Mineral Nutrition and Fertilization of Cassava

(Manihot esculenta Crantz)

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Centro Internacional de Agricultura Tropical

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MINERAL NUTRITION AND FERTILIZATION OF CASSAVA

(*Manihot esculenta* Crantz)

R. Howeler*

Cassava, a root crop that is propagated vegetatively from stem cuttings, originated in South America, where indigenous tribes learned to extract the poisonous juice from the roots for the preparation of meal *(101)*. The leaves were also used as a vegetable *(78)*. After the conquest of the Americas, the plant was taken to Africa and Asia, where it became an important crop for human as well as animal consumption *(143)*.

Cassava is grown throughout the lowland tropics, mainly as a subsistence crop. The thickened roots are harvested from 6-24 months after planting, depending on varietal and ecological factors. It is tolerant to adverse soil conditions and can be produced on very acid or infertile soils where other crops cannot grow satisfactorily. Because of its tolerance to water stress, cassava is used as a famine crop in North Africa, where it is the main food source during prolonged periods of drought *(138)*. Since cassava is one of the most efficient producers of carbohydrates among the higher plants *(142)*, interest has recently developed in its large-scale exploitation as an animal feed or as a raw material for the production of starch or power alcohol. In 1978 the countries with the highest production (over 5 million t/yr) were Brazil, Thailand, Zaíre, Indonesia, Nigeria, India and China *(62)*.

In order not to compete with existing crops, it is suggested that commercial cassava plantations be established in areas with marginal soils *(61)*. Although cassava has been traditionally grown without the use of fertilizers *(52)*, it is now known that the plant responds well to fertilization *(31, 32)*; and in order to realize its high yield potential, adequate fertilization practices have to be employed.

The literature on cassava nutrition and fertilization is scarce and often of limited usefulness because of incomplete information on soil characteristics, the amount and source of fertilizer used, and the method of application. The objective of this monograph is to review existing literature and based on the information available, present some general conclusions that may form the basis for more intensive research on the nutritional requirements of this important crop.

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NUTRIENT REMOVAL FROM THE SOIL

Farmers generally consider that cassava exhausts the soil and therefore prefer to plant it as the last crop in a rotation before returning the land to bush fallow *(133)*. Sittibusaya & Kurmarohita *(156)* report that after 15 years of continuous cassava production without fertilization in southeast Thailand, yields dropped from an initial level of 30 t/ha to only 17 t/ha. When these exhausted soils were fertilized with 375 kg N, 164 kg P and 312 kg K/ha*, yields increased from 22 to 41 t/ha.

In Indonesia den Doop *(53, 54)* found that three successive cassava plantings without applied K decreased yields from 15 to 4 t/ha. Various long-term experiments have shown that if adequate fertilizer is applied, good yields of continuously grown cassava can be maintained *(17, 77, 133)*. After 15 years of consecutive well-fertilized cassava, a subsequent rubber crop produced excellent yields in Malaysia *(17)*.

Hongsapan *(77)* considers that per ton of food produced, cassava depletes soil nutrient reserves less than maize, sugar cane, bananas or cabbage; on a per crop basis, however, cassava extracts more nutrients than most other tropical crops as shown in Table 1.

Table 1. **The removal of N, P, K and Mg in the harvested product of four tropical crops.**

Crop (production, t/ha)	N	P	K	Mg
	(kg/ha)			
Cassava (20.9)	87	37.6	117	35.1
Oil palm (20.4)	61	9.9	84	13.6
Rubber (1.13)	9	2.0	11	2.3
Maize (3.4)	82	20.7	69	14.7

Source: Kanapathy (*92*)

According to Prevot & Ollagnier *(137)* among tropical crops cassava extracts the largest amount of K from the soil as it has the highest K/N ratio in the harvested product. Other crops with high K/N ratios are bananas, oil palm, pineapple, coconut and sugar cane; whereas maize, rice and cotton have relatively low K/N ratios.

Table 2 shows the amount of nutrients in the whole cassava plant and in the roots (per ton of roots harvested), as reported by different authors in the literature. Although the data vary considerably due to different soil conditions, cultivars, plant age at harvest, etc., on the average cassava extracts about 2.3 kg N, 0.5 kg P, 4.1 kg K, 0.6 kg Ca and 0.3 kg Mg/t of roots when only the roots are removed from the field. Thus a yield of 25 t/ha of roots removes 57 kg N, 12 kg P, 102 kg K, 15 kg Ca and 7 kg Mg. If the whole plant is

* To prevent confusion, all nutrients are expressed on an elemental basis, **not** as P_2O_5, K_2O, CaO or MgO.

Table 2. **The amount of nutrients removed per ton of harvested cassava roots.**

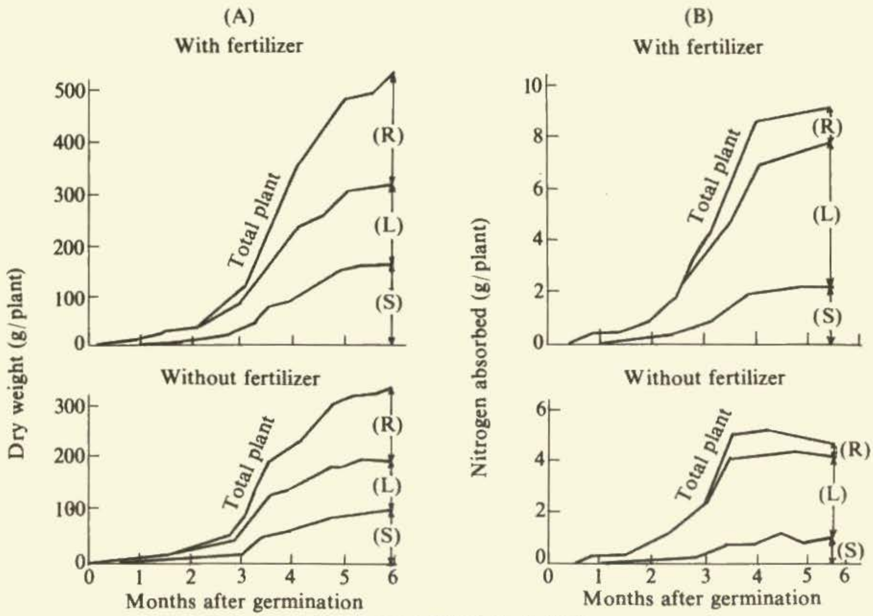
Plant part	Root yield (t/ha)	N	P	K	Ca	Mg	Source
		(kg/ha)					
Roots	40	1.83	0.37	1.82	0.36	1.08	Dulong (*57*)
Roots	52.7	0.72	0.53	5.08	0.65	0.37	Nijholt (*117*)
Total plant	—	2.50	0.92	9.04	3.06	0.99	Nijholt (*117*)
Roots	64.6	0.70	0.44	4.91	0.79	0.28	Nijholt (*117*)
Total plant	—	1.93	0.70	7.53	2.40	0.66	Nijholt (*117*)
Roots	6	1.00	0.29	2.64			Hongsapan (*77*)
Roots	42	3.64	0.40	4.40	0.60	0.14	Dufournet &
Total plant	—	6.02	0.67	5.95	1.00	0.69	Goarín (*56*)
Roots	26	6.85	0.77	3.50	1.00	0.12	Dufournet &
Total plant	—	10.96	1.38	4.69	2.15	0.46	Goarín (*56*)
Roots	25	2.20	0.19	1.60			Días (*51*)
Roots	50	3.06	0.34	3.70	0.50	0.12	Cours (*47*)
Total plant	—	5.06	0.56	5.00	0.84	0.58	Cours (*47*)
Roots	—	3.00	0.50	3.50	0.60	0.10	Cours (*47*)
Total plant	—	5.00	0.80	5.00	1.20	0.50	Cours (*47*)
Roots	2.6	1.49	0.49	2.11			Mejía (*110*)
Roots	—	2.02	0.43	3.02			Kanapathy &
Total plant	—	6.28	1.89	6.53			Keat (*91*)
Roots	21	1.01	0.44	2.09	0.37	0.48	Kanapathy (*92*)
Total plant	—	4.10	1.77	6.43	2.15	1.63	Kanapathy (*92*)
Roots	30	2.00	0.71	7.05			De Geus (*50*)
Roots	40	2.12	0.66	5.74	1.32		De Geus (*50*)
Roots	10	3.92	0.90	9.90	0.35		Obigbesan (*130*)
Roots	9	3.63	0.88	9.67	0.40		Obigbesan (*130*)
Roots	31	1.00	0.61	1.52			Sittibusaya &
Total plant	—	2.35	1.03	2.32			Kurmarohita (*156*)
Average							
Roots		2.33	0.52	4.11	0.61	0.34	
Total plant		4.91	1.08	5.83	1.83	0.79	

removed for forage and planting material, these amounts would increase to 122 kg N, 27 kg P, 145 kg K, 45 kg Ca and 20 kg Mg/ha. It is clear that cassava does extract large amounts of nutrients from the soil, but the return of stems and leaves to the field considerably reduces soil depletion. Besides K, cassava extracts large amounts of N, while the extraction of P, Ca and Mg is relatively low.

Besides nutrient extraction by the crop, soil fertility may deteriorate due to erosion since cassava tends to enhance soil erosion, especially during planting and after harvest. Gómez *(72)* calculated an erosion index of 9.8 for cassava, as compared with 1.0 for pasture, 1.1 for sugar cane, 1.7 for pineapple and 11.8 for coffee in a volcanic ash soil with 60% slope in Colombia. Unfortunately, cassava is often the only crop that will still grow on severely eroded slopes, thereby accelerating erosion even further. This practice should be limited as much as possible or combined with erosion-control practices such as minimum tillage, contour planting and the use of mulch or cover crops *(32, 85)*.

NUTRIENT ACCUMULATION IN THE PLANT

By biweekly sampling and analysis of different plant parts of cassava, Orioli et al. *(134)* in Argentina determined the distribution of dry matter (DM), N, P, K and Ca during a six-month growth cycle, both for fertilized and nonfertilized plants. Figure 1A shows that



Source: Orioli et al. (*134*)

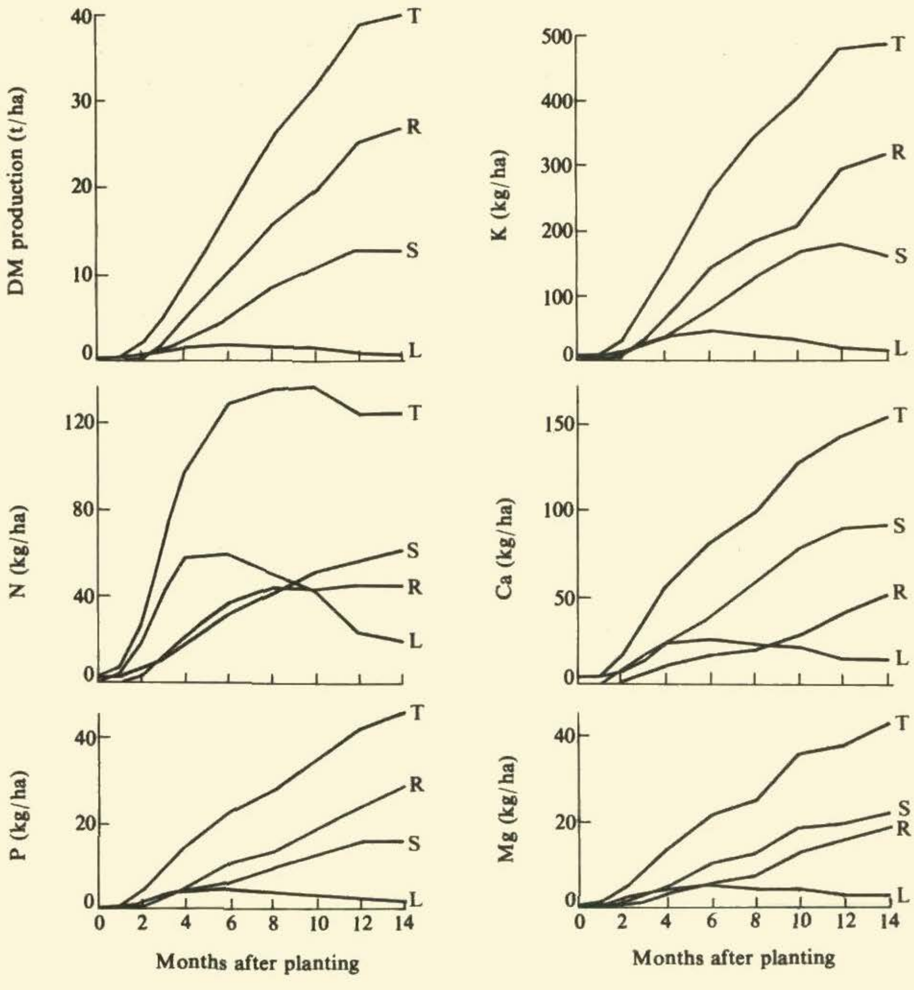
Figure 1. **The accumulation and distribution of dry matter (A) and nitrogen (B) in the roots (R), leaves (L) and stems (S) of cassava during the first six months of growth, with and without fertilization (monthly application of 20 kg N, 8 kg P and 16 kg K/ha) in Argentina.**

DM production was slow during the first three months but increased rapidly the next two months, before slowing down during the sixth month, probably due to the onset of winter. Roots accumulated DM at a rather constant rate during the entire growth cycle, while leaves and stems accumulated little during the sixth month. Although fertilized plants accumulated DM in greater quantities than unfertilized plants, Figure 1A shows that the relative distribution among plant parts was nearly the same under both conditions. The rate of N accumulation was low during the first two months, reached a maximum in the third and fourth months, and then declined to a very low rate during the last two months (Fig. 1B). The nonfertilized plants even lost N during these final two months. Although at six months the DM was fairly evenly distributed among the roots, stems and leaves, N was present mainly in the leaves, with relatively little accumulation in the roots and stems. This reflects the high protein content of the leaves and the low content of the roots. The rate of accumulation of P and K followed a pattern similar to that of N. Again most of the P and K was present in leaves; during the last month both leaves and stems lost P while the roots and stems lost some K. Calcium accumulation differed from that of NPK in that after the first two months, the rate of accumulation remained nearly constant throughout the growth cycle. Calcium accumulation in leaves and roots stopped after three months while that in stems continued. The relative nutrient accumulation curves for fertilized and nonfertilized plants were very similar although the fertilized plants absorbed nutrients in greater quantities.

Nijholt *(117)* determined DM and nutrient accumulation in different plant parts of two cassava cultivars grown for 14 months on a lateritic soil in Indonesia.Plants were sampled at monthly intervals. Figure 2 shows that under the tropical conditions of Indonesia, total DM accumulation continued throughout the growth cycle; however, DM accumulation stopped after six months in the leaves, slowed down in the stems, but continued in the roots. The accumulation and distribution of N,P,K,Ca and Mg during the growth cycle are also shown in Figure 2. The amount of N in the plant increased at a nearly constant rate up to six months, then remained constant, actually decreasing slightly after ten months due to leaf fall. Roots accumulated N up to eight months only, after which the amount remained nearly constant. Although root weight continued to increase up to 14 months, N content decreased from 1.03% at two months to 0.17% at 14 months. Only the stems continued to accumulate N throughout the growth cycle. The accumulation of P, K, Ca and Mg continued at a rather constant rate throughout the growth cycle although the amount in the leaves decreased after six months due to leaf fall. Potassium and P accumulated mainly in the roots; and Ca and Mg, mainly in the stems *(117)*.

NUTRIENT CONCENTRATIONS IN THE PLANT

The nutrient concentration varies considerably among plant parts and also changes during the growth cycle. Table 3 shows how the concentration of various nutrients varied with time in roots,stems and leaves. As the plant aged, N, P and K decreased significantly in all three parts of the plant. Calcium and Mg concentrations tended to increase with plant age in the leaves, but decreased in stems and roots. The N concentration was very high in leaves, much lower in stems and very low in the roots, reflecting the low protein



Source: Adapted from Nijholt *(117)*

Figure 2. **The accumulation of dry matter, N, P, K, Ca and Mg in leaves (L), stems (S), roots (R) and the total plant (T) of cassava cv. São Pedro Preto during a 14-month growth cycle in Indonesia.**

content of the last. The concentrations of P, K, Ca and Mg were also higher in leaves than in the stems and roots, but the differences were much smaller.

Cours et al. *(48)* determined that within the aerial part of the plant considerable differences occurred between older and younger parts. Table 4 shows that the young leaf blades were higher in N, P and K, but lower in Ca than older ones. Spear et al. *(159)* also reported that K concentrations were higher in younger leaves, while Ca and,to a lesser

Table 3. **Nutrient concentration of leaves, stems and roots of cassava cv. São Pedro Preto at various ages.**

Month	Leaves (% of DM)					Stems (% of DM)					Roots (% of DM)				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg	N	P	K	Ca	Mg
2	3.28	0.29	2.21	1.13	0.33	0.88	0.27	1.96	1.07	0.30	1.03	0.19	2.13	0.48	0.16
4	3.41	0.27	2.05	1.38	0.28	0.81	0.21	1.69	1.03	0.27	0.45	0.11	1.47	0.22	0.07
6	3.06	0.24	2.11	1.37	0.27	0.64	0.13	1.53	0.78	0.20	0.36	0.11	1.41	0.16	0.06
8	3.20	0.24	2.16	1.43	0.28	0.49	0.12	1.52	0.69	0.15	0.28	0.09	1.18	0.13	0.05
10	2.79	0.22	2.00	1.39	0.28	0.48	0.12	1.53	0.73	0.17	0.22	0.10	1.07	0.15	0.07
12	2.47	0.23	1.61	1.48	0.29	0.44	0.12	1.38	0.70	0.15	0.18	0.09	1.14	0.16	0.06
14	2.34	0.23	1.33	1.61	0.35	0.48	0.12	1.26	0.72	0.17	0.17	0.11	1.19	0.19	0.07

Source: Adapted from Nijholt (*117*)

Table 4. **Nutrient concentrations of different leaf blades, petioles and stems of cassava.**

Plant part	N	P	K	Ca
	(% of DM)			
Blade, top leaf	3.84	0.23	0.80	0.45
Blade, bottom leaf	2.48	0.18	0.72	0.81
Petiole, top leaf	1.68	0.17	1.04	1.13
Petiole, bottom leaf	1.40	0.08	1.15	1.02
Young branch, upper part	1.36	0.16	0.49	1.40
Young branch, lower part	1.28	0.06	0.40	0.45
Primary branch	1.00	0.05	0.51	0.37
Wood of main stem	0.76	0.07	0.40	trace
Phelloderm of main stem	1.12	0.06	1.81	0.85

Source: Cours et al. (*48*)

degree, Mg concentrations were higher in older leaves. They noted, however, that the relative concentration of K, Ca and Mg in the plant was greatly affected by the external K supply. Cours et al. *(48)* found that the petioles of top leaves were higher in N, P and Ca but lower in K than those of bottom leaves. The leaf blades were higher in N and P, but lower in K and Ca than the petioles. Also, the upper green branches were higher in N, P, K and Ca than the lower branches, which in turn were higher than the primary branch or the main stem. The phelloderm of the main stem was very high in K, and Cours et al. *(48)* recommended that this plant part be used for diagnosing K deficiency. In a more detailed study, Cours *(47)* found that the concentrations of N, P and K decreased from upper to lower leaves of the primary branch and from upper to lower branches, whereas the Ca and Mg concentrations increased from upper to lower leaves and from upper to lower branches.

Table 5 and 6 summarize the nutrient concentrations in plant parts reported by several investigators. Even among the same plant parts, nutrient concentrations vary considerably because of differences in soil fertility, climate, cultivars and plant age at sampling. Nevertheless, they give an indication of the levels of nutrients in different plant parts that can be expected under normal growing conditions.

DIAGNOSIS OF NUTRIENT DEFICIENCIES AND TOXICITIES

Diagnosis of nutritional problems is generally done by (a) observation of deficiency or toxicity symptoms, (b) soil and plant analyses and (c) application of various elements and observation of the plant's response.

Table 5. **Nutrient concentrations of different parts of the cassava plant as reported by various investigators.**

Plant part	N	P	K	Ca	Mg	S	Source
	(%)						
Young leaves	5.5	0.4	1.2	0.7	0.3		Cours (*47*)
Old leaves	5.0	0.3	0.7	1.4	0.4		Cours (*47*)
Stem cutting	0.95	0.39	2.47	0.42			Orioli et al. (*134*)
Leaves	2.80	0.25	1.27	2.23	0.55		Krochmal & Samuels (*95*)
Petioles	0.86	0.24	1.56	5.86	1.23		Krochmal & Samuels (*95*)
Stems	0.60	0.36	1.92	0.88	0.17		Krochmal & Samuels (*95*)
Roots	0.27	0.11	0.59	0.10	0.13		Kanapathy & Keat (*91*)
Leaves	4.31-4.82	0.33-0.37	0.58-0.92				Roche et al. (*140*)
Leaves	3.54-6.17	0.22-0.37	0.78-1.05	0.27-0.93	0.24-0.44		Cours (*47*)
Leaves	3.35-3.90	0.17-0.26	0.36-1.60	0.84-1.10			CTCRI (*27*)
Stems	0.93-1.28	0.09-0.23	0.39-0.76	0.45-1.04			CTCRI (*27*)
Roots	0.43-0.93	0.12	0.34-0.98	0.40-0.84			CTCRI (*27*)
Leaves + branches	3.18	0.33	1.33	1.08	0.64		Kanapathy (*92*)
Stems	0.61	0.49	1.13	0.52	0.36		Kanapathy (*92*)
Roots	0.28	0.12	0.57	0.10	0.14		Kanapathy (*92*)
Leaf blades	4.78-4.90	0.22	1.48-1.74	0.60-0.66	0.22-0.23	0.37	Ngongi (*115*)
Petioles	1.52-1.60	0.11	1.88-2.80	1.48-1.52	0.22-0.30		Ngongi (*115*)
Roots (peeled)	0.35-0.70	0.05-0.07	0.67-0.80	0.04	0.03-0.05	0.06	Ngongi (*115*)
Leaf blades	4.5 -6.5	0.2 -0.5	1.0 -2.0	0.75-1.5	0.25-1.0		CIAT (*28*)
Leaf blades	4.9 -5.6	0.25-0.27	1.5 -1.8	0.6 -0.7	0.22-0.23	0.34-0.37	CIAT (*29*)
Petioles	1.4 -1.6	0.12-0.13	2.2 -3.3	1.2 -1.5	0.30-0.41	0.13-0.14	CIAT (*29*)
Leaf blades	1.76-2.63	0.21-0.41	1.62-2.38	0.49-3.18	0.24-0.31		Edwards & Kang (*59*)
Upper leaf blades						0.34-0.40	CIAT (*33*)
Middle leaf blades						0.33-0.36	CIAT (*33*)
Lower leaf blades						0.28-0.31	CIAT (*33*)
Upper petioles						0.13-0.17	CIAT (*33*)
Middle petioles						0.01-0.03	CIAT (*33*)
Lower petioles						0.01-0.07	CIAT (*33*)

Table 6. **Micronutrient concentrations of various parts of the cassava plant as reported by different investigators.**

Plant part	B ($\mu g/g$)	Zn ($\mu g/g$)	Mn ($\mu g/g$)	Cu ($\mu g/g$)	Fe ($\mu g/g$)	Source
Roots		10.5-63.2	4.2-10	2.1-8.4	13.2-74.2	Muthuswamy et al. (*113*)
Roots		28.2	6.1	3.3	34.2	Muthuswamy et al. (*113*)
Roots (peeled)		204	273	20	152	Albuquerque (*6*)
Leaves + branches			262		72	Kanapathy (*92*)
Stems			65		45	Kanapathy (*92*)
Roots			10		17	Kanapathy (*92*)
Leaf blades					330	CTCRI (*25*)
Petioles					90-100	CTCRI (*25*)
Leaf blades				14		Chew et al. (*40*)
Roots				7		Chew et al. (*40*)
Leaves			150		140	Pages (*135*)
Leaf blades	15-40	40-100	50-150	6-12	100-200	CIAT (*28*)
Shoots	15-150*					Forno (*65*)
Leaf blades		27-75	76-248		181-265	Edwards & Kang (*59*)
Leaf blades		31.7-45.0				CIAT (*32*)

* Range from B deficiency to B toxicity

Symptoms

Nutrient deficiency and toxicity symptoms in cassava were determined by Krochmal & Samuels *(94)* and Howell *(84)* in sand culture, and by Lee *(100)*, Asher *(12)* and Howeler et al. *(83)* in nutrient solution. Color photographs and a detailed description of symptoms were published by Lozano et al. *(104)* and Asher et al. *(15)*. They can be briefly summarized as follows:

Deficiencies

N - reduced plant growth; in some cultivars uniform yellowing of leaves, starting with lower leaves but soon spreading throughout the plant

P- reduced plant growth, small leaves, thin stems; under severe conditions yellowing of lower leaves which become flaccid and necrotic and drop off

K - reduced plant growth, small leaves; under very severe conditions purple spotting, yellowing and necrosis of tips and margins of lower leaves; necrosis of petioles or stem tissue; fine cracks in stem

Ca - reduced root growth, small and deformed upper leaves

Mg - marked interveinal chlorosis of lower leaves, some reduction in plant height

S - uniform yellowing of upper leaves; similar symptoms sometimes observed on lower leaves

B - reduced plant height, short internodes, short petioles and small, deformed younger leaves; purple-gray spotting of fully expanded leaves; gummy exudate on stem and petioles; suppressed lateral root development

Cu - deformation and uniform chlorosis of upper leaves, leaf tips and margins bending upwards; petioles of fully expanded leaves long and droopy; reduced root growth

Fe - uniform chlorosis of upper leaves and petioles, which become white under severe conditions; reduced plant growth; young leaves small but not deformed

Mn - interveinal chlorosis of upper or middle leaves; uniform chlorosis under severe conditions; reduced plant growth; young leaves small but not deformed

Zn - interveinal yellow or white spotting of young leaves, which become very narrow and chlorotic at the growing point under severe conditions; necrotic spotting of lower leaves; reduced plant growth

Toxicities

Al - reduced plant height and root growth; yellowing of older leaves under severe conditions

B - necrotic spotting on older leaves, especially along leaf margins

Mn - yellowing of older leaves with purple-brown spotting along veins; leaves become flaccid and drop off

Cassava develops macronutrient deficiency symptoms at very much lower solution concentrations than other crops such as maize, sunflower and soybeans *(58)*. Such deficiency symptoms in cassava usually occur only when plant growth is severely reduced. Edwards et al. *(58)* and Spear et al. *(159)* suggested that cassava has a low phloem mobility, resulting in a slow redistribution of nutrients in the plant. Thus when the nutrient supply is inadequate, cassava decreases its growth rate to match the decrease in rates of nutrient uptake; the retranslocation of nutrients from older to younger tissue and the development of deficiency symptoms in the older tissue are therefore minimized. Spear et al. (*160*) observed a smaller gradient in K concentration from younger to older leaves in cassava than in maize and sunflower. Forno (*65*) found that cassava produced only very mild symptoms of N deficiency at low solution N concentrations, whereas maize, sorghum and cotton showed severe symptoms. On the other hand, cassava growth was markedly reduced. This corresponds with observations at CIAT (*104*) that cassava suffering from N deficiency showed stunted growth rather than deficiency symptoms.

Soil and plant analyses

The absence of clear deficiency symptoms of macronutrients in cassava indicates that nutritional problems may be easily overlooked. This may be the reason why cassava has the reputation of not "needing" a fertile soil. It also means that soil and plant analyses become more important for assessing the nutritional status of the plant. Soil sampling and analysis before planting enables diagnosis and correction of nutritional problems before they affect plant growth. Proper methods of soil sampling are described in many government bulletins.

It is very important to standardize plant sampling techniques since nutrient concentrations vary among plant parts and change with plant age. An index tissue is selected and sampled at a time that is most indicative of the plant's nutritional status. Spear et al. *(159)* found that the youngest fully expanded leaves (YFEL)— i.e., the fourth or fifth leaf from the top— were the most sensitive to changes in K concentration of the nutrient solution, while Howeler *(80)* recommended analyses of blades of the YFEL for the assessment of N, P, S and the minor elements and the petioles of the YFEL for K, Ca and Mg. Howeler *(80)* also recommended sampling of plant tissue at about 3 months after planting, at the time of maximum growth rate, or as soon as the plant renews growth vigorously, following a period of dormancy due to drought or low temperatures.

To aid in the interpretation of analytical results, many investigators have determined the relation between plant growth (or yield) and the nutrient content of the soil or of a certain index tissue of the plant. The plant's nutritional requirements are generally reported in terms of "critical concentrations"; i.e., the concentration of a nutrient in the soil or plant tissue below which the plant will respond to the application of that nutrient and above which no such response is to be expected. Generally, it is defined as the concentration corresponding to 90 or 95% of maximum yield. Similarly, the excessive supply of an element is assessed by the critical concentration for toxicity, the concentration above which plant growth declines due to excessive absorption of that element.

Critical concentrations are generally determined by growing plants in nutrient solution, sand culture or in the field with a varying concentration or supply of a certain nutrient. Although the critical concentration is generally considered a fairly constant species or cultivar characteristic, Spear et al. *(162, 163)* showed that in cassava the critical concentration of K was much higher when determined in nutrient solutions of constant K concentration (flowing culture) than in those of diminishing concentration due to K depletion in conventional solution culture. Using the same cultivar (H-97), Kumar et al. (*96*) obtained a critical K concentration of 1.8% in the 1967-68 season but only 0.9% in the 1968-69 season; thus critical concentrations may vary due to different soil or climatic conditions. Also, critical concentrations determined from plant growth response curves do not necessarily correspond with those determined from root yield response curves since maximum plant growth may result in excessive foliage and reduced root yields. Nevertheless, although the critical concentration varies somewhat according to the method of determination and the cultivar involved, it is a very useful parameter for assessing the plant's nutritional status.

Critical concentrations in soils for cassava have been reported for only a few elements, and their usefulness is limited because of the great diversity in methods of soil analysis (Table 7). Much more information on critical concentrations and greater standardization in analytical procedures are urgently needed as fertilizer recommendations are ultimately based on soil analysis, and there is little information presently available to interpret the results.

Soil pH is probably the most important parameter for diagnostic purposes since soil pH determines the availability of many essential plant nutrients. In very acid soils, P, Ca, Mg, Cu, Zn and Mo may be deficient, whereas Mn, Fe and Al may be in excess. At high pHs, on the other hand, P, K, Fe, Mn, B and Zn may be deficient *(109)*.

Critical nutrient concentrations in cassava tissue reported in the literature are summarized in Table 8. In general it may be concluded that a fertilizer response is not likely when the YFEL blades contain more than 5.0% N, 0.4% P, 1.2% K, 0.7% Ca, 0.3% Mg, 0.32% S, 17 μg/g B, 8 μg/g Cu, 100 μg/g Fe, 100 μg/g Mn and 60 μg/g Zn. A toxicity may be suspected if plant tops contain more than 140 μg/g B, 100 μg/g Al and 1000 μg/g Mn.

Techniques for diagnosing nutritional problems

Nutritional problems can often be diagnosed by applying a range of nutrients to either soil or plant tissue, followed by an observation of which element causes a disappearance of

Table 7. **Critical levels of soil parameters for cassava.**

Parameter	Level	Method of analysis*	Source
pH	4.6 and 7.8	1:1 soil water ratio	CIAT (*30, 32*)
Al	2.5 meq/100 g	1 *N* KCl	Howeler (*80*)
Al sat.	80%	Al/(Al + Ca + Mg + K)	CIAT (*32*)
P	7 μg/g	Bray I-extract	Howeler (*80*)
	10 μg/g	Bray II-extract	Howeler (*80*)
	8 μg/g	Olsen-EDTA extract	Howeler (*80*)
	9 μg/g	North Carolina extract	Howeler (*80*)
K	*0.15 meq/100 g*	*NH_4-acetate*	*Obigbesan (130)*
	0.09-0.15 meq/100 g	NH_4-acetate	Obigbesan (*130*)
	60 μg/g	North Carolina extract	Howeler (*80*)
	0.06 meq/100 g	—	Roche et al. (*140*)
Ca	0.25 meq/100 g	NH_4-acetate	CIAT (*32*)
Conductivity	0.5-0.7 mmhos/cm	Saturation extract	CIAT (*30*)
Na sat.	2.5%	NH_4-acetate	CIAT (*30*)
Zn	1.0 μg/g	North Carolina extract	Howeler (*80*)
Mn	5-9 μg/g	North Carolina extract	Howeler (*80*)
SO_4-S	$\simeq 8$ μg/g	—	Ngongi et al. (*116*)

* BRAY I = 0.025 *N* HCl + 0.03 *N* NH_4F
BRAY II = 0.1 *N* HCl + 0.03 *N* NH_4F
Olsen-EDTA = 0.5 *N* $NaHCO_3$ + 0.01 *M* Na-EDTA
North Carolina = 0.05 *N* HCl + 0.025 *N* H_2SO_4
NH_4-acetate = 1 *N* NH_4-acetate at pH 7

symptoms or the recuperation of plant growth. Painting of leaves or parts of leaves that show symptoms with a range of nutrients in solution and observing the disappearance of the symptoms may quickly identify the element causing the disturbance. The nutrient-addition and the missing-element techniques in soil fertility experiments are variations of this same diagnostic technique.

EXTERNAL NUTRITIONAL REQUIREMENTS

The external nutritional requirement is that concentration in the root environment corresponding to near-maximum yield. It is essentially equivalent to the critical concentration in the nutrient or soil solution. Cassava's external requirements in nutrient solutions have been determined mainly at the University of Queensland in flowing solution culture units in which the pH and temperature, as well as the concentration of nutrients in solution, are carefully controlled, and changes in concentration due to plant uptake prevented (*13, 14*). Using this technique, Forno (*65*) determined the external requirements for NO_3 and NH_4-N; Jintakanon et al. (*88*) determined external P

Table 8. **Critical nutrient concentration for deficiencies and toxicities in cassava plant tissue.**

Element	Plant tissue	Concentration*	Source
N def.	YFEL**, blades	5.1%	Fox et al. *(67)*
	Shoots	4.2%	Forno (*65*)
	YFEL, blades	5.7%	Howeler (*80*)
	YFEL, blades	4.65%	CIAT (*30*)
P def.	Shoots	0.47-0.66%	Jintakanon et al. (*88*)
	YFEL, blades	>0.44%	CIAT (*31*)
K def.	YFEL, blades	1.1%	Spear et al. (*162*)
	YFEL, petioles	0.8%	Spear et al. (*162*)
	Stems	0.6%	Spear et al. (*162*)
	Shoot & roots	0.8%	Spear et al. (*162*)
	YFEL, blades	1.2%	Howeler (*80*)
	YFEL, petioles	2.5%	Howeler (*80*)
Ca def.	Shoots	0.4%	Forno (*65*)
Mg def.	Shoots	0.26%	Edwards & Asher (*60*)
	YFEL, blades	0.29%	Edwards & Asher (*60*)
S def.	YFEL, blades	0.32%	Howeler (*80*)
Zn def.	YFEL, blades	60 $\mu g/g$	CIAT (*30*)
	YFEL, blades	37-51 $\mu g/g$	CIAT (*31*)
	YFEL, blades	43-60 $\mu g/g$	Edwards & Asher (*60*)
B def.	Shoots	17 $\mu g/g$	Forno (*65*)
B tox.	Shoots	140 $\mu g/g$	Forno (*65*)
Mn def.	Shoots	100-120 $\mu g/g$	Edwards & Asher (*60*)
Mn tox.	Shoots	250-1450 $\mu g/g$	Edwards & Asher (*60*)
Al tox.	Shoots	70- >97 $\mu g/g$	Gunatilaka (*74*)
	Roots	2000-14000 $\mu g/g$	Gunatilaka (*74*)

* Range corresponds to values obtained with different cultivars

** YFEL= youngest fully expanded leaves

requirements, and Spear et al. (*159, 160*) determined K requirements; while Islam et al. (*87*), Gunatilaka (*74*) and Edwards & Asher (*60*) determined the effect of pH, Al and Mn on the growth of cassava, respectively. Much of this work, compiled by Edwards et al. (*58*), Edwards & Asher (*60*) and Asher (*13*), is summarized in Table 9.

The external requirement for NO_3-N was nearly ten times higher than that for NH_4-N, and cultivars with a high NO_3 requirement also had a high NH_4 requirement (*65*). NH_4-N requirements were similar to those of soybean, maize and sunflower; but NO_3-N requirements of 8 out of 11 cassava cultivars were higher than those of other species.

Table 9. **Concentration (μM) of nutrients in solution corresponding to different nutritional status of cassava (*13*) and the external nutritional requirement** *(60, 63, 88).*

Element	Deficiency	Adequate	Toxic	External requirements*
NO_3-N	≤ 500	> 2500 (2)		3400-4650 (11)**
NH_4-N	≤ 30	> 120 (2)		26- 420 (11)
P	≤ 12	> 50		28- 78 (12)
K	≤3-100	> 10-125		4- 65 (12)
Ca	≤ 10	> 100 (2)		65- 450 (2)
Mg				28- 320 (2)
Al			> 20-80	

* The concentration corresponding to 95% of maximum DM production

** Range of values observed in the number of cultivars shown in parentheses

In nutrient solution (*88*) cassava had a much higher P requirement (28-78 μM = 0.90-2.5 μg/ml) than soybean (0.58 μM = 0.018 μg/ml), cotton (0.67 μM = 0.021 μg/ml) and maize (1.0 μM = 0.031 μg/ml). Since the low solution P concentration affected root growth less than top growth, Edwards et al. (*58*) suggested that the P requirement for root bulking may be lower than that for top growth. This agrees with reports from CIAT (*31, 32*) that the harvest index decreased with increasing P applications and that higher P rates were required for maximum top yields than for maximum root yields (*31*). Jintakanon (pers. comm.) found that when grown in soil cassava reached maximum growth at the same P concentration in soil solution (2.5 μM P = 0.077 μg/ml) as maize and soybean. CIAT (*32*) reported an external P requirement for cassava of 0.015-0.025 μg/ml in soil solution (determined in 0.01 $M CaCl_2$ according to the method of Fox & Kamprath, *68*), while beans *(Phaseolus vulgaris)* required 0.08 μg/ml *(31)* and maize 0.06 μg/ml *(69)* Similarly, vander Zaag et al. *(172)* obtained a P requirement of 0.05 μg/ml for cassava grown in Hawaii; they also reported values of 0.006 and 0.04 μg/ml obtained in Malaysia and Nigeria.

The crop's low P requirement in soil compared with that in nutrient solution may be due to an effective mycorrhizal association under natural soil conditions. Recent work at IITA has shown that at low soil-solution P concentrations, total DM yields of mycorrhizal cassava plants were double those of nonmycorrhizal plants (B.T. Kang, pers. comm., 1978). Similar results were obtained by Howeler et al. (*81*), who reported that mycorrhizal inoculation of cassava grown in a sterilized soil increased DM production up to threefold and total P uptake up to sevenfold at intermediate levels of P application. In a nonsterilized soil, inoculation had much less effect, increasing DM production and P uptake up to about 50%.

The marked effect of inoculation in a sterilized soil indicates that cassava is highly dependent on an effective mycorrhizal association for P uptake from low-P soils. It appears that the mycorrhizal hyphae extending from the root into the surrounding soil take up P from the soil outside the depletion zone surrounding each root and transport this P to the root. The hyphae thus function as a highly effective extension of the root system. When grown in flowing nutrient solution, cassava plants became highly infected with mycorrhiza after inoculation at low and intermediate P concentrations, but not at high concentrations (*82*). Maize, rice, cowpeas and beans, however, did not become infected at any concentration and were more effective than cassava in taking up P at low solution P concentration. The rather coarse, inefficient root system of cassava seems to make this crop highly dependent on a mycorrhizal association. Vander Zaag et al. (*172*) and Yost & Fox (*171*) reported that the dry weight of cassava tops from a soil in which the mycorrhizal population had been killed with methyl bromide was only 10% of that in the unsterilized soil at low P application rates. Sterilization seriously reduced plant growth as well as the P content of the plant; it also reduced uptake of K, Zn and S, while it had little effect on the Ca uptake per leaf (*172*).

Spear et al. (*159*) found that cassava grew better than maize or sunflower at low solution K concentrations, but the external K requirement for maximum growth was similar for all three species. At all solution K concentrations studied, cassava had a lower K absorption rate than maize or sunflower, but utilized the absorbed K more efficiently in DM production (*160*). As with P, root growth appears to be less affected by low K concentration than shoot growth (*159*), and harvest index decreases with an increase in K supply (*31, 32*). However, Malavolta et al. (*105*) and Obigbesan (*130*) observed an increase in root/top ratio with increasing K application.

At low Ca concentrations cassava grew better than four other species, but its requirements for maximum growth (65-450 μM) were higher than that of maize (3.3 μM) but lower than that of soybeans (1035 μM) (*65*). Cassava also tolerated a high concentration of Al of 160 μM (4.3 μg/ml), while maize and soybeans were seriously affected by only 37 μM Al (1.4 μg/ml) (*74*). Similarly, cassava was found to be more tolerant to high solution concentrations of Mn than soybeans, beans and cowpeas (*60*) and more tolerant to low pH than maize and tomatoes (*87*). It can be concluded that cassava has nutritional requirements for maximum growth that are as high or even higher (in the case of P) than those of many other crops, but it can adapt better to low-nutrient conditions as a result of a highly efficient utilization, a slow redistribution of nutrients, a lower nutrient gradient from young to old tissue, fewer deficiency symptoms, slower growth rates and a larger root/shoot ratio, resulting in less yield reduction. This corroborates field observations that cassava grows better than most crops on poor soils, but requires high fertilization rates to attain maximum yields.

SOIL REQUIREMENTS OF THE PLANT

Recommendations with regard to cassava's climatic and soil requirements (*73, 103, 108, 111*) have been based more on visual observations than on quantitative data. López & Estrada (*103*) recommended that cassava be grown on light fertile loam or clay loam soils, while Normanha (*124*) stated that cassava grows best at pH 6-7. Evenson & Keating (*61*) also recommended a light-textured, rather level soil to facilitate mechanized production. For Australian conditions they suggested growing cassava in soils that are too poor for sugar cane. Cock & Howeler (*42*) observed that cassava can grow on a large range of soils varying in texture from light to heavy, in pH from about 3.5 *(102)* to 7.8 *(31)* and from fertile to infertile soils, but that it will not tolerate excess water or high-salinity conditions. Cassava has produced highest yields on well-drained, medium to heavy, fertile soils with a pH of about 5.5-7.0. Maximum yields of nearly 80 t/ha/yr have been reported *(32)* on heavy (>50% clay), but extremely fertile soils of the Cauca Valley in Colombia. However, cassava would appear to have little future on these fertile soils which are utilized for production of more valuable crops such as sugar cane and soybeans. Moreover, cassava is harvested more easily on light-textured, well-drained soils. Tan & Bertrand *(168)* reported that in Latin America cassava is grown mainly on Oxisols, Ultisols and Entisols, with a potential production on Aridisols (with irrigation), Andepts (if not too cold) and Alfisols. In Africa it is grown mainly on Oxisols, Ultisols and some Alfisols, while in Asia it is grown mainly on Oxisols and Ultisols.

RESPONSE TO FERTILIZATION

Since cassava is generally grown on rather infertile soils and has a medium-to-high external nutritional requirement, it is clear that the application of fertilizers is essential to obtain maximum yields. Moreover, cassava extracts large amounts of nutrients from the soil, especially K and N, and continuous cultivation without adequate fertilization would soon lead to soil depletion and reduced yields *(156)*.

Cock *(41)* has shown that cassava has an optimum leaf area index of 2.5-3.5 and that high rates of fertilization may lead to excessive top growth and a leaf area index of more than 4. High levels of fertility increased leaf size, the number of active apices and the rate of leaf formation per apex, but had no consistent effect on leaf life. Cassava grown under low fertility restricted its leaf area but maintained leaf photosynthetic efficiency *(32)*; furthermore, the distribution index (root growth rate divided by top growth rate) was higher, indicating that most of the carbohydrate produced was transported to the roots *(33)*. Thus cassava is a crop that yields relatively well under low-fertility conditions by reducing its leaf area index, thereby maintaining a high level of nutrients in the leaves and increasing the translocation of carbohydrates to the roots. On the other hand, cassava is very sensitive to overfertilization, making it excessively leafy, particularly at high plant populations *(33)*.

Nutrients seldom react independently, interacting with each other instead. Howeler et al. (*79*) and Edwards & Kang (*59*) have shown that overliming induced zinc deficiency and reduced yields of cassava. Spear et al. (*161*) found that high concentrations of K in solution reduced the uptake of Ca and Mg, while Ngongi et al. (*116*) reported that high rates of KCl resulted in severe S deficiency in field-grown cassava. Thus the proper level of fertilization and the correct balance of nutrients applied are of utmost importance.

Nitrogen

Nitrogen is a basic component of protein, chlorophyll, enzymes, hormones and vitamins. It is also a constituent of the cyanogenic glycosides linamarin and lotaustralin, which produce hydrocyanic acid (HCN) when cells are damaged. HCN is the bitter, highly toxic component of cassava leaves, stems and roots, which must be eliminated before consumption by drying or cooking the roots *(125)*.

Cassava extracts relatively large amounts of N from the soil, especially if leaves and stems are removed with the roots; about 57 kg N/ha are removed in a crop yield of 25 t of roots/ha. If the recovery of applied N is estimated to be about 50% (43-69% according to Fox et al., *67*), about 115 kg of N should be returned to the soil to maintain its fertility.

Nitrogen deficiency is most common in sandy or very acid soils where a low pH or toxic levels of Al and/or Mn may reduce the microbial decomposition of organic matter; it is also common in volcanic ash soils. Although these soils normally have a high amount of organic matter, decomposition is slow and does not contribute much to the N supply.

In Madagascar investigators *(8, 9)* recommended incorporation of farm yard manure (FYM) or green manure such as *Mucuna utilis, Vigna* or *Crotalaria*. *Crotalaria* is, however, very susceptible to acid soils and does not produce well at a pH below 5 *(28)*. When Nitis & Sumatra *(118)* intercropped cassava with *Stylosanthes guyanensis* in Bali, they obtained a 17% yield increase over cassava alone. Nitis *(119)* reported that intercropped *Stylosanthes* supplied about 9 kg N/ha to the cassava; and when fertilized with P, K and micronutrients, the legume supplied about 72 kg N/ha. CIAT *(32)*, however, reported a depression in cassava yield from intercropped legumes including *Stylosanthes* due to light and/or water competition. During 1979, yield reduction of cassava due to various intercropped grain legumes ranged from 1 to 68%, with sword bean *(Canavalia gladiata)* giving the severest competition *(33)*. CTCRI *(26)* also reported yield reductions of cassava due to intercropping.

De Geus *(50)*, Kumar et al. *(97)* and Mandal et al. *(107)* indicated that cassava responds well to applications of FYM, especially when fortified with some chemical fertilizers *(26)*. In southern India a 66% yield increase was obtained by the application of 15 t/ha of FYM *(22)*. The Department of Agriculture in Zanzibar, Tanzania *(10)* reported a doubling of yield from 19 to 36.5 t/ha with the application of 22.6 t/ha of FYM, while no yield increases were obtained with $(NH_4)_2SO_4$ or KCl. In the Ivory Coast, Botton & Perraud *(19)* obtained a 21% yield increase with FYM and a 5-10% increase with home sewage. Lambourne *(99)* reported better results with FYM (10 t/ha) than with chemical fertilizers or green manures (basic slag and *Crotalaria)*.

On Ultisols of Puerto Rico, Fox et al. *(67)* obtained no response to applied N in a soil having 0.23% N, but a significant response to 120 kg N/ha in a soil having 0.17% N. In Costa Rica, Schmitt *(148)* recommended the application of 60-70 kg N in addition to 26-30 kg P and 108 kg K/ha. In the same country, Acosta & Pérez *(1)* obtained a yield response to 50 kg N/ha, with a yield depression at higher rates. Tarazona et al. *(169)*

reported a positive response to 50-60 kg N/ha in 16 out of 23 trials in farmers' fields in Colombia. The greatest response was obtained on volcanic ash soils near Popayán. On Oxisols of the Llanos of Colombia, CIAT *(30)* reported a nonsignificant response to 100 kg N/ha in the dry season planting; but during the rainy season, a significant response was obtained to 100 kg N/ha as urea and to 200 kg N/ha as sulfur-coated urea (SCU) (*26*). On similar soils, Ngongi *(115)* obtained a response to 100 kg N/ha but only in the presence of 125 kg K/ha; and an application of 200 kg N/ha reduced yield. On volcanic ash soils in Colombia, Rodríguez *(141)* reported highest yields with 145 kg N in combination with 85 kg P and 38 kg K/ha. In Brazil no significant response to N was obtained in Rio de Janerio *(127)* or in Bahia *(71)*, nor was a response to N observed in São Paulo *(151)*; on infertile soils in Goiás, Normanha *(123)* recommended the application of only 20 kg N/ha.

In western Nigeria, Amon & Adetunji *(7)* recommended about 25 kg N in combination with 50 kg K/ha, while Abigbesan & Fayemi *(129)* obtained high yields of 56 and 64 t/ha in 15 months, applying 60 and 90 kg N/ha, respectively. In Ghana, Stephens *(164)* reported a response mainly to P, as well as a slight response to 25 kg N/ha. In the same country, Takyi *(166)* obtained a 50% yield increase applying 60 kg N and 20 kg P/ha, while no response was observed to K and lime. On an unplowed soil at Otrokpe, however, Takyi *(167)* obtained an almost linear response to N up to 134 kg/ha, which doubled yields from 12 to 24 t/ha. The strong N response was obtained at a site where 6 crops of maize had preceded cassava. In Madagascar cassava responded mainly to K, bu tan application of 30-60 kg N/ha was recommended *(8, 50)*.

On acid lateritic soils of Kerala State in India, Mandal et al. *(106)* obtained highest yields with 100 kg N/ha, half applied as a basal and half as a top dressing at two months. In the same country, Saraswat & Chattiar *(147)* obtained a response up to 150 kg N/ha; however, the most economic rate was 100 kg N/ha,applied as calcium ammonium nitrate. CTCRI reported that in Kerala State, cassava responded mainly to application of N at the rate of 50-100 kg/ha. Applying half of the N as a foliar spray increased the efficiency of utilization (*22-25*). The application of N had no significant effect on root number but increased root size; it also increased the HCN and protein contents of the roots significantly, while having little effect on the DM and starch content (*24-27*).

In Thailand, where cassava is grown mainly on gray or red-yellow podzolic soils of moderate acidity (pH 5) and low organic matter content (<2%), the crop responded mainly to the application of N (50-100 kg/ha). In 135 NPK trials the average magnitude of response to fertilization varied from 12-52% in 6 soil series *(156)*. On acid peat soils of Malaysia, Chew *(37, 39)* observed that cassava yields increased most by applying N (180 kg N/ha). For similar soils Kanapathy *(92)* stated that continuous cultivation of cassava was possible with the application of 120 kg N and 75 kg K/ha/crop. In Indonesia (Java) cassava did not respond to the application of N *(93)*, responding mainly to K; thus den Doop *(53, 54)* did not recommend applying N. More recently, however,Hadi & Gozallie *(75)* recommended the application of 90 kg N in combination with 13 kg P and 0-42 kg K/ha at three locations in Java.

For cassava foliage production,Cheing *(36)* obtained highest yields in Kuala Lumpur with the application of 150 kg N in addition to 30 kg P, 150 kg K and 20 kg Mg/ha. Under these conditions, he was able to harvest 43 t of foliage DM and nearly 10 t of protein/ha/yr by cutting the plants every 3 weeks at a 50-cm height. In Serdang, Malaysia, Ahmad *(4)* obtained extremely high root yields of 78 t/ha/yr with a basal application of 90 kg N, 29 kg P and 98 kg K/ha and a top dressing of 34 kg N/ha at 6 months. The same fertilizer rates gave highest production of plant tops, cut 5 times successively between 3 and 12 months for fodder production; however, this practice reduced root yields by about 50%.

Many workers *(22, 23, 144, 145)* found no significant differences among N sources such as urea, $(NH_4)_2SO_4$, $Ca(NO_3)_2$ or $NaNO_3$, although in India calcium ammonium nitrate was found to be superior to urea, $(NH_4)_2SO_4$ and $NaNO_3$, probably because of its Ca content *(21)*. SCU was not found to be superior to urea in Colombia *(28)*, Puerto Rico *(67)* or Nigeria *(3)*. The application of various slow-releasing N fertilizers did not result in significantly better yields than a split application of urea *(120)*.

Many investigators *(1, 67, 115, 129, 170)* have reported a negative response of cassava to high N applications, which produced excessive foliage and little roots. Krochmal & Samuels *(95)* reported a root yield reduction of 41% and an increase in top growth of 11% due to high N applications. Vijayan & Aiyer *(170)* noted a decrease in the number of thickened roots, as well as in starch content, with N applications above 75 kg/ha. On the other hand, de Jong *(89)* observed that fertilization had little influence on DM content, and,therefore, on starch content. Increases in HCN content due to high N rates have also been reported by several workers *(26, 27, 97, 114, 129, 170)*. Apparently, high N applications stimulate the formation of nitrogenous products such as protein and cyanogenic glycosides and inhibit the synthesis of starch *(51, 105)*. Sinha *(153)* found no correlation between the HCN content of leaves and that of roots. He concluded that the sites of HCN metabolism are different for these two plant parts and suggested that N should be applied foliarly in order to reduce the higher HCN content of roots associated with high soil N applications.

Phosphorus

Phosphorus is a basic component of nucleoproteins, nucleic acids and phospholipids, as well as all the enzymes involved in energy transport. Phosphorus is essential for processes such as phosphorylation, photosynthesis, respiration, decomposition and synthesis of carbohydrates, proteins and fats. Malavolta et al. *(105)* reported a reduction in starch content of cassava roots from 32 to 25% when P was eliminated from the nutrient solution. Muthuswamy et al. *(114)* reported that the application of P had no effect on the HCN content of roots. Using a sand culture technique, Krochmal & Samuels *(95)* observed that of the three macronutrients, the application of P had the greatest effect on yield. They noted only a slight reduction of plant growth in the absence of P but no P-deficiency symptoms developed. CIAT *(30)* reported that in the absence of P, total DM production was reduced to 10% that of normal, but that no deficiency symptoms could be observed. Asher *(12)* also reported that a decrease in total DM production of more than 70% was required before cassava plants developed symptoms. Edwards et al. *(58)* found that cassava has an extremely high P requirement, needing from 50-127 μM P for maximal growth, whereas maize required 3 μM and soybeans 0.7 μM. At the lowest solution P concentration (0.05 μM), cassava achieved 18% of maximum yield (mean of 12 cultivars), whereas maize and soybeans achieved 21 and 34% of maximum yield, respectively. Phosphorus-deficiency symptoms in cassava occurred only at plant top P concentrations a great deal lower than in maize and soybeans. Thus cassava requires high P concentrations for maximum growth in solution, but is able to adjust its growth rate to low-P conditions (*58*).

Phosphorus deficiency is most common in acid soils, especially in those having high levels of Fe and Al, such as Oxisols, Ultisols and Inceptisols. Oxisols and Ultisols are dominant in the Campo Cerrado of Brazil, the Llanos Orientales of Colombia, the Llanos of Venezuela, and in extensive areas of tropical Africa. In Asia Ultisols are common in Malaysia, parts of India and Indonesia. Phosphorus deficiency and extremely high P fixation are characteristic of many Inceptisols such as those of the Andes Mountains (Andosols) in Central and South America, parts of the Llanos of Colombia, along the Amazon in Brazil, in Hawaii, Cambodia, India and Indonesia.

In Costa Rica, Acosta & Pérez *(1)* did not observe a P response in cassava except where N was applied. In volcanic ash soils of Colombia, Rodríguez *(141)* obtained maximum yields with 85 kg P/ha. Tarazona et al. *(169)* reported a positive response to 131 kg P/ha in 13 out of 14 trials in farmers' fields located principally in acid, P-deficient soils of the states of Cauca and Meta in Colombia. They did not find much correlation between the response to applied P and the soil-available P. In Oxisols of the Llanos of Colombia, CIAT *(30)* obtained a highly significant response to the application of 87 kg P/ha as triple superphosphate (TSP); when basic slag or simple superphosphate (SSP) were used, the crop responded up to 175 kg P/ha. The lack of P was the main limiting factor for cassava in these soils, its application increasing yields from 7 to 25 t/ha. At low rates of applied P, both foliage and root yield increased; but at high rates, foliage increased more than root yield, resulting in a decreased harvest index. Under Colombian conditions the application of 87 kg P/ha gave the highest net return; basic slag was the most economical P source *(30)*. In eastern Peru (Tarapoto), Curva *(49)* obtained a significant response only to applications of P (52 kg P/ha). In Brazil, Normanha *(121, 123)* found that P was the main limiting nutrient for cassava in São Paulo and Goiás states, where he recommended the application of 26-52 kg P/ha as bone meal or SSP. On poor sandy soil in São Paulo, Silva & Freire *(152)* failed to obtain a significant response to P. In Rio de Janeiro, Nunes et al. *(127)* reported an 86% yield increase with the application of 17 kg P/ha, the main limiting element; the most economical rate of application was 29 kg P/ha. Siqueira *(154)* obtained an increase in yield from 7.7 to 24 t/ha by the application of SSP in Bahia, where Santana and Carvalho *(146)* also observed a response mainly to P. In the Amazon estuary, Albuquerque *(6)* obtained maximum yields with 44 kg P/ha applied as SSP.

In western Nigeria, Amon & Adetunji *(7)* did not recommend the use of P, while in Ghana, Stephens *(164)* and Takyi *(166)* obtained highest yields with 10 and 20 kg P/ha, respectively. Although cassava responded mainly to K in Madagascar, the use of 57 kg P/ha was recommended *(8, 50)*.

1

Response to P fertilization in Carimagua, Colombia; in left foreground without P application, on right and in background with P application.

2

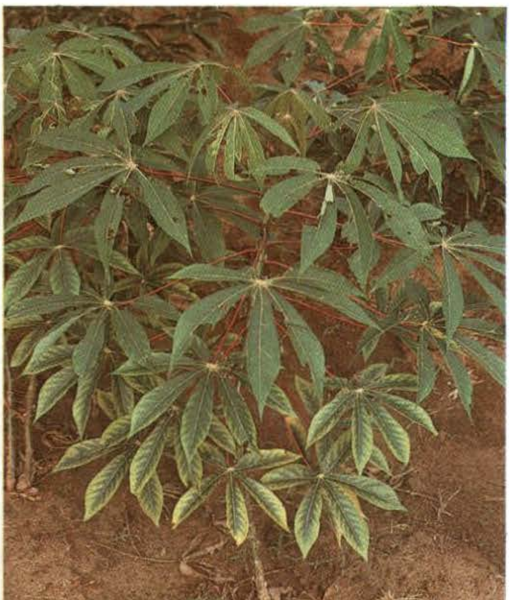
Response of cv. M Aus 7 to P in solution culture - note the reduction in growth due to P deficiency on left, but the lack of deficiency symptoms.

3

Severe P deficiency in cv. M Aus 10 as indicated by yellowing of bottom leaves.

4

Response to K fertilization in Carimagua, Colombia; in right without K, on left with 125 kg K/ha applied.

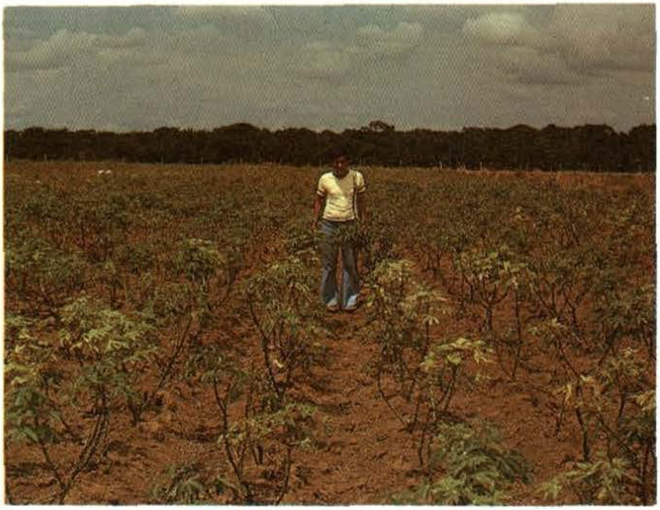


5 *Interveinal chlorosis of lower leaves due to Mg-deficiency.*

6 *Boron deficiency, indicated by fine chlorotic spotting on leaves*

7

Interveinal spotting and deformation of young leaves due to Zn deficiency



8

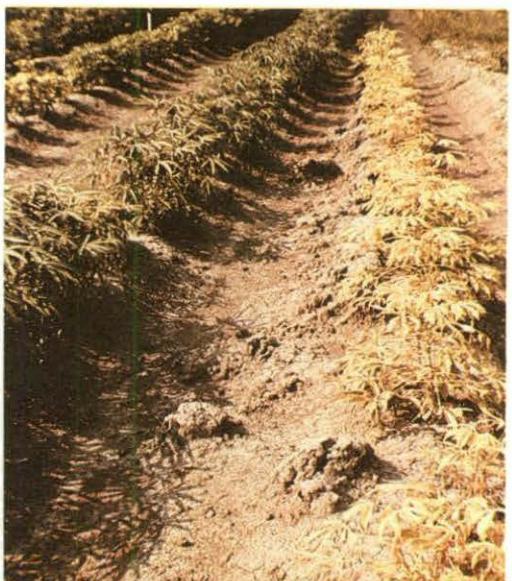
Plants of cv. MMex 23 showing severe yellowing due to Zn deficiency in Carimagua, Colombia.

9

Leaf symptoms of Mn-deficiency ranging from severely deficient (left) to healthy (right)

10

Copper deficiency in cv. M Aus 10



11

cv. M Col 22 (left) showing tolerance to soil salinity, and cv. M Ven 290 (right) showing severe susceptibility.

In Kerala State in India, Vijayan & Aiyer *(170)* and CTCRI *(22-24)* reported highest yields with 44-65 kg P/ha in combination with 100 kg N and 83 kg K/ha, basic slag being the most economical P source. In the same state, Chadha *(34)* obtained a 25% yield increase with 35 kg P/ha. In Thailand, Hongsapan *(77)* reported highest yields with 14-21 kg P/ha, while Sittibusaya & Kurmarohita *(156)* recommended the application of 22-44 kg P/ha for northeastern Thailand and 44-88 kg P/ha for the exhausted soils in the Southeast. For Malaysian peat soils, Chew *(39)* recommended 22 kg P/ha although Kanapathy *(92)* did not observe a P response in these soils.

The most commonly used P sources are single and triple superphosphate. Basic slag is as effective as TSP, especially on acid soils; and where available, this is generally a more economical source (*23, 30*). In highly acid soils of the Llanos of Colombia, TSP was superior to band-applied SSP; incorporated basic slag and rock phosphates were also highly effective sources (*30*). Mixing rock phosphates with sulfur or sulfuric acid improved the P availability considerably. Rock phosphates from different parts of the world vary greatly in P availability; cassava responded to their application according to the citrate solubility of the rock phosphate sources tested (*76*). Phosphate rocks from North Carolina, Morocco and Peru were among the best sources during the first year of cropping (*30*), but less-soluble sources from Colombia, Tennessee and Florida were nearly as effective in subsequent years (*31, 32*).

Potassium

Potassium is not a basic component of proteins, carbohydrates or fats, but is involved in their metabolism. Potassium is essential for carbohydrate translocation from the tops to the roots *(105)*, and an inadequate supply of K for cassava will thus lead to excessive top and little root production *(130)*. Blin *(18)* and Obigbesan *(128)* reported that K increased the starch and decreased the HCN content of roots, an effect opposite to that of N. Muthuswamy et al. *(114)* and Kailasam et al. *(90)* found no effect of P and K on the HCN content of roots, but CTCRI *(26, 27)* and Ashokan & Sreedharan *(16)* reported that application of K and wood ashes significantly decreased the HCN content of roots. Moreover, Payne & Webster *(136)* found a higher HCN content of roots in K-deficient than K-sufficient soils.

Asher et al. *(15)* and Krochmal & Samuels *(94)* reported that K deficiency is characterized mainly by reduced plant growth and an early senescence of older leaves and petioles, which fall prematurely. Dias *(51)* noted excessive branching of K-deficient plants, while Ngongi *(115)* reported that K deficiency decreased leaf size, leaf lobe number, leaf retention and plant height.

Since a harvest of cassava roots removes more K than any other element from the soil (about 102 kg K/ha in 25 t of roots), K deficiency is common in soils where other crops do not respond to K, especially after several years of continuous cassava production. K deficiency can be expected in most sandy soils. The Llanos Orientales of Colombia are severely deficient in K; on the other hand, many Andosols in South America are reasonably well supplied with K.

In Puerto Rico, Samuels *(144)* obtained a response to 83 kg K/ha, while Murillo *(112)* did not find a K response in lateritic soils in Costa Rica. In Colombia, a K response was observed in 11 out of 14 trials in farmers' fields *(169)*. Ngongi *(115)* obtained a significant response to 200 kg K/ha in the Llanos Orientales and to 100 kg K/ha in the Cauca Valley. High K application reduced the Mg content of leaves and petioles, possibly inducing Mg deficiency. Ngongi *(115)* also observed a strong N x K interaction in the Llanos, in which an N response was obtained only in the presence of K. On the same soils, CIAT *(30)* reported maximum yields with 133 kg K/ha, but the response to K was not nearly as marked as that to P. In Brazil Nunes et al. *(127)* did not find a significant K response in Rio de Janeiro; whereas in São Paulo and Goiás, Normanha *(123, 124)* recommended the application of 25-83 kg K/ha. Silva & Freire *(152)* obtained a significant K response on poor sandy soils in São Paulo, but Dias *(51)* stated that K deficiency is not common in this state. In Bahia *(70)* a significant K response was obtained at only 2 of 8 experimental sites, while on the Cerrado soils of Minas Gerais *(44-46)* a response was obtained only to the lowest rate of application (50 kg K/ha). In the Amazon estuary, Albuquerque *(6)* obtained maximum yields with 150 kg K/ha.

In eastern Nigeria, Irving (*86*) reported a K response on light acid soils. In western Nigeria, Amon & Adetunji (*7*) recommended the use of 50 kg K/ha, while Obigbesan (*130*) failed to obtain a significant response to applications of 50-75 kg K/ha in 3 different soils. He also reported that K fertilization did not affect the DM content of the roots but that it increased the root/top ratio. In Ghana, Takyi (*166*) found no K response on a forest Ochrosol. In Madagascar K deficiency was the main limiting factor for cassava production (*140*), and applications of 92 kg of K/ha were recommended (*8, 9, 50*). Potassium application significantly increased the K content of the phelloderm (*48*) but decreased N and P contents.

In India, Kumar et al. *(96)* and CTCRI *(21, 22, 24)* reported a small, but significant response to 83 kg K/ha with a negative response to higher levels *(25)*. Chadha *(34)*, however, obtained yield increases of up to 75% with 133 kg K/ha. He found a strong N x K interaction and recommended the application of N and K in the ratio of 1 to 1.46. On Malaysian peat soils cassava could be grown continuously with 75 kg K and 120 kg N/ha *(92)*; Chew *(38)* recommended 92-133 kg K/ha for these soils. In Indonesia both Nijholt *(117)* and den Doop *(53, 54)* considered K to be the main limiting nutrient. Den Doop obtained a response to 125 kg K/ha in the first planting and a strong residual effect to the application of 250 kg K/ha in the second and third plantings. Den Doop *(55)* also reported that K application increased the availability of soil P and that K availability was reduced during drought.

Potassium deficiency is generally controlled by the application of KCl or K_2SO_4 although application of wood ashes, Syngenite and Schoenite (the last two sources extracted from seawater) was found to be equally effective in southern India *(25, 26)*. In the Cauca Valley of Colombia, KCl and K_2SO_4 were equally effective K sources; but in the low-S soils of the Llanos, K_2SO_4 or KCl mixed with sulfur was superior to KCl alone (*116*).

Calcium and magnesium

Calcium plays a major role in the water regulation of the plant, while Mg is a component of chlorophyll and is therefore essential for photosynthesis.

Calcium deficiency in cassava presents itself mainly as a reduction in root growth *(15)*. Forno et al. *(64)* found that lack of Ca during mist propagation of cassava resulted in poor root development; this was overcome by the addition of 150 μM Ca to the misting solution *(64)*. Spear et al. *(161)* reported that a solution K concentration of over 525 μM resulted in reduced plant growth due to induced Ca and Mg deficiency. High K concentrations resulted in lower Ca and Mg contents in the leaves. Ngongi *(115)* also reported a reduction in Ca and Mg contents in leaves due to high K applications but found that the sum of cations in the leaf blades and petioles remained rather stable over K fertilization rates. Conversely, Spain et al. *(158)* reported a decrease in K levels in the leaves at high liming rates. Edwards & Kang *(59)* observed little change in K and Mg contents of leaves due to liming while the Ca content increased from 0.49 to 3.18%. Solorzano & Bornemisza *(157)* reported that cassava absorbed nearly three times as much Ca as Mg, most of which was accumulated in the top and returned to the soil when the roots were harvested.

Calcium and Mg deficiencies in cassava are most common on acid infertile Oxisols and Ultisols, while Mg deficiency has also been observed in low-Mg but high-K volcanic ash soils in Colombia *(33)*.

Calcium deficiency is generally controlled by the application of lime although the more soluble source, gypsum, can also be used, especially in soils low in sulfur *(33)*. Magnesium deficiency can be controlled by applying dolomitic lime, magnesium oxide or magnesium sulfate. In the Llanos of Colombia, Ngongi *(115)* obtained a significant response to the application of 50 kg Mg/ha as $MgSO_4.7H_2O$ or MgO the former being superior, probably due to its S content and greater solubility. Applications above 50 kg Mg/ha resulted in a yield decrease due to induction of Ca deficiency. Other trials at the same location *(33)* resulted in a significant response to 60 kg Mg/ha but failed to show significant differences between Mg sources. Dolomitic lime was the most economical source under Colombian conditions. In Malaysia,Cheing *(36)* applied 20 kg Mg/ha for maximum production of cassava foliage.

Sulfur

Sulfur is a basic component of various amino acids and is thus required for protein synthesis. In the absence of sufficient S, plants accumulate excessive amounts of inorganic N, amino acids and amides in the leaves, without the formation of protein *(165)*. In industrial areas much of the plant's S requirements are met by the sulfur in the atmosphere, which is brought down in rain water. Sulfur deficiency is therefore most common in low-S soils that are far removed from industrial areas. In Colombia, Ngongi *(115)* observed sulfur-deficiency symptoms during the dry season only in cassava plants that had received applications of KC1, but not in those to which KC1 + S or K_2SO_4 had been applied. The sulfur-containing sources were superior in the Llanos soil having only

4-4.5 ppm sulfate-S, but KCl and K_2SO_4 were equivalent in the Cauca Valley soil with 9 ppm sulfate-S. Ngongi *(115)* concluded that S was a limiting nutrient and that high applications of chlorides may inhibit sulfate uptake, inducing S deficiency.

Micronutrients

Micronutrient deficiencies are not frequently reported for cassava but may be more common than is generally realized. Chew *(38)* reported that on the peat soils of Malaysia cassava is stunted, and the upper part of the plant turns completely yellow in the absence of Cu fertilization. A basal application of 2.5 kg Cu/ha as $CuSO_4 \cdot 5H_20$ increased yields from 4 to 12 t dry roots/ha (*40*).

Zinc-deficiency symptoms in cassava have been observed throughout the world, both on acid and alkaline soils; and the crop appears to be particularly susceptible to an inadequate supply of this element. In the alkaline soils at CIAT *(31)* best results were obtained with a foliar application of 1% $ZnSO_4$ or by dipping stem cuttings in 4% $ZnSO_4$ just prior to planting; in acid soils of the Llanos, a soil application with 5-10 kg Zn/ha as ZnO was most effective *(31)*. Howeler et al. *(79)* reported that in Llanos soil cassava responded mainly to Zn with only a small response to Cu and Mn. Although these soils are low in B. cassava did not respond to B application, nor have deficiency symptoms of B, Cu or Mn been observed. In Trivandrum, India, researchers obtained a significant response to applications of 10 kg borax, 12.5 kg $ZnSO_4.7H_2O$ and to 1 kg ammonium molybdate/ha *(25, 26, 98)*. Soil application of these elements was found to be superior to foliar application.

Forno et al. *(66)* observed that B uptake was highly dependent on temperature and that plant growth and B content of leaves were increased by increasing root temperatures from 19 to 26°C. B toxicity was induced by increasing the temperature to 33°C at a solution B concentration that was not toxic at lower temperatures.

Iron deficiency is induced by high levels of Cu, Mn and Zn (*83*). It has been observed on acid, high-Mn soils as well as on calcareous alkaline soils of the Yucatan Peninsula in Mexico.

Liming and the use of other soil amendments

Many soils in the tropics are unproductive because of extreme soil acidity, which in the case of mineral soils is generally accompanied by Al and/or Mn toxicity as well as deficiency of Ca, Mg and Mo. These soils can be made productive by liming, which increases the pH and Ca content and decreases the amounts of exchangeable and soluble Al and Mn. Howeler et al. *(79)* showed that small applications of lime increased yields in the Llanos but that large applications had a detrimental effect due to induction of Zn deficiency. Only in the presence of Zn did cassava, like most other crops, show a positive response to a liming rate of 6 t/ha. In Nigeria, Edwards & Kang *(59)* also obtained a positive response, but to only 1.0-1.6 t lime/ha, with a marked negative response at higher rates due to induced Zn deficiency.

In Puerto Rico, Samuels *(144)* obtained a positive response to the application of 2 t lime/ha in a soil with pH 4.5. In Bahia, Brazil, no lime response was obtained in three years of testing *(43)*. Silva & Freire *(151)* and Normanha *(124)* recommended the application and deep incorporation of lime in São Paulo. Normanha *(121)* recommended the use of 2 t/ha of dolomitic lime if the soil had a pH below 5. In India, CTCRI *(23, 24)* also recommended application of 2 t lime/ha since it increased the available-P content of the soil. Rodríguez *(141)* recommended the application of 1.5 t lime/ha for each meq Al/100 g, although data from CIAT *(28, 32)* indicate that most cassava cultivars can tolerate Al levels as high as 2-3 meq/100 g.

On peat soils in Malaysia, Kanapathy & Keat *(91)*, Lim et al. *(102)* and Chew *(37)* observed that cassava survived without liming on a soil of pH 3.2, while maize and peanuts died. Since the Al content of these soils is low, they attributed this mainly to a tolerance to low pH. For optimum yields, however, they recommended the use of 3 t hydrated lime/ha and suggested that its beneficial effect was mainly that of increasing pH rather than that of supplying Ca. Edwards et al. *(58)* also reported that cassava is more tolerant to a low solution pH (3.3) than maize or tomatoes, but that the optimum pH per se for cassava is about 5.5. Similarly, in a Nigerian Ultisol with a pH of 4.2, Edwards & Kang *(59)* found that yields of tops of soybeans were reduced to 9.5% of maximum, cowpeas to 52% and cassava to only 79-84% in the absence of lime. Thus cassava was found to be very tolerant to acid soils. CIAT *(31)* also reported that cassava was much more tolerant to acid soils than beans, maize, sorghum and rice and had a tolerance similar to that of cowpeas. Taking the average response of 42 cultivars, it was found that cassava produced more than 95% of maximum yield at a pH above 4.6 and an Al saturation below 80% *(32)*. Thus for most acid soils cassava requires no lime or only small applications.

Lime is generally applied as finely ground limestone ($CaCO_3$) or dolomite ($CaCO_3$+ $MgCO_3$). Other lime sources are CaO, MgO or $Ca(OH)_2$; basic slag may have a 60-70% $CaCO_3$-equivalence, and rock phosphates often contain small amounts of lime. Lime is applied before planting and incorporated by plowing and disking.

Although cassava is quite tolerant to acid soils, it does not tolerate an extremely high pH and is quite sensitive to soil salinity and alkalinity. CIAT *(30)* reported that cassava yields were drastically reduced when the pH was above 7.8, the percentage Na saturation was above 2.5, or the electrical conductivity was above 0.5-0.7 mmhos/cm. In comparison, bean yields were less affected by these conditions *(31)*. Cassava cultivars varied greatly in their tolerance, and certain cultivars could be selected for high pH soils. Although the application of 2 t S/ha was effective in increasing yields under the high pH conditions at the CIAT farm *(30)*, this practice is too costly to be recommended. Changing to a different crop or a different cultivar with better salt tolerance is a more practical solution.

Methods of fertilizer application

Cassava has a coarse root system with a small number of rather thick roots,which have relatively few root hairs *(81)*. For this reason it may be highly dependent on mycorrhizal associations for the uptake of nutrients, especially P, which has low mobility in the soil *(171, 172)*. Campos & Sena *(20)* and Sena & Campos *(149)* reported for an Oxisol at Cruz das Almas, Brazil that cassava roots at 7 months reached a depth of 90 cm, 66% of the roots being present in the top 10 cm of soil, and that at 12 months roots reached a depth of 140 cm with 86% in the top 10 cm of soil. At both harvest times about 96% of the roots were found in the top 30 cm of soil. Thus it appears that cassava has some deep roots, possibly for water absorption during drought, but that the bulk of the root system is found very near the surface; thus applications of fertilizers to depths beyond 10-20 cm are probably ineffective.

Using radioactive P, Ofori *(132)* established that once the roots start functioning as carbohydrate sinks, they no longer play an active role in nutrient absorption. He suggested that broadcasting P on the soil surface once the plant is established may be most effective since the actively absorbing roots were found to be located in the top 10 cm of soil.

Normanha & Freire *(122)* obtained poor germination when N and K were applied in the planting furrow, especially during the dry season. They recommended lateral placement of P and K at planting with a top dressing of N at three months *(124, 126, 159)*. In the Llanos of Colombia placement of 1 t/ha of 10-20-20 fertilizers directly under the stem cutting (planted vertically or horizontally) was not detrimental even during the dry season planting *(33)*. Broadcasting half of the fertilizers and banding the other half at planting was found to be the best method of fertilization during the wet-season planting, while broadcasting without ridging was superior during the dry-season planting *(33)*. In a trial at Darien, Colombia, Ramírez *(139)* found no significant difference between banding, circle and spot placement of a compound NPK fertilizer. Similarly, in Thailand no significant differences were obtained between broadcast, banding under the stem cutting or side banding at 20 or 50 cm from the cutting *(156)*. In other trials, highest yields were obtained by banding the fertilizers in 15-cm deep furrows before planting in the furrow *(155)*. In Malaysia, Chan *(35)* found no significant differences between broadcasting or spot dressing of N at planting. With the application of TSP in the Llanos of Colombia, no significant differences were observed between band or broadcast applications *(30)* although in higher P-fixing soils, band application is expected to be superior. For less-soluble P sources such as rock phosphates or basic slag, broadcasting was far superior to banding *(30)*. In India, higher yields were reported *(24)* with placement of P at a 5- or 10-cm depth than with surface placement.

Time of application

Several researchers *(106, 124, 144, 150)* have recommended that N and K fertilizers be applied at or shortly after planting, with an additional top dressing at 2-3 months. In India, Kumar et al. *(97)* reported best results with the application of half of the K at planting and half at one month. In the same country Ashokan & Sreedharan *(16)* recommended a split application of K if only small amounts are applied, while CTCRI *(22)* reported highest yields with split applications of N (½ basal, ½ at 2 months), P (½ basal, ½ at 1 or 2 months) and K (½ at 1 and 2 months) although in other trials *(23)* a basal application of P was found to be significantly superior to a split application. Rodríguez (*141*) obtained highest yields when NPK fertilizers were all applied at planting rather than as a split application. CIAT *(30, 31)* found no significant differences between a basal or split application of either N or K fertilizers, but a basal application of P was superior to a split application *(30)*. More recently *(33)*, a split application of K with one third applied at 0, 30 and 90 days was found to be superior to a basal application.

SELECTION OF CULTIVARS TOLERANT TO SOIL PROBLEMS

Although applications of lime to acid soils and gypsum or sulfur to alkaline soils may make these soils more productive, the cost of these amendments is often prohibitive. In such situations it is often more practical to adjust the plant to the soil than vice versa. Selection of species and cultivars with tolerance to specific soil problems is a viable alternative to the traditional practice of fertilization and soil amendment.

Cassava is highly tolerant to acid soils; but within the species, cultivars differ greatly in their tolerance to low pH per se or to high solution concentrations of Al *(74)* and Mn *(60)*. CIAT *(31)* has screened hundreds of cultivars for tolerance to acid soils and found some cultivars quite productive even at pH 4.3 and 85% exchangeable Al.

Similarly, it was found that cassava cultivars differed in their external requirements for NH_4 or NO_3-N *(65)*, for P *(88)* and K *(159)*, and differed in rates of absorption and translocation or in the efficiency of utilization of these nutrients in DM production. CIAT (*31*) also reported large cultivar differences in P and K requirements in the field; and differences in low-Zn tolerance have often been observed.

NUTRITIONAL STATUS X PEST AND DISEASE TOLERANCE

Literature on interactions between the nutritional status of cassava and disease and pest tolerance is very limited, but this appears to be an area of potential importance. In Colombia disease and pest attacks seem to be most devastating in the Llanos Orientales, where soils are highly infertile. Although climatic conditions of the region contribute to severe disease incidence during the rainy season and high pest populations during the dry season, it appears that plants are more susceptible to and do not have the vigor to recuperate from attack because of nutritional deficiencies. Thus cassava bacterial blight (CBB) damage was observed to be severer in stunted plants due to inadequate lime application rather than to inadequate P fertilization. It appears that inadequate Ca nutrition may have enhanced plant susceptibility to CBB infections. Both Arene *(11)* and Adeniji & Obigbesan *(2)* reported that CBB incidence was reduced by application of moderate levels (75 kg K/ha) of K. A high level of applied K (100 kg K/ha), however, increased disease incidence and decreased yields. Interactions between K or Si nutrition and disease incidence have been reported for other crops and should be investigated for cassava.

Conversely, diseases may affect the nutritional status of plants. Obigbesan & Matuluku *(131)* reported that CBB caused a reduction in the macronutrient and an increase in the micronutrient content of cassava leaves; the disease also reduced the starch content of roots. Alagianagalingam & Ramakrishnan *(5)* reported that cassava leaves infected with African mosaic virus had lower N contents and that the disease enhanced the diurnal fluctuations in the total N content of the leaves.

SUMMARY AND CONCLUSIONS

Cassava tolerates a low pH and low concentrations of N, K and Ca, as well as high concentrations of Al and Mn in nutrient solutions, better than several other crops. For maximum growth, however, the external requirements of cassava for N, K and Ca are similar to those of other crops, but much higher in the case of P. Similarly, cassava grows relatively well on acid and highly infertile soils, but may require heavy fertilization to attain maximum yields. The P requirement of cassava in soils appears similar to that of other crops as the result of an effective mycorrhizal association.

Table 10 summarizes the response to fertilization and liming. In the three most extensive tropical soils (Oxisols, Ultisols and Inceptisols) P is generally the element most limiting to yield. In the Llanos of Colombia yields increased threefold by adequate P fertilization. Cassava extracts large amounts of K from the soil (about 100 kg K for each 25 t of roots) and may cause depletion of this element if grown continuously without adequate K fertilization. Under those conditions the crop responds to high rates of applied K. Compared with many other crops, cassava has a low requirement for N; high N applications may lead to excessive top growth, a reduction in starch synthesis and poor root thickening.

Cassava is very tolerant of acid soils where other crops may suffer from Al or Mn toxicity. Although it also tolerates a low pH, the optimum range is between 5.5 and 7.5. The crop often responds to low rates of liming but is susceptible to overliming, which may induce micronutrient deficiencies. It is particularly susceptible to Zn deficiency, which may be overcome by applying zinc sulfate to the soil, as a foliar spray, or as dip for stem cuttings.

Figure 3 indicates the main cassava-producing countries *(62)*, as well as the elements most limiting to cassava production in each region or country as reported in the literature. In general, P deficiency is most common in cassava-growing areas of *Latin America*, while N and K deficiencies are more common in Africa and Asia.

By screening large numbers of cultivars for tolerance to adverse soil conditions such as acidity or low P availability, it may be possible to select and breed genetic material that is well adapted to growing on poor soils with minimum fertilizer inputs.

Table 10. **The response of cassava to the application of major nutrients and lime in different parts of the world as reported in the literature.**

Country	Region	Soil	N (kg/ha)	P (kg/ha)	K (kg/ha)	Mg (kg/ha)	Lime (t/ha)*	Source
Puerto Rico		Ultisol	120					Fox et al. *(67)*.
					83		2	Samuels (*144*)
Costa Rica			60-70	26-30	108			Schmitt *(148)*
			50	—				Acosta & Pérez (*1*)
		Lateritic			—			Murillo (*112*)
Colombia	Various	Incept-Oxisol	50-60	131	42-50			Tarazona et al. (*169*)
	Antioquia	Inceptisols	145	85	38			Rodríguez (*141*)
	Cauca Valley	Inceptisols			100			Ngongi (*115*)
	Llanos	Oxisols	100		200	50		Ngongi (*115*)
	Llanos	Oxisols	100					CIAT (*29*)
	Llanos	Oxisols	100	87-175	133			CIAT (*30*)
	Llanos	Oxisols	130	175	133		0.5-2	CIAT (*31,32*)
	Llanos	Oxisols				60		CIAT (*33*)
Peru	Tarapoto	Ultisol	—	52	—			Curva (*49*)
Brazil	São Paulo, Goiás		20	26-52	25-83		2	Normanha (*121, 123, 124*)
	São Paulo	Sandy	—	—	50-100			Silva & Freire *(151, 152)*
	Rio de Janeiro		—	29	—			Nunes et al. (*127*)
	Minas Gerais	Oxisols			50			Correa et al. (*44-46*)
	Bahia	Oxisols	200	30	—			Santana & Carvalho (*146*)
	Bahia	Oxisols		26-52	50-100			Gomes et al. (*71*)
	Amazon estuary			44	150			Albuquerque (*6*)

Table 10 cont.

Country	Region	Soil	N	P	K	Mg	Lime	Source
			(kg/ha)*				(t/ha)*	
Nigeria	Western		25	—	50			Amon & Adetunji (*7*)
	Western	Various	60-90		—			Obigbesan & Fayemi (*129*)
	Eastern	Light, acid	9-27		17			Irving (*86*)
		Ultisol					1-1.6	Edwards & Kang (*59*)
Ghana			25	10				Stephens (*164*)
		Forest Ochrosol	60	20	—		—	Takyi (*166*)
	Otrokpe		134					Takyi (*167*)
Madagascar			30-60	57	92			Anon (*8*), De Geus (*50*)
			100	—	150			Roche et al. (*140*)
			30	120	100			Cours et al. (*48*)
India	Kerala	Oxisol	100					Mandal et al. (*106*)
	Kerala	Oxisol	100-150					Saraswat & Chattiar (*147*)
	Kerala	Oxisol	50-100	44-65	83			CTCRI (*22-25*)
	Kerala	Oxisol	100	44-65	83			Vijayan & Aiyer (*170*)
	Kerala	Oxisol		35	133			Chadha (*34*)
	Kerala	Oxisol			83			Kumar et al. (*96*)
Thailand				14-21				Hongsapan (*77*)
	Northeast	Podzols	50-100	22-44				Sittibusaya & Kurmarohita (*156*)
	Southeast	Exhausted Podzols	50-100	44-88				Sittibusaya & Kurmarohita (*156*)
Malaysia	Southeast	Peat	180	22	92-133		3	Chew (*37, 38*)
	Southeast	Peat	120	—	75			Kanapathy (*92*)
	Kuala Lumpur		150	30	150	20		Cheing (*36*)
	Serdang		124	29	98			Ahmad (*4*)
Indonesia	Java		90	13	0-42			Hadi & Gozallie (*75*)
	Java	Inceptisols	—		*125-250*			Den Doop (*53, 54*)

* Numbers underlined indicate the principal limiting nutrients, while a dash indicates no response

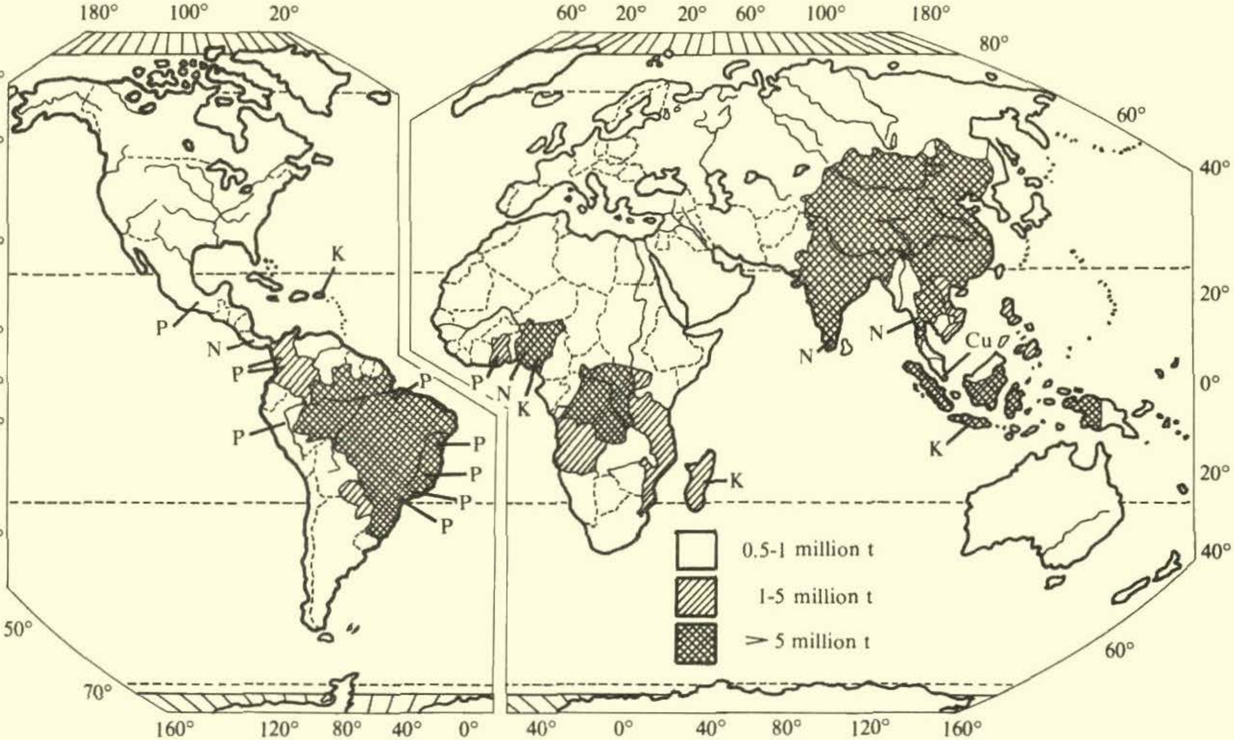


Figure 3. **World cassava production in 1978 *(62)* and the main limiting nutrients for cassava as reported by various authors in the literature.**

RESEARCH PRIORITIES

Since cassava production will extend more and more into areas with marginal soils, it is essential that research on its nutrition and soil fertility requirements be increased. The following areas require special attention:

1. Nutrient uptake, translocation and utilization of individual elements and their interaction
2. Root morphology, root extension and factors affecting root bulking
3. The effect of nutrients on DM partitioning between tops and roots
4. Mycorrhiza and other microorganisms that may affect nutrient uptake
5. Genetic tolerance to adverse soil conditions and the incorporation of this tolerance into high-yielding cultivars
6. The interaction between plant nutrition and tolerance to diseases and pests
7. The relation between soil characteristics and cassava production, and the determination of minimum levels of available nutrients required for near-maximum production
8. The use of cheap sources of plant nutrients such as rock phosphates, organic manures, industrial waste products, etc.
9. The most efficient fertilizer application techniques, including development of adequate equipment and tools
10. The nutritional value of fallowing, rotation and intercropped legumes

Coordinated, international research efforts will be required to cover all these topics adequately in order to achieve the objective of increased production and productivity of cassava with a minimum of costly inputs.

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