06	0.05	127	10	16	3.0	4
Fertilised											
Leaf blades											
Upper	5.19	0.38	1.61	0.76	0.28	0.30	298	177	47	10.6	26
Middle	4.00	0.28	1.36	1.08	0.27	0.26	430	207	63	9.6	30
Lower	3.55	0.24	1.30	1.40	0.22	0.23	402	220	77	8.5	37
Fallen[1]	1.11	0.14	0.54	1.88	0.23	0.19	3333	247	120	8.9	38
Petioles											
Upper	1.49	0.17	2.18	1.58	0.36	0.10	87	238	33	4.9	17
Middle	0.84	0.09	1.84	2.58	0.41	0.07	88	359	49	3.0	14
Lower	0.78	0.09	1.69	3.54	0.42	0.07	95	417	70	3.2	15
Fallen	0.69	0.06	0.82	3.74	0.20	0.08	294	471	155	3.1	17
Stems											
Upper	2.13	0.23	2.09	2.09	0.47	0.14	94	140	37	9.8	14
Middle	1.57	0.21	1.26	1.30	0.26	0.11	110	120	46	10.8	12
Lower	1.37	0.28	1.14	1.31	0.23	0.09	210	99	36	10.0	10
Roots											
Rootlets[1]	1.71	0.19	1.03	0.71	0.33	0.20	3780	368	136	-	10
Thickened roots	0.88	0.14	1.05	0.16	0.06	0.05	127	15	15	3.9	4

[1] Fallen leaves and rootlets were probably contaminated with micronutrients from the soil.

Cassava is quite sensitive to over-fertilization, especially with N, which will result in excessive leaf formation at the expense of root growth. Cock (1975) reported that cassava has an optimal leaf area index of 2.5-3.5 and that high rates of fertilization may lead to excessive leaf growth and a leaf area index of >4. High N applications not only reduce the harvest index (HI) and root yield, but can also reduce the starch and increase the HCN content of the roots. Moreover, nutrients generally interact with each other, and the excessive application of one nutrient may induce a deficiency of another. Howeler *et al*. (1977) and Edwards and Kang (1978) have shown that high rates of lime application may actually reduce yields by inducing Zn deficiency. Spear *et al*. (1978b) showed that increasing the K concentration in nutrient solution decreased the absorption of Ca and especially Mg, leading to Mg deficiency. However, in both nutrient solution and field experiments with varying rates of applications of K, Ca and Mg, Howeler (1985b) did not find a

significant effect of increasing K on the Ca concentration in the leaves. The Mg concentration decreased slightly in the field, but increased in the nutrient solution experiment. Increasing Mg supply markedly decreased the concentrations of K and Ca. Similarly, Ngongi *et al.* (1977) reported that high applications of KCl induced S deficiency in a low-S soil in Colombia; while Nair *et al.* (1988) found that high rates of P application induced Zn deficiency. Hence, it is important not only to apply the right amount of each nutrient, but also the right balance among the various nutrients.

Table 4. Nutrient concentrations in YFEL blades of cassava at 3-4 MAP, corresponding to various nutritional states of the plants; data are averages of various greenhouse and field trials (*Source:* Howeler, 1996a, b).

Nutrient	Nutritional states[1]					
	Very deficient	Deficient	Low	Sufficient	High	Toxic
N (%)	<4.0	4.1-4.8	4.8-5.1	5.1-5.8	>5.8	-[2]
P (%)	<0.25	0.25-0.36	0.36-0.38	0.38-0.50	>0.50	-
K (%)	<0.85	0.85-1.26	1.26-1.42	1.42-1.88	1.88-2.40	>2.40
Ca (%)	<0.25	0.25-0.41	0.41-0.50	0.50-0.72	0.72-0.88	>0.88
Mg (%)	<0.15	0.15-0.22	0.22-0.24	0.24-0.29	>0.29	-
S (%)	<0.20	0.20-0.27	0.27-0.30	0.30-0.36	>0.36	-
B (μg g^{-1})	<7	7-15	15-18	18-28	28-64	>64
Cu (μg g^{-1})	<1.5	1.5-4.8	4.8-6.0	6-10	10-15	>15
Fe (μg g^{-1})	<100	100-110	110-120	120-140	140-200	>200
Mn (μg g^{-1})	<30	30-40	40-50	50-150	150-250	>250
Zn (μg g^{-1})	<25	25-32	32-35	35-57	57-120	>120

[1] Very deficient = <40%   maximum yield
   Deficient   = 40-80% maximum yield
   Low   = 80-90% maximum yield
   Sufficient   = 90-100% maximum yield
   High   = 100-90% maximum yield
   Toxic   = <90%   maximum yield
[2] - = no data available

Nitrogen. Severe N deficiency is usually observed in very sandy soils low in OM, but may also be found in high-OM, but acid soils, mainly due to a low rate of N mineralization.

Significant responses to N have been observed more frequently in Asia than in Latin America or Africa. In nearly 100 NPK trials conducted by FAO on farmers' fields in Thailand, there was mainly a response to N, followed by K and P (Hagens and Sittibusaya, 1990). Similar results were obtained in 69 trials conducted in Indonesia (FAO, 1980). In Africa relatively few fertilizer trials have been conducted with cassava, mainly because very few cassava farmers apply fertilizers. In West Africa the responses to N were probably the most frequent (Okogun *et al.*, 1999). In Latin America responses to N were the least frequent, with significant responses reported in only 5 out of 41 trials conducted in Brazil (Gomes, 1998) and in 5 out of 22 trials conducted in Colombia (Howeler and Cadavid, 1990).

On a very sandy soil (89% sand, 0.7% OM) in Jaguaruna, Santa Catarina, Brazil, two local varieties showed a nearly linear response up to 150 kg N/ha. For both varieties highest yields were obtained with a split application of N, with one-third applied at 30, 60 and 90 days after planting (Moraes *et al.*, 1981). A similarly spectacular response to N was also observed in a clay soil with 1.2% OM in Jatikerto, East Java, Indonesia (**Figure 4**). In this case, cassava was intercropped with maize, which competed strongly for the limited supply of N in the soil (Wargiono *et al.*, 1998). In Nanning, Guangxi, China, there was also a highly significant response to N (Zhang Weite *et al.,* 1998), up to 200 kg N/ha in one cultivar (SC205), but only up to 50 kg N/ha in the other (SC201). As the latter cultivar is extremely vigorous, high N levels produced too much top growth at the expense of root production. Similar negative responses to high N applications

have been reported by Vijayan and Aiyer (1969), Acosta and Perez (1954), Obigbesan and Fayemi (1976) and Fox *et al.* (1975). Krochmal and Samuels (1970) reported a root yield reduction of 41% and top growth increase of 11% due to high N applications. These high rates also stimulate production of N-containing compounds, such as protein and HCN, and may result in a decrease in root starch content. High rates of N application may also increase the intensity of diseases such as cassava bacterial blight (Kang and Okeke, 1984). Thus N rates must not only be adjusted to a particular soil but also tailored to the needs of a particular cultivar.
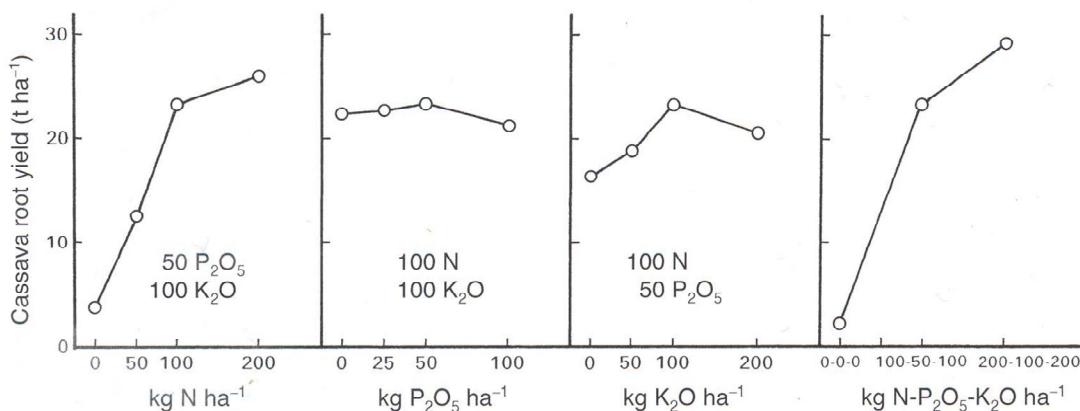

*Figure 4. Response of cassava cv. Faroka to the annual application of various levels of N, P and K during the 7th cycle in Jatikerto, East Java, Indonesia in 1994/95 (**Source:** Wargiono et al., 1998).*

Trials on optimum time and fractionation of N applications have generally shown non-significant differences between single applications at planting, at one MAP or various fractionations (0-3 MAP) using N rates up to 100 kg N ha^{-1} (Howeler, 1985a). At higher rates, fractionation was found to be better than a single application.

There are usually no significant differences among N sources such as urea, NH_4NO_3, mono- or di-ammonium phosphate. Vinod and Nair (1992) reported significantly higher yields with slow-release N sources such as neem cake-coated urea or super-granules of urea.

When cassava is grown for forage production, spacing is greatly reduced (0.6 x 0.6 m), and green tops are cut off at 3-4 month intervals. The offtake of N is very high, sometimes >300 kg N ha^{-1} yr^{-1} (CIAT, 1988a,b; Putthacharoen *et al.*, 1998). High rates of N (>200 kg ha^{-1}) need to be applied to sustain high levels of shoot and root production.

Phosphorus. Cassava's tolerance to low P concentrations in soil solution is not due to the efficient uptake of P by the root system; in fact, cassava grown in flowing nutrient solution required a much higher P concentration for maximum growth than rice, maize, cowpeas or common beans (Jintakanon *et al.*, 1982; Howeler *et al.*, 1981; Howeler 1990). When inoculated with endotrophic VAM, the growth of cassava in nutrient solution improved significantly (Howeler *et al.*, 1982a). Masses of mycorrhizal hyphae growing in and around the fibrous roots of cassava markedly increased the plant's ability to absorb P from the surrounding medium (**Photo 1**). When planted in natural soil, the crop's fibrous roots soon become infected with native soil mycorrhizae. The resulting hyphae grow into the surrounding soil and help in the uptake and transport of P to the cassava roots. Through this highly effective symbiosis, cassava is able to absorb P from soils with low levels of available P, mainly by extending the soil volume from which P can be absorbed through the associated mycorrhizal hyphae.

Responses of cassava to P application depend on the available-P level of the soil, the mycorrhizal population and the variety used. Van der Zaag *et al.* (1979) reported high yields of 42 t ha^{-1} in an oxisol in Hawaii with only 3 µg P g^{-1} (NaHCO$_3$-extractant) using the cultivar Ceiba. CIAT (1988a) similarly reported that some varieties produced yields of 40-50 t ha^{-1} without P

application in a soil with only 4.6 µg P g^{-1} (Bray II). In other soils with equally low levels of available P but with a less-efficient mycorrhizal population, cassava responded very markedly to P applications. Thus in the oxisols of the Eastern Plains of Colombia, with only 1.0 µg P g^{-1} (Bray II), cassava responded markedly to applications of 200-400 kg P$_2$O$_5$ ha^{-1} (**Figure 5**). Of the seven P sources tested, banding of triple superphosphate (TSP) or broadcast applications of basic slag were most effective. Partially acidulated rock phosphate (RP) or RP mixed with elemental sulphur (S) were also quite effective in these acid soils (CIAT, 1978). Locally produced simple superphosphate (SSP) was less effective, except at high rates of application. Similarly, Santos and Tupinamba (1981) reported significant responses to 60 or 120 kg P$_2$O$_5$ ha^{-1} in three soils of Sergipe, Brazil, with TSP and hyperphosphate being more effective than two local sources of RP. Soluble-P sources like TSP, SSP, mono- or di-ammonium phosphate, should be band applied near the stakes; while less-soluble sources such as basic slag and RPs should be broadcast and incorporated. All P should be applied at or shortly after planting as fractionation of P had no significant effect on yield. Alternative methods of P application, such as stake treatments or foliar sprays, are not as effective as soil application in increasing yields (Howeler, 1985a).
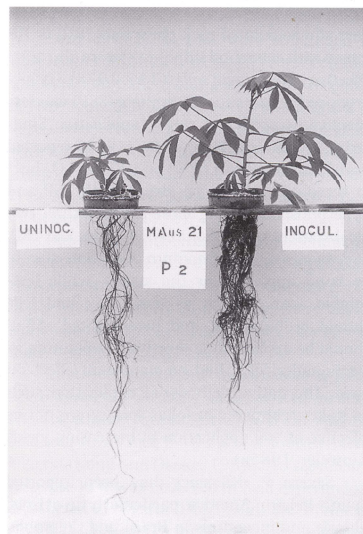

Photo 1. Cassava cv. M Aus 21, grown in flowing solution culture with 1 µM phosphate, with (right) and without (left) mycorrhizal inoculation.

Severe P deficiency has been reported mainly in Latin America, particularly on oxisols, ultisols and inceptisols in Brazil and Colombia. These soils are highly P fixing and have available (Bray II or Mehlich I) P levels of only 1-2 µg g^{-1}. During the first year(s) of cropping, cassava responds markedly to P application; but with continuous cropping on the same land, responses to P become less significant as soil P levels build up from previous applications (Nair *et al.*, 1988; Howeler and Cadavid, 1990; Kabeerathumma *et al.*, 1990).

In Asia P deficiency is seldom the principal limiting factor for cassava production because most cassava is grown on soils with more than 4 µg g^{-1} of available P and/or that have been previously fertilised with P. Nevertheless, significant responses to P application have been observed in Guangzhou (Guangdong), Nanning (Guangxi) and on Hainan Island of China; in northern and southern Vietnam; and on Leyte Island of the Philippines. In low-P soils in Kerala State, India, significant initial responses to 100 kg P$_2$O$_5$ ha^{-1} were reported; but these declined over time. Nair *et al.* (1988) determined an optimum economic rate of 45 kg P$_2$O$_5$ ha^{-1}.

In Africa few P experiments have been conducted with cassava. Responses to P application have been reported mainly in Ghana (Stephens, 1960; Takyi, 1972) and Madagascar (Cours *et al.*, 1961). Ofori (1973) reported a negative effect of P application on cassava yields on a forest ochrosol in Ghana.
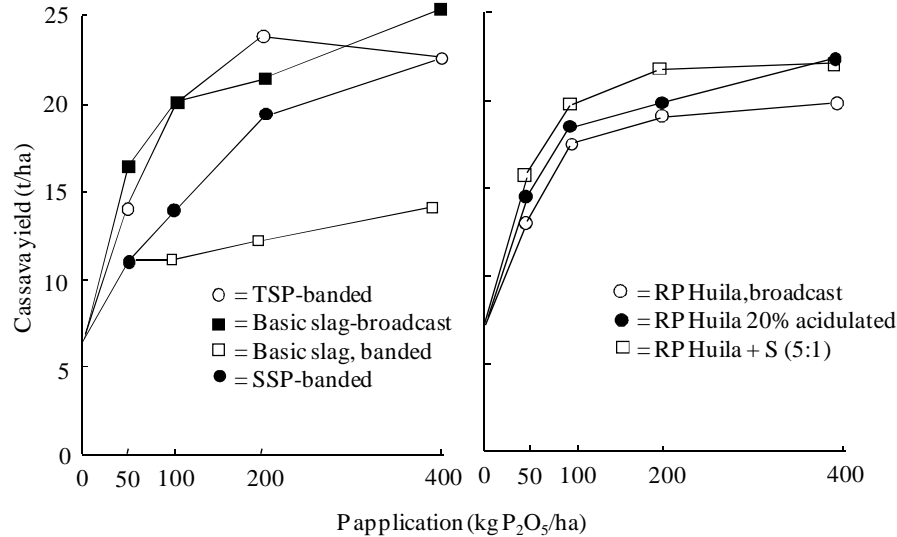
Figure 5. Response of cassava cv. Llanera to application of different levels and sources of P in Carimagua, Colombia (**Source:** CIAT, 1977).

Large varietal differences have been observed in cassava's ability to grow on low-P soils (CIAT, 1988a,b). Pellet and El-Sharkawy (1993a,b) found that varietal differences in response to applied P were not due to genetic differences in P-uptake efficiencies, but rather to contrasting patterns of DM distribution and P-use efficiency (root yield total P^{-1} in plant). Low-P tolerant cultivars had a high fine root-length density, moderate top growth, and a high, stable HI.

Potassium. Although K is not a basic component of protein, carbohydrates or fats, it plays an important role in their metabolism. Potassium stimulates net photosynthetic activity of a given leaf area and increases the translocation of photosynthates to the tuberous roots. This results in low carbohydrate levels in the leaves, further increasing photosynthetic activity (Kasele, 1980).

Blin (1905), Obigbesan (1973) and Howeler (1998) reported that K application not only increased root yields but also their starch content. Similar increases in starch content with increasing applications of K have been observed in Carimagua (CIAT, 1982) and Pescador, Colombia (Howeler, 1985a), as well as in southern Vietnam (Nguyen Huu Hy *et al.*, 1998) and China (Howeler, 1998). In general root starch content increases up to 80-100 kg K_2O ha^{-1} and then decreases at higher rates of K application. Obigbesan (1973) and Kabeerathumma *et al.* (1990) reported that K also decreased the HCN content of roots, while Payne and Webster (1956) found highest levels of HCN in roots produced in low-K soils.

Potassium deficiency in cassava is generally found in tropical soils with low-activity clay such as oxisols, ultisols and inceptisols, as well as in alfisols derived from sandstone. After land clearing the alfisols have a reasonable level of exchangeable K, but often show a significant K response in the second year of planting because of low K reserves in the parent material (Kang and Okeke, 1984).

Long-term experiments in Asia and Colombia have shown that K deficiency invariably becomes the main limiting factor when cassava is grown continuously on the same soil without adequate K fertilization (see "Long-term effect…"). **Figure 6** shows that without K application, yields declined from 22.4 to 6.3 t ha^{-1} during ten years of continuous cropping in Trivandrum, Kerala, India (Kabeerathumma *et al.*, 1990). During that time, exchangeable K of the soil gradually declined from 0.18 to 0.064 meq 100 g^{-1}. High yields of 20-30 t ha^{-1} could be maintained with annual applications of 100 kg N, 100 P_2O_5 and 100 K_2O ha^{-1}. The high rate of P used led to a buildup of soil P to excessive levels (~100 µg P g^{-1}). There was also a slight buildup of exchangeable K to a

level of 0.25 meq 100 g^{-1}. This contrasts with reports by Howeler and Cadavid (1990), which show that eight years of continuous cropping with annual applications of 150 kg K_2O ha^{-1} in Quilichao, Colombia, maintained the exchangeable K content at only 0.2 meq 100 g^{-1}. In a very poor sandy soil near the Atlantic Coast of Colombia, Cadavid *et al.* (1998) also found that annual applications of 50 kg N, 50 P_2O_5 and 50 K_2O ha^{-1} increased yields during eight years of continuous cropping, but had no effect on soil K, which remained at a low level(0.06 meq 100 g^{-1}).
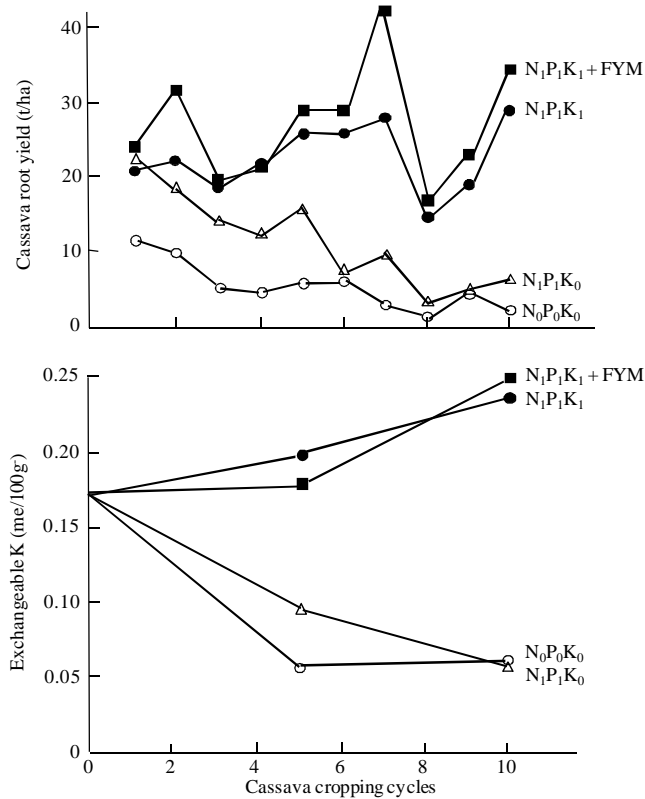

Figure 6.   *Cassava yield (top) and the exchangeable K content of the soil (bottom) during 10 years of continuous cropping with various NPK treatments in Trivandrum, Kerala, India (**Source:** Kabeerathumma et al., 1990).*

Table 5 shows the responses in other long-term NPK trials conducted in four Asian countries. After 4-10 years of continuous cropping, there was a significant response to N in 8 out of 11 sites, to P in 4 and to K in 7. Responses to K increased most markedly with time (Nguyen Huu Hy *et al.*, 1998; Howeler, 2000); but in Malang, Indonesia, responses to N increased more markedly (Wargiono *et al.*, 1998).

Data from short-term NPK trials conducted in Brazil (Gomes, 1998) indicate that significant responses to K were obtained in only 9 out of 48 trials; similarly in Colombia there was a significant K response in 6 out of 22 locations, mainly in the Eastern Plains.

In Africa, significant responses to K have been found on strongly acid soils of eastern Nigeria (Okeke, unpublished) and on slightly acid soils (0.23 meq K 100 g^{-1}) of southwestern Nigeria (Kang and Okeke, 1984). Obigbesan (1977) did not observe a significant K response on three soils of western Nigeria, nor did Takyi (1972) in Ghana. In Madagascar, however, Roche *et al.* (1957) and Cours *et al.* (1961) found that K was the main limiting nutrient, and applications of 110 kg K_2O ha^{-1} were recommended (Anon., 1952; 1953).

Table 5. Response of cassava to annual application of NPK after several years of continuous cropping in long-term fertility trials conducted at various locations in Asia (Source: CIAT, 1998).

Country/location		Years of cropping	Response to		
			N	P	K
China	-Guangzhou	4	**[1]	**	**
	-Nanning	8	**	**	NS
	-Danzhou	6	**	NS	*
Indonesia	-Umas Jaya	10	NS	NS	NS
	-Malang	8	**	NS	**
	-Lampung	6	**	*	**
	-Yogyakarta	4	NS	NS	NS
Philippines	-Leyte	6	NS	NS	NS
	-Bohol	4	**	NS	**
Vietnam	-Thai Nguyen	8	**	**	**
	-Hung Loc	8	**	NS	**

[1] NS = no significant response.
  * = significant response (P<0.05).
  ** = highly significant response (P<0.01).

Experiments on different sources of K have generally shown no significant differences between the use of KCl, K_2SO_4 or Sulphomag (CIAT, 1985a), while in southern India the use of syngenite and schoenite (extracted from seawater) were also found to be equally effective (CTCRI, 1974; 1975). In low-S soils in the Eastern Plains of Colombia, however, Ngongi et al. (1977) obtained much better yields with application of K_2SO_4 or KCl+S than with KCl. This was mainly a response to S; the same experiment conducted in Jamundí, Colombia, did not show any difference between K sources.

Experiments on the optimum time of K application have produced somewhat contradictory results, but generally there were no significant differences between single or fractionated applications or among different times of application (CIAT, 1982). Overall, a single application at one MAP produced the highest yield. In India, Ashokan and Shreedharan (1980) recommended split application of K only when low rates were applied, but CTCRI (1972) found no significant differences among different times of application in Trivandrum, India.

Calcium and magnesium. Calcium plays an important role in the supply and regulation of water in the plant, while Mg is a basic component of chlorophyll and as such is essential for photosynthesis.

Symptoms of Ca deficiency are seldom observed in the field; but in very acid soils with low levels of exchangeable Ca (<0.25 meq 100 g^{-1}), the crop may respond to Ca applications. In Carimagua-Alegría, Colombia, highly significant responses to application of Ca were obtained on a sandy loam soil with a pH of 5.1 and only 0.18 meq Ca 100 g^{-1} and 0.05 meq Mg 100 g^{-1} (**Figure 7**). Highest yields were obtained with application of 200-400 kg Ca ha^{-1} as broadcast gypsum. Broadcast calcitic or dolomitic limes were less effective, while band-applied gypsum was ineffective in increasing cassava yields (CIAT, 1985a). As these Ca sources are relatively insoluble, they should all be broadcast and incorporated before planting. The good response to gypsum was not a response to S because either $MgSO_4$ or S were applied uniformly to all plots.

In the same soil in Carimagua, a Mg-experiment was conducted to determine the optimum rates and best sources of Mg (CIAT, 1985a). There was a significant response up to the highest level of 60 kg Mg ha^{-1}, but there were no overall significant differences among sources; the more soluble Sulphomag was more effective at intermediate rates, while banded $MgSO_4$ or broadcast MgO were better at higher rates of application (**Figure 8).**
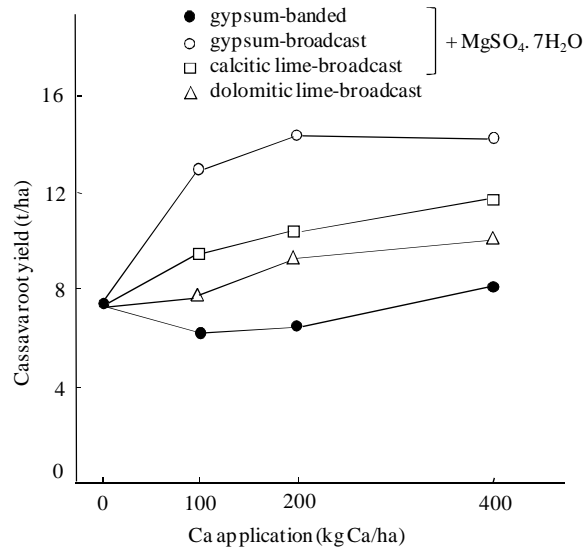

*Figure 7. Effect of different levels, sources and methods of applying Ca on root yield of cassava cv. CM 523-1, in Carimagua, Colombia (**Source:** CIAT, 1985a).*
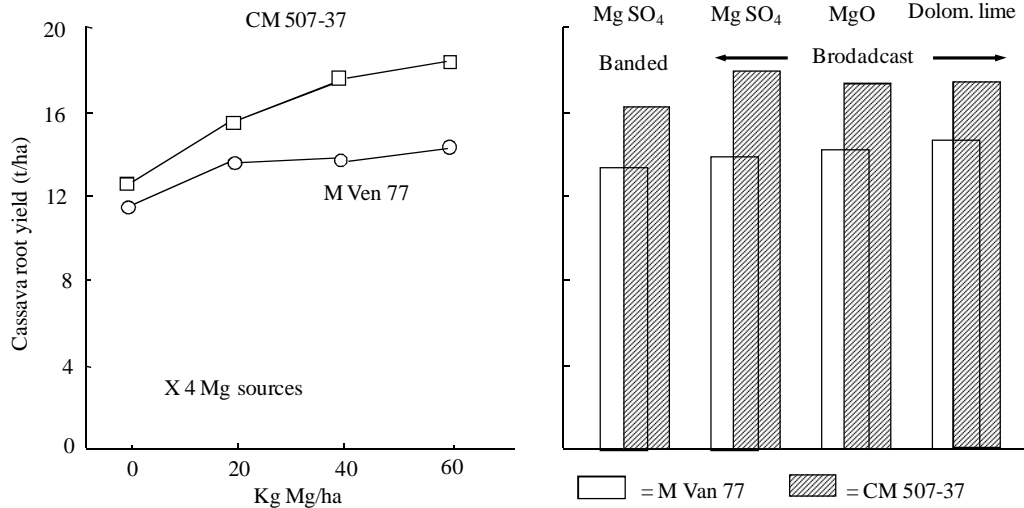

*Figure 8. Response of cassava cv. CM 430-37 to various levels of Mg applied as four different sources in Carimagua-Alegria, Colombia (**Source:** CIAT, 1985a).*

Experiments conducted in nutrient solution culture showed that increasing concentrations of Ca in solution markedly reduced the concentrations of K and Mg in YFEL blades at 2 MAP, and that increasing concentrations of Mg in solution similarly decreased the concentrations of K and Ca in the leaves. In field experiments in Carimagua, however, increasing levels of Ca or Mg had no effect on leaf concentration of K, and only slightly decreased the concentrations of Mg or Ca, respectively (Howeler, 1985b). There appears to be a strong antagonistic effect between K and Mg and between Ca and Mg, but not between K and Ca.

Sulphur. This basic component of certain amino acids is essential for producing protein. In industrial areas much of the plant's S requirements are met from S emissions into the atmosphere, but in isolated areas cassava may suffer from S deficiency. This has been reported only for Carimagua, Colombia, which is far removed from any industrial centres. Soils there contained only 23 µg of Ca phosphate-extractable S g^{-1} of soil; with application of 40 kg S ha^{-1} as elemental S this increased to 36 µg g^{-1}. A clear response to applying S up to 20-40 kg S ha^{-1} was observed. There were no significant differences among S sources although yields were slightly higher with banded K- and Mg-sulphate than with broadcast elemental S. Clear S-deficiency symptoms were observed in the check plots. These plants had 0.20-0.25% S in YFEL blades, compared with 0.30-0.32% in plants that had received S applications. Critical levels of 0.27 and 0.33% S were estimated in two field experiments (Howeler, unpublished).

Micronutrients. Deficiencies are generally observed in high pH or calcareous soils, but deficiencies of Zn have been observed in both acid and alkaline soils. Lime application to acid soils with low levels of available Zn may induce Zn deficiency, resulting in low yields and even death of young plants (see "Acid soils").

- *Zinc*. Cassava is quite susceptible to Zn deficiency, especially in the early stages of growth. Plants showing early symptoms of Zn deficiency may later recuperate once the fibrous root system is well established and roots become infected with mycorrhizae. If the deficiency is severe, however, plants may either die or produce very low yields. A trial was conducted in Carimagua-Alegría to determine the response of two varieties to soil application of different levels of Zn as $ZnSO_4$. $7H_2O$ after applying 2 t ha^{-1} of lime (CIAT, 1985a). Both varieties were seriously affected by Zn deficiency in the check plots, but reached maximum yields with application of 10 kg Zn ha^{-1}, band applied with NPK at planting. Relating the root yield of M Ven 77 and the Zn concentration in YFEL blades, a critical level of 33 µg Zn g^{-1} was estimated. Broadcast application of 10-20 kg ha^{-1} of Zn as ZnO was also effective in increasing yields in acid soils (CIAT, 1978).

  In high-pH soils application of $ZnSO_4$. $7H_2O$ to the soil is not so effective because the applied Zn is precipitated rapidly (CIAT, 1978). Foliar application or stake treatments may be more effective. When 20 cassava cultivars were planted in a high-pH (7.9), low-Zn (1.0 µg g^{-1}) soil, with or without treating stakes for 15 min in a solution of 4% $ZnSO_4$. $7H_2O$ before planting, yields increased from an average 11.5 to 25.0 t ha^{-1} due to the Zn treatment (CIAT, 1985a). Large varietal differences in low-Zn tolerance were observed, with some cultivars dying off completely without the Zn treatment, while others produced high yields with or without Zn. Dipping stakes for 15 min in a $ZnSO_4$. $7H_2O$ solution and air-drying the stakes overnight before planting is a very inexpensive yet effective way to reduce Zn deficiency in cassava when grown on low-Zn soils.

- *Copper*. This deficiency in cassava has been reported only on peat soils in Malaysia (Chew, 1971). Chew *et al*. (1978) recommended a basal application of 2.5 kg Cu ha^{-1} as $CuSO_4$. $5H_2O$.

- *Iron and manganese*. Deficiency symptoms of Fe are often observed in calcareous soils such as in the Yucatan peninsula of Mexico, parts of northern Colombia, Southeast Java of Indonesia and western Nakorn Rachasima province of Thailand. Mn deficiency has been observed in sandy soils along the coast in Northeast Brazil, in alkaline soils at CIAT, Colombia, and in northern Vietnam, near houses where lime had been used for their

construction. A practical solution is probably a stake treatment with 2-4% $FeSO_4$. H_2O or $MnSO_4$. $4H_2O$ before planting, or foliar sprays with sulphates or chelates.

- *Boron.* Symptoms of B deficiency have been observed in both acid soils of Carimagua and Quilichao, as well as in alkaline soils at CIAT, Colombia. Similar symptoms were also observed in North Vietnam and southern China, although the exact nature of that problem was never identified. In Colombia, application of 1-2 kg B ha^{-1}, band applied as borax at planting, eliminated the symptoms, increased plant height, increased B concentrations in the leaves from 3 to 40 µg g^{-1}, but had no significant effect on yield. Thus it seems that cassava is quite tolerant of low levels of available B in the soil.

Soil amendments

Soil amendments are usually applied to increase the pH of acid soils or decrease the pH of alkaline soils, but they can also serve to improve the physical conditions of the soil or improve nutrient availability.

Acid soils. Very acid soils present a complex of problems for plant growth, including low pH, high concentrations of Al and/or Mn, low levels of Ca, Mg and K, and sometimes low P and N. Cassava as a species is particularly tolerant of soil acidity and high levels of Al (Gunatilaka, 1977; CIAT, 1979; Islam *et al.*, 1980), but some varietal differences in acid soil tolerance have also been observed (CIAT, 1982; 1985a; Howeler, 1991a). In very acid (pH<4.5) and high Al (>80% Al saturation) soils, lime application may increase cassava yields, mainly by supplying Ca and Mg as nutrients. High rates of lime may, however, induce micronutrient deficiencies, particularly Zn, resulting in decreased yield (Spain *et al.*, 1975; Edwards and Kang, 1978). **Figure 9** shows that without Zn, cassava responded to lime applications only up to 2 t ha^{-1}, but with applied Zn there was a positive response up to 6 t ha^{-1} of lime. Analysis of cassava leaves confirmed that liming reduced Zn uptake and that with 6 t ha^{-1} of lime without Zn, the Zn concentrating in YFEL blades dropped below the critical level of 40-50 µg g^{-1}. Large varietal differences have been found for both high-Al and low-Zn tolerance (Spain *et al.*, 1975).
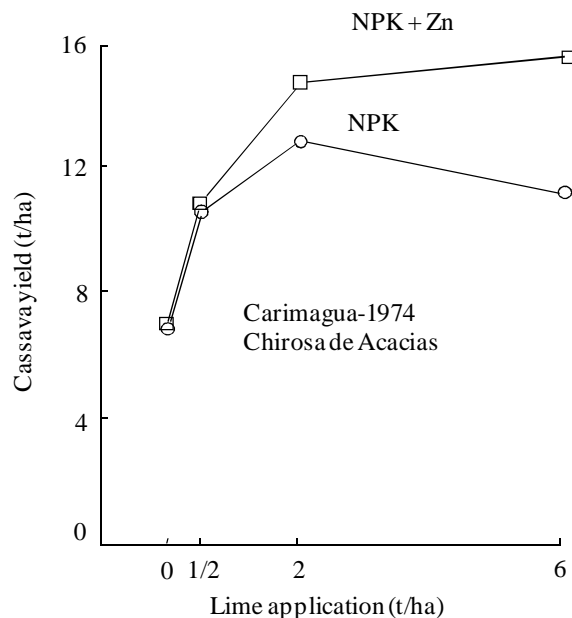

Figure 9. The response of cassava, cv Chirosa de Acacias, to lime with and without the Application of 20 kg/ha of Zn in Carimagua in 1974.

Saline-alkaline soils. Cassava is not well adapted to saline and alkaline soils and may suffer from a combination of high pH, high Na, high salt and low uptake of micronutrients. Yields can be improved by applying 1-2 t ha^{-1} of elemental S or 1-2 t ha^{-1} of H_2SO_4 (CIAT, 1977), but this is seldom justified economically. Most cultivars will tolerate a pH up to about 8.0, Na saturation up to about 2%, and conductivity up to 0.5 mS cm^{-1} (CIAT, 1977). Large varietal differences in tolerance have been observed, and the use of tolerant varieties is probably the most practical solution.

Animal manures and compost

Many cassava farmers apply animal manures or compost to cassava with good results, but little research has been conducted to determine optimum rates and methods of application.

In Vietnam and south China most farmers apply 5-10 t ha^{-1} of pig manure, in Indonesia up to 9 t ha^{-1} of cattle manure, and in Cauca province of Colombia, 4-5 t ha^{-1} of chicken manure. Animal manures tend to have low nutrient contents (<10% of that in most compound fertilizers), but they do contain Ca, Mg, S and some micronutrients not found in most chemical fertilizers (Howeler, 1980b). In addition, they may improve the physical conditions of the soil, although this has not been well documented.

Silva (1970) reported good responses to applications of 6-15 t ha^{-1} of cattle manure in Rio Grande do Norte of Brazil; higher applications decreased yields. Howeler (1985a) reported that 4.3 t ha^{-1} chicken manure (corresponding to 170 kg P_2O_5 ha^{-1}) increased cassava yields in Mondomo, Colombia, from 19 to 31 t ha^{-1}. The chicken manure was about twice as effective as cattle manure or 10-30-10 compound fertilizer, applied at equivalent levels of P. The total amount of nutrients applied with the chicken manure was considerably higher than that applied in the chemical fertilizer, but the greater beneficial effect must also be due to improved soil structure, presence of essential elements other than NPK, and the stimulation of beneficial microorganisms such as VAM. If these manures have to be transported over long distances, the higher cost of transport and application may make them more expensive than chemical fertilizers. Moreover, in many countries like Thailand, animal manures are not readily available.

In Bahia, Brazil, Gomes *et al.* (1983) obtained very high yields with a system called "*parcagem*", which is basically *in situ* application of cattle manure, where a large number of cattle are enclosed overnight on a small piece of land. It was calculated that 30 animals kept overnight on 1 ha for 60 days will produce about 8 t of dry manure containing 40 kg N (plus the N in the urine). At an equal dosage of 40 kg N ha^{-1}, cassava yields with the *parcagem* system (combined with additional P and K) increased 30-90% as compared to application of only chemical fertilizers. This system may be economically viable in areas with large cattle populations. Good results were also obtained in Bahia when applying 5 t ha^{-1} of cattle manure combined with 10 kg P_2O_5 ha^{-1} (Diniz *et al.*, 1994).

Little information is available on the effectiveness of applying compost, which is considerably lower in nutrients than animal manures (Howeler and Thai Phien, 2001); but when applied in large quantities (10-15 t ha^{-1}), they may supply considerable amounts of nutrients as well as improving the soil's physical condition and water-holding capacity. Application of 6-10 t ha^{-1} of compost made from cassava peel residues in starch factories has given promising results in Thailand. In Brazil the application of 5 t ha^{-1} of *vinhoto* (by-product of alcohol production) increased yields, especially when fortified with 60 kg P_2O_5 and 1 t lime (Souza *et al.*, 1992).

Green manures, cover crops and mulch

Planting of green manures and their subsequent mulching or incorporation into the soil have been practised traditionally as a form of "improved fallow" to maintain soil fertility. Research on the use of green manures and cover crops to maintain soil fertility in cassava fields was recently reviewed

(Howeler *et al.*, 2000). In the absence of chemical fertilizers, green manures increased yields slightly in Quilichao, Colombia, but significantly on sandy soils in Media Luna, Colombia. In the presence of fertilizers the effect was minimal. Most effective were kudzu (*Puerarea phaseoloides*), Zornia (*Zornia latifolium*) and groundnuts (*Arachis hypogea*) in Quilichao; and local weeds and *Canavalia ensiformis* in Media Luna. In Thailand *Crotalaria juncea* was the most productive and effective in increasing yields. The growing of green manures before planting cassava was found to be impractical, however, as cassava yields were markedly reduced by planting too late in the wet season (Howeler, 1992; 1995).

Research on cover crops in both Colombia (Ruppenthal, 1995; Muhr *et al.*, 1995) and Thailand (Howeler, 1992; Tongglum *et al.*, 1992; 1998) indicate that almost all species compete too strongly with cassava for soil water and nutrients, resulting in unacceptably low cassava yields, especially in the second and third year after cover-crop establishment. It is clear that cassava is a weak competitor, and yields are seriously reduced by competition from weeds or cover crops.

Planting intercrops such as maize, groundnuts, cowpeas, common beans, mungbeans or soyabeans and incorporating the residue after harvest may improve soil fertility (especially if the intercrops are fertilised), help reduce erosion and provide the farmer with additional food or income, without reducing cassava yields too seriously (Leihner, 1983).

Application of mulch of local weeds, cut-and-carry grass or crop residues such as rice straw or maize stalks can also improve soil fertility and moisture, as well as reduce surface temperature and erosion. In Africa application of mulch, especially that of leguminous species, increased cassava yields in acid sandy soils (Ofori, 1973; Hulugalle *et al.*, 1991). In sandy soils on the Atlantic Coast of Colombia, Cadavid *et al.* (1998) reported that annual applications of 12 t ha^{-1} of dry *Panicum maximum* grass as mulch significantly increased cassava yields during eight consecutive years of cropping, especially in the absence of chemical fertilizers. It also increased root DM content and decreased HCN levels. Annual mulching gradually increased soil P and especially soil K, and prevented a decline in soil Ca and Mg. In addition, the mulch cover reduced soil temperatures in the top 20 cm of soil and enhanced the maintenance of soil C. Thus application of mulch, where available, can be another effective way of improving soil productivity.

Inoculation with mycorrhizae

As indicated above, cassava can grow well in low-P soils because of a highly efficient symbiosis with VAM, which occur naturally in the soil. Without VAM cassava would require an application of at least 1-2 t ha^{-1} of P to obtain the same yield as plants with VAM but without P (Howeler, 1980a; Howeler *et al.*, 1982b). Compared with six other tropical crops and forages, cassava was found to be the most dependent on VAM (Howeler *et al.*, 1987).

Soils, however, differ in both quantity and quality of native mycorrhizae and, thus, in the crop's responses to P application (Sieverding and Howeler, 1985; Howeler *et al.*, 1987). Of many VAM species tested, *Glomus manihotis* was one of the most effective species for increasing cassava growth and yield in acid soils. *G. manihotis* was also found to compete strongly with other VAM species in the range of 50-200 kg ha^{-1} of applied P. Inoculation with *G. manihotis* markedly increased cassava growth in greenhouse experiments using sterilised soils. The effect was significant but less dramatic in non-sterilised soil. When plots in the field were sterilised with methyl bromide to kill the native VAM in the topsoil, re-inoculation of the soil with VAM markedly improved initial plant growth (**Photo 2**). Non-inoculated plants grew poorly, showing clear symptoms of P deficiency. Once the roots of these non-inoculated plants reached the non-sterilised subsoil, however, they soon became infected with VAM and recuperated. In Quilichao, Colombia, which has a highly effective native VAM population dominated by *Glomus manihotis*, non-inoculated plants in the sterilised plots attained as high yields as those in the unsterilised soil. Inoculated plants growing in the sterilised soil produced 40% higher yields (Howeler *et al.*, 1982b). In other experiments at Quilichao, soil sterilization markedly reduced yields, but

inoculation of plants growing in unsterilised soil did not increase yields (**Figure 10**) because of the highly effective native VAM population.

Photo 2.   Effect of inoculation with VAM (right) on the growth of cassava, cv. CM 91-3, grown in soil sterilized by fumigation with methyl bromide in Quilichao, Colombia.
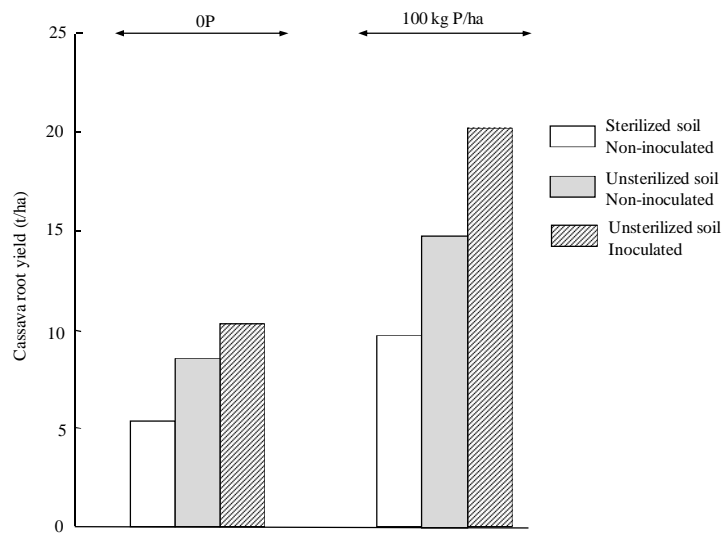

*Figure 10.   Effect of soil sterilization, P application and mycorrhizal inoculation on root yield of cassava cv. M Ven 77, grown in Carimagua-Yopare, Colombia; numbers on bars indicate the percent response to inoculation (**Source:** Howeler and Sieverding, 1983).*

In soils with a less effective native VAM population, such as in Carimagua, Colombia, inoculation of plants grown in sterilised soil increased yields nearly three-fold without applied P and 164% with 100 kg P ha^{-1}. In unsterilised soil the effect of inoculation was not significant without applied P, but significant with 100 kg P ha^{-1}. In a similar trial in Carimagua, using different sources of P, VAM inoculation in unsterilised soil had no effect without P application but increased yields significantly (22%) at an intermediate application of 100 kg P ha^{-1} (Howeler and Sieverding, 1983).

Numerous experiments on VAM inoculation of cassava growing in natural soils in Colombia indicate that responses vary from location to location, depending on the efficiency of the native VAM population and the ability of the introduced species to compete with the native population. In areas with less-effective native populations, such Carimagua, Colombia, yields increased 23% by inoculation, but this may decrease over time once cassava cultivation has stimulated a buildup of native mycorrhizae. In other locations the effect of inoculation was smaller and not consistent. It is clear that mycorrhizae are absolutely essential for cassava growth, but it seems difficult to improve on an already highly efficient, naturally occurring symbiosis.

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Appendix Table 1. Soil characteristics and the relative yield of cassava obtained in 56 NPK trials conducted in Brazil from 1950 to 1983.

	State	Location	pH	% OM	ppm P	ppm K	Soil classification	Relative yield (%)[1] N	P	K	References[2]
1.	Ceará	Pacajus	5.3	0.5	<1.0	20	Sandy soil	80	71	98	1
2.	Ceará	Pacajus					Sandy soil	91	83	89	1
3.	Ceará	Pacajus					Sandy soil	100	99	88	2
4.	Ceará	Pacajus					Sandy soil	100	82	82	2
5.	Ceará	Capistrano	6.2	0.6	2.0	45	Red-yellow Podzolic	63	67	88	1
6.	Ceará	Capistrano					Red-yellow Podzolic	59	76	100	1
7.	Rio Grande Norte	Macaiba *et al.*	5.3	0.6	1.0	24	Red-yellow Oxisol	94	32	91	3
8.	Paraiba	Santa Rita	4.6	2.8	7.0	39	Red-yellow Podzolic	75	25	96	4
9.	Paraiba	Rio Tinto	5.0	1.1	2.0	24	Red-yellow Podzolic	63	10	98	5
10.	Pernambuco	Goiana	5.3	0.9	<1.0	16	Red-yellow Podzolic	71	38	88	5
11.	Sergipe	Lagarto	6.3	1.3	2.0	44	Red-yellow Podzolic	85	17	100	6
12.	Sergipe	Estancia	4.9	1.4	3.0	20	Red-yellow Podzolic	93	39	98	6
13.	Sergipe	NS das Dores	5.7	1.1	2.0	36	Red yellow Oxisol	93	18	80	6
14.	Bahia	C. do Almeida	5.0	2.1	1.0	56	Oxisol	89	66	84	7
15.	Bahia	C. do Almeida	5.3		5.0	33	Oxisol	86	88	78	8
16.	Bahia	C. do Almeida	5.1		3.0	20	Oxisol	57	100	66	8
17.	Bahia	Irará	5.0	1.0	0.9	15	Oxisol	97	26	61	7
18.	Bahia	Irará	5.6		3.0	24	Oxisol	64	35	88	8
19.	Bahia	Irará	5.6		1.0	18	Oxisol	89	72	89	8
20.	Bahia	Itiruçu	5.8	4.0	1.0	64	Oxisol	100	70	100	7
21.	Bahia	Jaguaquara	5.9	4.0	17.0	132	Oxisol	100	100	91	8
22.	Bahia	Jaguaquara	5.4		4.0	87	Oxisol	93	61	86	8
23.	Bahia	Sapeaçu	5.0	2.1	2.0	36	Oxisol	90	51	100	8
24.	Bahia	Sapeaçu	4.8		3.0	33	Oxisol	84	96	78	8
25.	Espirito Santo	Sao Mateus	5.1	2.2	2.0	52		79	85	97	9
26.	Espirito Santo	Sao Mateus			-	-		78	79	90	9
27.	Espirito Santo	Linhares	4.9	1.8	1.0	58		99	69	98	9
28.	Espirito Santo	Linhares			-	-		92	88	97	9
29.	Riode Janeiro	Sao Joao Barra	5.8	1.5	1.0	48	Oxisol	98	31	89	10
30.	Rio de Janeiro	Sao Joao Barra			1.0	52		99	79	100	10
31.	Rio de Janeiro	Sao Joao Barra			1.0	52		92	61	91	10
32.	Rio de Janeiro	S. Pedro da Aldeia	6.1	-	1.0	44	Oxisol	100	95	88	10
33.	Sao Paulo	Sorocaba	5.2	2.6	51.7	59	Sandy soil	80	66	90	11
34.	Sao Paulo	Sorocaba et al.	-	-	-	-	Sandy soil	96	63	100	11
35.	Sao Paulo	Araras	5.4	2.6	15.5	47	Sandy soil	96	91	46	12

Appendix Table 1. (continued)

	State	Location	pH	% OM	ppm P	K	Soil classification	N	P	K	References[2]
36.	Sao Paulo	Araras	5.1	-	18.6	39	Sandy soil	82	82	75	12
37.	Sao Paulo	Araras	5.5	3.4	31.0	86	Oxisol	89	100	100	12
38.	Bahia	Cruz das Almas	4.9	1.3	3.0	37	Red-yellow Oxisol	100	83	87	13, 8
39.	Bahia	Cruz das Almas					Red-yellow Oxisol	-	-	47	14
40.	Bahia	Cruz das Almas					Red-yellow Oxisol	-	-	42	14
41.	Bahia	Cruz das Almas					Red-yellow Oxisol	-	71	87	15
42.	Bahia	Cruz das Almas					Red-yellow Oxisol	90	100	85	16
43.	Minas Gerais	Felixlandia	4.9	1.9	2.0	25	Dard red Oxisol	-	95	99	17
44.	Santa Catarina	Ararangua	5.4	1.1	2.2	24	Sandy soil	-	-	57	18
45.	Santa Catarina	Ararangua	5.4	1.1	2.2	24	Sandy soil	-	-	53	18
46.	Santa Catarina	Jaguaruna	5.5	0.7	2.8	14	Sandy soil	36	-	-	18
47.	Santa Catarina	Içara	4.6	3.4	4.4	43	Red-yellow Podzolic	-	-	67	18
48.	Santa Catarina	Içara	4.6	3.4	4.4	43	Red-yellow Podzolic	-	-	58	18
49.	Santa Catarina	Ituporanga	4.4	4.3	0.8	77	Dysthrophic Inceptisol	100	-	96	18
50.	Sergipe	Arauá	5.1	1.1	1.0	24	Oxisol	-	42	-	19
51.	Sergipe	Malhador	5.2	1.2	1.0	16	Oxisol	-	40	-	19
52.	Sergipe	Salgado	6.2	1.2	<1.0	8	Oxisol	-	10	-	19
53.	Sergipe	Araua	5.1	1.1	1.0	24	Oxisol	-	9	-	20
54.	Sergipe	Araua					Oxisol	-	7	-	21
55.	Sergipe	Lagarto	6.3	1.3	2.0	44	Red-yellow Podzolic	-	0	-	21
56	Amazonas	Manaus	-	-	-	-	-	-	27	-	22

[1] Relative yield is yield without the nutrient over the highest yield obtained with the nutrient.

[2]
1 = Queiroz et al. (1980)
2 = Queiroz and Pinho (1981)
3 = Rio Grande do Norte (1976)
4 = Silva (1970)
5 = Silva et al. (1969)
6 = Sobral et al. (1976)
7 = Gomes et al. (1973
8 = Gomes et al. (1981)
9 = Zangrande (1981)
10 = Nunes et al. (1974)
11 = Normanha and Pereira (1950)

12 = Silva and Freire (1968)
13 = EMBRAPA –CNPMF (1981)
14 = Gomes and Ezeta (1982)
15 = EMBRAPA-CNPMF (1984)
16 = CNPMF/EPABA (1978)
17 = Tanaka et al. (1981)
18 = Moraes et al. (1981)
19 = Santos and Tupinamba (1981)
20 = UEPAE de Aracaju (1981)
21 = UEPAE de Aracaju (1983)
22 = UEPAE de Manaus (1978).