NUTRITIONAL DISORDERS OF CASSAVA

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(Manihot esculenta Crantz.)

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Preface

Cassava now ranks sixth in importance as a world crop, from the standpoint of production, and only the major cereals rank ahead of it. Vastly underrated and even denigrated in the past, for years it has suffered from neglect by agricultural science. In part the lack of attention given to cassava by agricultural scientists has resulted from its lowly status as a food crop for poor and marginal farmers and its use as a subsistence crop.

Over the last decade we have experienced a great change in the status of cassava and in the amount of research attention given to the crop. An impressive number of national and international institutions have initiated significant research programs on cassava, and the fruits of that research is beginning to have an impact on the crop and the production systems under which it is grown.

This booklet is a significant product of the recent research. It presents diagnostic information on cassava nutrition, including visual symptoms of deficiency of specific nutrient elements. The excellent photographs, coupled with a review of the state of knowledge for each major and minor element, make it an important reference work for agriculturists engaged in research or educational activities.

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Introduction

Cassava is a root crop widely cultivated throughout the lowland tropics where it is estimated to serve as a staple food for over 200 million people (Coursey and Halliday, 1974). Much of this cassava is grown in subsistence agricultural systems without the use of chemical fertilizers. The crop has a well-earned reputation for being able to produce small but acceptable amounts of edible carbohydrate on soils which are too poor to sustain the growth of other staple crops. In addition, cassava appears to be more drought tolerant than many other crop species (Cock and Howeler, 1978). Frequently, in shifting agricultural systems cassava is used to extract what little chemical fertility has been left by other crops, before the land is returned to bush fallow. In addition to the low-protein starchy roots, the leaves, which may be quite high in protein, are sometimes eaten by people or fed to livestock.

During the past two decades there has been growing recognition of the value of cassava roots as a low-cost energy source for livestock rations and a substantial international trade in dried cassava chips and pellets has developed between some tropical countries and temperate zone countries with intensively managed livestock industries. More recently still, there has been a growing interest in cassava as a source of industrial starch, and as a substrate for the production of fuel alcohol (McCann and Prince 1978, Evenson and Keating 1978, Smythe 1978). The efficient large-scale cultivation of cassava for such industrial purposes will require a much higher level of inputs than is customary for much of the world's cassava production and there may well be room for selection of cultivars specifically for high yield under intensive mechanized agriculture.

Optimum conditions for cassava production

Cassava can be grown under a wide range of climatic and soil conditions. Evenson and Keating (1978) suggested that soil temperatures should be above 18°C, and De Boer and Forno (1975) considered 1000 mm annual rainfall as the lower limit for cassava production. However, cassava can be grown with a much lower annual precipitation as long as sufficient soil moisture is available during the first two months after planting. It is generally recommended that cassava be grown on well-drained sandy loam to clay loam soils, since cassava will not tolerate excess water. However, very high cassava yields (80 t/ha/year) have been reported on a heavy (> 50% clay) and very fertile alluvial soil of the Cauca Valley of Colombia (CIAT, 1978). Cassava would appear to have little future on these heavy soils, because they are utilized for production of economically more valuable crops. In addition, cassava is harvested more easily on lighter-textured soils. For mechanized production, slopes should be less than 16% and the fields should be free of boggy patches at planting and harvest times to facilitate the movement of machinery. Even under manual cultivation cassava should not be planted on steep slopes since the digging of roots leaves the soil in a highly erodible condition.

Normanha (1961) stated that cassava grows best in soils of pH between 6 and 7. However, Islam *et al.* (1980) found that cassava achieved a whole plant dry matter yield greater than 90% of maximum over a pH range from about 5.0 to 7.5 when grown in flowing solution culture (Figure 1a). Cassava was also more tolerant of low pH than other crop species, achieving higher relative yields at pH 3.3 and 4.0 on a low aluminium acid peat soil in Malaysia, (Lim *et al.,* 1973). Unlike maize and groundnut, cassava cv. Black Twig survived at pH 3.2 (measured in water) and achieved a root yield equal to 17% of that obtained when the soil pH was increased to 4.6 by liming. In mineral soils also, cassava generally has been shown to be highly acid tolerant, exhibiting little or no yield depression at soil pH values as low as 4.3 (Spain *et al.* 1975, Howeler *et al.* 1977, Edwards and Kang 1978). However, some cultivars have shown greater yield depressions at soil pH values below 4.5 (Figure 1b) than in solution culture (Figure 1a). The greater sensitivity of soil-grown cassava to low pH may be associated with toxicities of aluminium or manganese, and deficiencies of calcium, phosphorus or molybdenum. Cassava yields may also decline more rapidly at soil pH values above 8 (Figure 1c) than in solution culture, due to a complex of pH-related problems including salinity, poor drainage and low availability of boron, iron, manganese, copper or zinc.

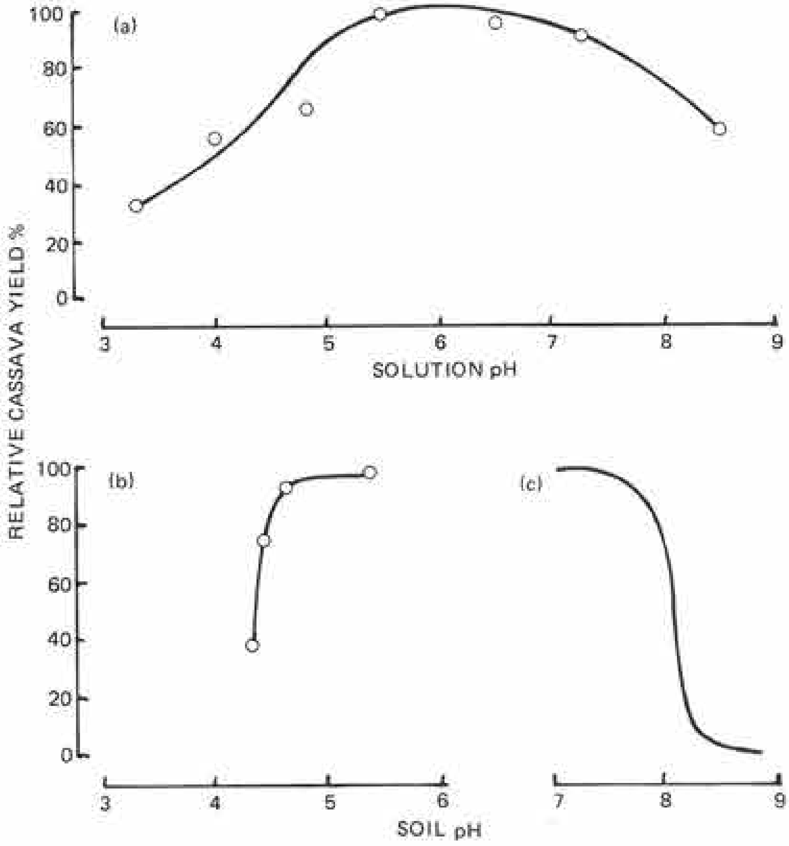

Figure 1: Effect of pH on cassava growth: (a) total dry matter production of 4 weeks-old cassava plants of cv. Nina grown in flowing solution culture (Islam *et al.*, 1980); (b) average root yield of 42 cassava cultivars grown on acid soil at Carimagua, Colombia (CIAT 1978); (c) average root yield of 3 cassava cultivars grown on alkaline soil at CIAT, Colombia (CIAT 1976).

Quantitative nutrient requirements of cassava

Until recently the mineral nutrition of cassava had not been the subject of intensive or detailed scientific investigation. While it seems reasonable to assume that cassava will require the same nutrient elements as other more intensively studied crop plants, symptoms of chlorine and molybdenum deficiency have not been described. However significant molybdenum responses have been reported in the field (Cours et al., 1961; CTCRI, 1972, 1973, 1974). Boron deficiency symptoms have been induced under controlled experimental conditions (Forno *et al.* 1979) and a significant yield response to boron has been reported in a field trial in Southern India (CTCRI, 1973).

The total requirement of each nutrient element for any crop depends on two factors: (1) the level of yield, and (2) the average concentration of the element throughout the plant needed to secure that yield. Under favourable growing conditions cassava can be expected to produce about 18 tonnes of total dry matter per hectare during the first 12 months of growth. This level of productivity corresponds approximately with a fresh root yield of 30 t/ha. Higher yields are possible but are seldom attained under practical farming conditions.

Howeler (1978) has reported approximate nutrient removal values calculated from data in the literature. Table 1 shows similar nutrient removal values calculated from dry matter distribution and the nutrient concentrations in various plant parts. The relatively large requirement for potassium is evident, with 76 kg/ha being removed in a root harvest of 30 t/ha. If the tops are also removed during harvest, the amount of potassium removed is more than doubled and leads to an even larger drain on soil potassium reserves.

Although micronutrient requirements are from one to several orders of magnitude lower than macronutrient requirements, the supply of micronutrients can be extremely important under field conditions. Thus, Chew *et al.* (1978) have observed severe copper deficiency symptoms on cassava growing on peat soils in Malaysia, and significant responses to copper fertilizer have been obtained on lateritic soils in Southern India (CTCRI, 1973, 1974). Severe zinc deficiency symptoms have been observed on cassava at three widely separated locations in Northern Australia and significant yield responses to zinc fertilizer have been reported from Southern India (CTCRI, 1972, 1973, 1974). Severe zinc deficiency has also been induced quite readily in casava by liming acid tropical soils in Colombia (Howeler *et al.* 1977) and Nigeria (Edwards and Kang 1978).

Where the soil is incapable of supplying all the essential mineral nutrients in adequate amounts, the limiting nutrients will need to be provided from some external source such as chemical fertilizer, organic wastes or crop residues. To make efficient use of these materials it is essential that the limiting elements be identified for each site, and the cheapest effective source of each limiting element be applied to correct the problem. In this sense a "balanced" fertilizer is one which applies adequate but not excessive amounts of each deficient element. Since more than 50 percent of the total nutrients in the cassava plant are present in the tops, the return of these to the soil can reduce substantially the rate of nutrient removal from a site, and hence the long-term fertilizer cost.

Table 1. Approximate amounts of each nutrient element needed to produce a thirty tonne/ha crop of cassava.

Element	Concentration≠ %				Total amounts required for a 30 t/ha root harvest — kg.				
(a) Macronutrients	Roots	Stems	Leaves	Petioles	Roots+	Stems+	Leaves+	Petioles+	Total+
Potassium	0.73	1.69	1.20	2.35	76	76	23	25	200
Nitrogen	0.36	0.66	4.18	1.43	38	30	81	15	164
Calcium	0.09	0.63	0.99	2.31	9	28	19	24	80
Phosphorus	0.10	0.34	0.26	0.14	10	15	5	1	31
Magnesium	0.09	0.23	0.39	0.49	9	10	7	5	31
Sulphur	0.06	—	0.31	0.14	6	—	6	1	—
	Concentration≠ µg/g								
(b) Micronutrients	Total Plant								
Iron	200								3.60
Manganese	75								1.35
Zinc	75								1.35
Boron	25								0.45
Copper	8								0.14

≠ Average concentrations obtained from reports in the literature (Howeler 1978).

+ Calculated using the following assumptions:

	Roots	Stem	Leaf Blades	Petioles
Fresh matter distribution (%)	50	30	13	7
Dry matter percentage	35	25	25	25

Diagnosis of nutritional problems

Accurate diagnosis is essential if nutritional problems are to be dealt with effectively. Visual symptoms of nutrient deficiencies and toxicities often play an important part in diagnosis under field conditions, and the visual method has the advantage that it is not directly dependent on costly equipment or laboratory support services. However, because different nutritional disorders may sometimes produce rather similar visual symptoms it is always wise to seek confirmation of the diagnosis by means of plant analysis, soil analysis, or both. Unfortunately, clearly recognizable symptoms in cassava are usually only associated with rather severe nutritional disorders. Less severe conditions may result in substantial reductions in crop vigour and yield without the development of specific symptoms. Here again soil and plant analysis can be of great assistance in making a correct diagnosis.

This booklet is concerned mainly with visual symptoms of nutrient deficiency and toxicity. However, where available, supplementary information on soil and plant analysis has been included also as a further aid to diagnosis. This information is generally reported in terms of critical concentrations. The critical concentration for deficiency of an element is defined as that concentration (in soil or plant tissue) below which the application of that element will generally result in a yield increase, and above which no such increase is to be expected. Similarly, the critical concentration for toxicity is that concentration above which a yield reduction is to be expected. This booklet will indicate those critical concentrations in soils and plant tissues that have been determined. Some of the critical tissue concentrations come from glasshouse pot culture experiments. Since recent work of Spear *et al.* (1978a) has shown that the values obtained depend to some extent on such details of technique as the size of pot chosen, there would appear to be a need to check all such values against the performance of plants grown under actual field conditions. Since critical concentrations for plant tissue can vary with cultivar, plant age, climatic conditions and other factors (Ulrich and Hills 1967, Bates 1971), sampling of plant tissue should be standardized as much as possible. We recommend taking the youngest fully expanded leaves and analyzing either the leaf blades or petioles, as the best indicators of the nutritional status of the plant. Nutrient concentrations in leaf blades are shown in Table 2. Leaf samples are generally taken when plants are about 3-4 months of age or when they start growing vigorously after a prolonged dry or cold period. Sampling during periods of slow growth due to non-nutritional causes is not recommended.

Table 2. Nutrient concentrations in youngest fully expanded leaf blades of cassava at 2 – 5 months of age. (Howeler, 1978).

Element	Nutritional Status			
	Deficient	Critical Concentration	Normal	Toxic
	(%)	(%)	(%)	
Nitrogen	< 4.5	5.7	5.0 – 6.0	
Potassium	< 1.0		1.2 – 2.0	
Calcium	< 0.5		0.6 – 1.5	
Phosphorus	< 0.2	0.4	0.3 – 0.5	
Magnesium	< 0.2		0.25 – 0.5	
Sulphur	< 0.3	0.32	0.3 – 0.4	
	(µg/g)	(µg/g)	(µg/g)	(µg/g)
Iron	< 50		60 – 200	> 250
Manganese	< 50		50 – 250	> 1000
Zinc	< 35	35 - 50	40 – 100	
Boron	< 15		15 – 50	> 140
Copper			7 – 15	

This booklet indicates also how the various nutritional problems encountered in field-grown cassava may be corrected. Since soils differ greatly in physical and chemical characteristics, only very rough guidelines can be given about the use of fertilizers and soil amendments. Only through local experience with the crop and analysis of soil and plant tissue can more precise fertilizer recommendations be made.

Importance of leaf position in visual diagnosis

The normal patterns of distribution and redistribution of mineral nutrients within the plant result in a tendency for symptoms of nutritional disorders to occur in particular positions on the plant. Thus, in addition to observing the appearance of affected leaves on an unhealthy plant we should also take careful note of the location of these leaves.

Mineral nutrients absorbed by the root system tend to be distributed among the various parts of the shoot in a pattern closely resembling the pattern of water loss due to transpiration. Thus fully expanded leaves, which present a large evaporating surface relative to their volume tend to receive a greater share of the water and mineral nutrients entering the shoots than do fruits or the tightly rolled immature leaves at shoot apices. When the soil solution contains above-optimum concentrations of a particular mineral element the tendency will be for an excess of the element to accumulate in the leaves. The highest concentrations will be found in the oldest leaves since it is in these that the accumulation has been going on for the longest period of time. It is therefore to be expected that the older leaves will show symptoms of nutrient toxicity first and most markedly. Often this proves to be the case, but where an excess of one element reduces the uptake of a second element or interferes with its utilization in the plant tissues, the main symptoms may be those of a deficiency of the second element. In this case the position of the symptoms will be that characteristic of the deficiency of the second element which may or may not be on the older leaves.

Under deficiency conditions most plants tend to withdraw elements such as nitrogen, phosphorus, potassium, magnesium, sulphur, sodium, and chlorine from the older leaves and redistribute the deficient element to young, actively growing parts of the plant. Since the redistribution of these elements is via the phloem transport system such elements are said to be *phloem mobile*. In general we expect to see the first and most obvious symptoms of deficiency of phloem mobile elements on the older (lower) leaves. This pattern of symptom development is generally followed in cassava although the phloem mobility of nitrogen and sulphur appears to be lower than in many other crops.

Calcium and boron are not redistributed to any extent under deficiency conditions and are therefore described as *phloem immobile* elements. With such elements the plant must have a continuous external supply if healthy growth is to be maintained and any interruption of this supply will cause deficiency symptoms on young actively growing parts of the plant including the root tips.

The remaining essential elements are of intermediate phloem mobility and usually show symptoms of deficiency mainly on the younger growth. However where the supply of such an element has fluctuated widely during the growing season we may find deficiency symptoms on leaves formed during a period of deficiency, with healthy leaves both above and below. On some soils this pattern is observed with manganese deficiency. In some crops the mobility of sulphur in the phloem appears to be lower than for the other phloem mobile elements and sulphur should probably be classified as having intermediate phloem mobility.

Disorders producing symptoms mainly on the older leaves

Nitrogen deficiency

With most crops nitrogen deficiency symptoms develop first on the older leaves and spread to progressively younger leaves until the whole plant may be chlorotic. Such a pattern of symptom development was reported by Krochmal and Samuels (1968) with the cassava cultivar Fowl Fat. The general chlorosis has been observed in cassava grown both in soil (Plate 1a) and solution culture (Plate 1b). However, at the University of Queensland it has been observed (Lee 1973) that in many cultivars the older leaves that were present on the cutting before transfer to a nitrogen deficient solution were less susceptible to chlorosis than later formed leaves (Plate 1c). This suggests that little translocation of nitrogen occurs out of these older leaves. Under severe nitrogen deficiency in the field, plants are observed to be stunted and spindly (Plate 1d) with chlorotic lower leaves. The chlorosis does not spread inwards from the tips and margins of the leaves as with many other nutritional disorders. Instead, the whole leaf becomes chlorotic at about the same time. Close inspection of these leaves shows that the fine veins retain some green colour so that the leaves retain a slight greenish tint. The upper leaves of the plant will usually be much paler than normal. Three characteristics allow nitrogen deficiency to be distinguished from phosphorus deficiency which also causes stunting of the plant and chlorosis of the lower leaves. Firstly, the nitrogen deficient lower leaves tend to retain their turgor for a considerable period after becoming chlorotic, whereas the chlorotic lower leaves of phosphorus deficient plants tend to hang limply from the petioles. Secondly, with phosphorus deficient plants the minor veins of chlorotic leaves tend to be the same colour as the remainder of the leaf so that the leaf is yellow rather than greenish yellow. Thirdly, the upper leaves of phosphorus deficient plants tend to be a much darker green than those of nitrogen deficient plants. Since moderately nitrogen deficient plants may show no clearly recognizable symptoms except reduced growth rate, absence of specific symptoms does not necessarily mean that the nitrogen supply is adequate.

In experiments conducted in flowing nutrient solutions maintained at a range of constant nitrogen concentrations, cassava showed only mild leaf symptoms at extremely low nitrogen concentrations (less than 1 μM) which caused very severe symptoms in maize, sorghum, cotton and sunflower (Forno 1977). At a nitrate-nitrogen concentration of 0.4 μM the yields of sorghum, maize and sunflower were only 5, 7 and 9% of maximum respectively, whereas eleven cassava cultivars had an average yield of 40% of maximum at the same concentration (Edwards *et al.* 1977). Thus cassava appears more tolerant of nitrogen deficiency than most crops, although large cultivar differences have been observed. In solution culture experiments maximum growth of eleven cassava cultivars was obtained at solution nitrate concentrations from 3400 to 4450 μM or at solution ammonium concentrations from 26 to 420 μM. Similar concentrations were needed for maximum growth of sorghum, maize and sunflower. However, maximum yield of cassava roots might be obtained at somewhat lower nitrogen concentrations since excessive top growth associated with a high external nitrogen supply has been shown to lead to reduced root yields (CIAT 1978).

Normal nitrogen contents of upper leaves at 3-5 months after planting range from 5 to 6% with a critical concentration determined at 5.7% (Howeler 1978). Petioles will normally contain between 1 and 2% nitrogen, while stems and roots are extremely low in this element, containing between 0.25 and 1% (Table 1).

Nitrogen deficiency can be expected on sandy soils as well as on acid oxisols and ultisols. Although little work has been done on the effects of crop rotation on cassava nutrition, field observation suggests that nitrogen deficiency is much more likely when a cassava crop follows a crop of maize than when it follows a leguminous crop such as beans. Thus nitrogen fertilizer costs might be reduced substantially by the inclusion of suitable legumes in the cropping system. Some interesting experiments have been conducted also on intercropping cassava with legumes (CTCRI, 1975), but possible effects on the nitrogen nutrition of the crop have not been examined.

Ngongi (1976) observed that moderate applications of nitrogen (50-100 kg N/ha) significantly increased yields, while higher applications decreased yields by producing excessive top growth at the expense of root growth. This appears to be especially true for the more vigorous cultivars. Nitrogen applications should be made at or shortly after planting and repeated at 2-3 months or when the plants start growing vigorously again after a cold or dry season. Soil applications of fertilizer are impractical after canopy closure. No significant differences have been observed between various nitrogen sources such as urea, ammonium sulfate, calcium nitrate or sodium nitrate when applied at equal rates of nitrogen application (Samuels 1970).

Phosphorus deficiency

Phosphorus deficiency can greatly reduce the growth of cassava without the development of clearly recognizable symptoms (Plates 2a, b, c). Hence, mild deficiencies can be diagnosed only by plant analysis, soil analysis or field experimentation. Leaves are normally pendant in some cultivars (Plate 2a), but in others pendant leaves only develop in severely phosphorus deficient plants (Plate 2f). However, the most conspicuous symptom of severe phosphorus deficiency which is readily recognized in the field is the uniform yellow chlorosis developed by the lower leaves (Plates 2d, e) which may hang limply from the petioles (Plate 2e). Unlike nitrogen deficiency, the minor and often the major veins of the lower leaves tend to be the same yellow colour

Plate 1. *Nitrogen deficiency.* (a) Low nitrogen (left) and high nitrogen (right) plants of cassava cv CMC 40. (b) Response of cassava to nitrogen in solution culture. Note healthy colour of high nitrogen plant at right, pale colour of nitrogen deficient plants at centre and left. (c) Young rooted cassava cutting (cv Mameya) grown in nitrogen deficient nutrient solution. Note anomalous distribution of symptoms for a phloem-mobile element. (d) Field response of cassava cv M Mex 59 to nitrogen. Plants in foreground show substantial growth reduction compared with high nitrogen plants in background.

a

b

c

d

as the interveinal tissue. Sometimes an upward curling of the lateral leaf margins of the chlorotic lower leaves is observed before they become limp (Plate 2e). Frequently some green colour is retained in the interveinal areas adjacent to the point of petiole attachment and the major veins may remain green for some time (Plates 2d, e). The affected leaves in some cultivars turn purple instead of yellow. Eventually, affected leaves shrivel and fall from the plant. Severely phosphorus deficient plants often have thin stems, short petioles, narrow leaf lobes and a reduced number of lobes per leaf. However, unlike nitrogen deficient plants the upper leaves tend to retain a healthy green or purple-green colour, with only a few lower leaves becoming chlorotic.

Normal phosphorus concentrations of upper fully expanded leaves range from 0.3 to 0.5%, and a critical concentration of 0.44% has been determined (Howeler 1978). Petioles of upper leaves normally contain 0.12-0.20% P, while roots contain only 0.08-0.12% (Table 1). Cassava has been found to be completely free of phosphorus deficiency symptoms at much lower plant phosphorus concentrations than other species, which is considered to be one of the mechanisms by which cassava shows adaptation to low phosphorus soils (Edwards *et al.* 1977).

Considerable uncertainty exists concerning the external phosphorus requirements of cassava for maximum growth. Thus Jintakanon *et al.* (1979) found that in a short-term experiment (1 month) in flowing solution culture eleven cassava cultivars required phosphorus concentrations in the nutrient solution ranging from 28 to 78 μM. The corresponding values of maize, soybean and cotton were 1.0, 0.6 and 0.6 μM respectively. In a somewhat longer flowing culture experiment (6 weeks) with eight cassava cultivars Howeler *et al.* (1979) found that all cultivars were severely phosphorus deficient at 1 μM P but grew well at 10 μM and 100 μM there being no significant difference in growth between those two concentrations. In a pot experiment of 2 months duration with a strongly phosphorus fixing oxisol, soil solution concentrations of 95-130 μM P were required for 95% of maximum growth in cv M Aus 10 (Howeler *et al.* 1979). Earlier work on the same soil (Jintakanon, unpublished) had indicated a much lower external phosphorus requirement (approx. 2.5 μM) but the results of this experiment are suspect because of yield depression at the higher rates of phosphorus application due to magnesium deficiency. All these results are therefore consistent with the view that the rather coarse, sparsely branched root system of cassava is inefficient in phosphorus absorption and that relatively high external phosphorus concentrations (10-100 μM) are required for maximum growth.

Plate 2. *Phosphorus deficiency.* (a) Response of cassava cv. Llanera to P in sand culture. (b) Response of cassava cv. Llanera to P on a highly P deficient oxisol at Carimagua, Colombia. Plot in left foreground received no P, plot to right of peg received 875 kg P/ha. (c) Response of cassava cv. M Aus 7 to P in solution culture. (Note absence of obvious symptoms other than growth reduction in Plates 2a, b, c.) (d) Symptoms of severe P deficiency in cv. M Aus 10 — note chlorotic lower leaves. (e) Upwards curling of lateral margins of the lobes of a P deficient leaf of cv. M Aus 17. (Note retention of green colour near point of petiole attachment in Plates 2d, e.) (f) Comparison of healthy (right) and P deficient (left) plants of cv. M Aus 10 showing pendant leaves on the latter.

a

b

c

d

e

f

However, two recent field experiments suggest a very different situation. Thus in an ultisol at Quilichao, Colombia on which final yields of roots and shoots of cv. Llanera increased strongly with phosphorus application, 95% of the maximum root yield of 45 t/ha was obtained at a soil solution phosphorus concentration of between 0.5 and 0.8 μM (CIAT 1978). In a similar experiment on an oxisol at Kauai, Hawaii, Van der Zaag *et al.* (1979) reported that in cv. Ceiba 95% of maximum yield was reached at a soil solution concentration of 0.2 μM P and maximum yield at 0.8 μM. However, the results of this experiment are difficult to interpret because of possible limitations due to elements other than phosphorus. As in the experiment of Jintakanon (unpublished) yields were strongly depressed at the higher rates of phosphorus addition i.e., at soil solution concentrations above 0.8 μM P. Five other cultivars gave poor root yields at the site and showed no response to phosphorus fertilizer. Leaf analyses at five months were suggestive of deficiencies of magnesium, sulphur and zinc, the values in cv. Ceiba leaves being 0.16%, 0.20% and 26 μg/g respectively. Additional magnesium and sulphur were added at this time but zinc was apparently not applied.

Research at IITA showed that cassava roots form mycorrhizal associations, although the rate of infection by *Glomus fasiculatus* was rather slow (IITA 1976). Growth stimulation was observed when cassava plants in sterilized soil were inoculated with *G. mosseae* but there was no beneficial effect of inoculation on unsterilized soil (IITA 1977). Potty (1978) confirmed the existence of mycorrhizal associations on cassava growing in an Indian soil. Important effects of mycorrhizal associations in the phosphorus nutrition of cassava have since been demonstrated (Van der Zaag *et al.* 1979, Yost and Fox 1979). Yost and Fox (1979) reported that elimination of the natural mycorrhizal population in a Hawaiian soil by fumigation with methyl bromide reduced the yields of cassava tops at 118 days to only 10% of those obtained in unsterilized soil at the same soil solution phosphorus concentrations (in the region of 0.1-0.2 μM). A recent pot experiment conducted at the University of Queensland showed that plants of cassava cv M Aus 10 grown for two months on a methyl bromide sterilized, highly phosphorus fixing soil responded strongly to inoculation with mycorrhiza at low to intermediate phosphorus application rates (Table 3). There was no growth response to inoculation in the absence of applied phosphorus, nor where phosphorus was applied at high rates.

Further research is needed to clarify the role of mycorrhiza in the phosphorus nutrition of cassava and to explain why generally high external phosphorus requirements have been found in short term soil and solution culture experiments, compared with apparently low external requirements in the field.

Table 3. Effect of mycorrhizal inoculation on total dry matter yield of cassava cv M Aus 10 grown for two months in a methyl bromide sterilized oxisol (krasnozem).

Phosphorus rate	Total dry matter Yield	
t/ha	Non-inoculated	Inoculated
	g/plant	
0	10.8	9.5
0.5	13.7	30.7
2	20.1	54.7
4	67.6	69.1

Phosphorus deficiency is generally the most limiting nutritional factor for cassava grown on oxisols, ultisols and many volcanic ash soils. It can be corrected by band application of soluble phosphorus sources such as single or triple superphosphates, ammonium phosphates, or phosphorus containing "complete" fertilizers, or by incorporation of rock phosphates or basic slag into the soil. Single superphosphate is recommended for soils that are also low in sulphur. Although a good crop of cassava is only likely to remove about 30 kg P/ha from the soil, higher rates of application ($\geqslant$100 kg P/ha) may be needed in the first year on phosphorus fixing soils. Thereafter lower rates of application will often suffice. Excessively high application rates may induce zinc deficiency on low zinc soils. All P sources should be applied at or shortly after planting. Critical available phosphorus contents of soils for cassava production were found to be 4.8 μg/g as determined by Olsen-EDTA, 6.6 μg/g by Bray I, and 8 μg/g by Bray II extraction (Howeler 1978).

Potassium deficiency

Deficiency of potassium, like that of phosphorus, is mainly characterized by a severe reduction in plant height, thin stems, short petioles and small leaves (Plates 3a, b). Only in case of a very severe potassium deficiency are specific symptoms observed. In the early stages these include the appearance of small purple spots on the older leaves (Plate 3c), upward curling of lateral leaf margins, and in some cases downward curling of the leaf tips (Plate 3d). As the deficiency intensifies, chlorotic areas develop at the tips and along the margins of the leaves (Plate 3d) and eventually join up to form a border necrosis (Plate 3e). Older leaves and petioles senesce prematurely and fall off. In some cultivars, Spear *et al.* (1978b) have observed the development of longitudinal grooves in the upper stem internodes of potassium deficient plants with fine cracks appearing in the stem bark adjacent to these grooves. Spear *et al.* (1978b) have also observed purple or brown discoloration on petioles (Plate 3f) and occasionally stem tissue, followed by collapse of the affected petioles or stem. Cours *et al.* (1961) reported that potassium deficiency induced the development of anthracnose *(Colletotrichum* or *Glomerella manihotis)*. However no known cassava pathogens could be isolated from the petiole lesions in the study of Spear *et al.* (1978b). Krochmal and Samuels (1968) reported a browning or purpling of the leaf due to potassium deficiency, followed by marginal chlorosis. Howell (1974) reported yellowing or browning of leaf tips and adjacent margins of older leaves of potassium deficient plants.

Normal cassava plants have a potassium concentration of 1.2-2.0% in the youngest fully expanded leaves, 1.5-3.0% in the corresponding petioles, and 0.5-1.0% in roots (Table 1). Potassium contents of petioles vary over a wider range than those of leaf blades and thus appear to be better indicators of potassium status of the plant than leaf blades. As in the case of nitrogen and phosphorus, potassium contents decrease markedly from upper to lower leaves in potassium deficient plants (Cours *et al.* 1961, Spear *et al.* 1978b). High levels of calcium and/or magnesium decrease potassium uptake.

Potassium is removed from the soil in large quantities by high yielding crops, each tonne of fresh cassava roots containing about 2.5 kg of potassium. Continuous cassava production without adequate potassium fertilization may thus lead to rapid exhaustion of soil potassium reserves (Nijholt, 1935). Potassium deficiency is most common on sandy soils, and on low base-status oxisols and ultisols, while many volcanic ash soils are well-supplied with this element. Potassium deficiency is generally corrected by band application of potassium chloride or sulphate, the latter being preferred on soils of low sulphur status (Ngongi *et al.* 1977). Potassium fertilizers are usually applied at or shortly after planting and again at 2-3 months or when the plant starts growing vigorously again after a cold or dry season. Excessive application of potassium may lead to magnesium and/or calcium deficiency due to depression of the uptake of these elements (Spear *et al.* 1978c).

Magnesium deficiency

The most striking symptom of magnesium deficiency is an interveinal chlorosis of the lower leaves. The chlorosis commences at the tips and margins of the leaf lobes and spreads inwards between the veins towards the midrib, the chlorotic tissue often being bright yellow (Plates 4a, b). Sometimes however, the chlorotic areas are pale green rather than yellow (Plate 4c). Under severe magnesium deficiency the chlorotic areas may become necrotic and take on a whitish or brownish colour (Plates 4d, e). Spear *et al.* (1978c) have shown that high concentrations of potassium strongly inhibit magnesium uptake, and that magnesium deficiency is easily induced by above-optimum levels of potassium supply (Plate 4f).

Plate 3. *Potassium deficiency.* (a) Response of cassava to K in solution culture. (b) Response of cv. Llanera to K in the field. Plot at right has received no K, plot at left 125 kg K/ha. (c) Purple spots on lower leaf of potassium deficient plant of cv. M Aus 3. (d) Potassium deficient leaf of cv. M Aus 3 showing downwards curvature of tips of leaf lobes and development of marginal chlorosis. (e) Marginal necrosis of potassium deficient leaf. (f) Potassium deficient plant of cv. M Aus 10 with two necrotic patches (arrowed) on the petiole of the lowest leaf.

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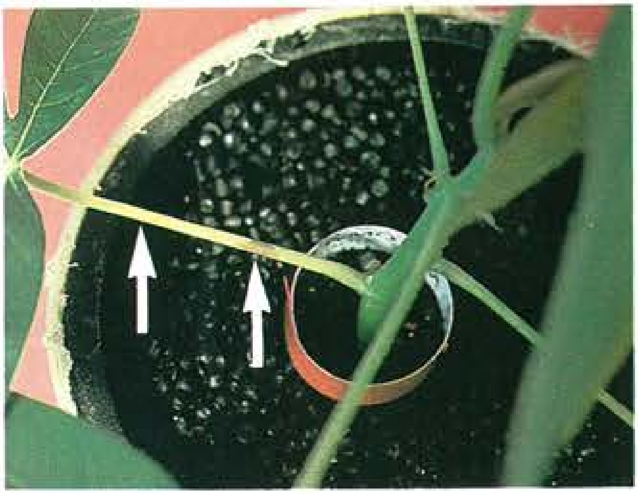

Critical tissue concentrations for magnesium deficiency have not yet been precisely defined. Spear *et al.* (1978c) found that potassium-induced magnesium deficiency was associated with magnesium concentrations in the youngest fully expanded leaf of 0.29% or less. Research at CIAT suggests that the normal range for upper leaves is from 0.26-0.5% Mg with deficient plants having less than 0.2% Mg. Recent work of Whitehead (1979) indicates a critical concentration of 0.16% in the blade of the youngest fully expanded leaf of cv Nina. Magnesium concentrations in deficient plants were generally higher in leaf blades than in petioles. However in plants supplied with adequate magnesium, concentrations in leaf blades and petioles were similar, or higher in the petioles (Table 1).

Available evidence suggests that cassava may be rather susceptible to magnesium deficiency. In flowing culture studies, Spear *et al.* (1978c) found that magnesium absorption rates in 12 cassava cultivars were lower than in sunflower or maize and that cassava yields were significantly reduced by magnesium deficiency at high external potassium concentrations whereas the yields of the other two species were unaffected. In a subsequent flowing culture experiment, Whitehead (1979) showed that cv Nina and cv M Aus 7 required higher solution magnesium concentrations for maximum yield (60 μM) than did cowpea or cotton (8 μM) but lower concentrations than french bean ($\geq$420 μM). However at very low external magnesium concentrations (0.5 to 1.5 μM) Whitehead found that the growth of cassava was reduced less by magnesium deficiency than most other crops. Further research on this element appears warranted.

Plate 4. *Magnesium deficiency.* (a) Magnesium deficient plant in the field at Carimagua, Colombia. (b) Close-up of magnesium deficient leaf. (c) Less common symptom of magnesium deficiency in cv. Mameya in which chlorotic areas are light green rather than yellow. (d) Magnesium deficient leaf of cv. Nina showing onset of necrosis in the chlorotic areas. (e) Chlorosis and necrosis of magnesium deficient leaf of cv. M Aus 7. (f) Potassium-induced magnesium deficiency in cv. M Aus 3.

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Magnesium deficiency is most likely to be encountered on sandy soils, oxisols and ultisols of low base status, and on volcanic ash soils of high potassium status. It can be corrected by incorporation of dolomitic lime or magnesium oxide (20-50 kg Mg/ha) into acid soils, or by band application of magnesium sulphate (10-40 kg Mg/ha). Magnesium sulphate is the preferred source where it is necessary to correct an observed magnesium deficiency or where the soil is low also in sulphur.

Manganese toxicity

The first symptom of manganese toxicity is usually the appearance of small dark brown spots on the lower leaves. These spots are concentrated mainly along the veins (Plate 5a). As the toxicity becomes more severe, areas on affected leaves not covered by brown spots take on a yellow or greenish yellow colour (Plates 5b, c). Later these leaves become flaccid and eventually fall from the plant. Manganese toxicity can severely reduce the growth of both shoots and roots (Plates 5d, e).

A high external manganese supply can induce iron deficiency, which is characterised by interveinal chlorosis of the younger leaves (Plate 5f; see also section on iron deficiency). In solution culture this secondary symptom of manganese toxicity can be cured by raising the level of iron supply (Howeler unpublished).

Plate 5. *Manganese toxicity.* (a) Lower leaf of cv Nina showing early symptoms of manganese toxicity. Note concentration of small brown spots along the midrib and some lateral veins. (b) Manganese toxicity symptoms in the field (cv Llanera). Manganese concentration in affected leaves was 6000 $\mu g/g$. (c) Severe manganese toxicity. Note progression of symptoms from younger leaves (chlorosis + brown spots) to older leaves (brown spots only). (d) Response to solution manganese concentration by cv Nina. Manganese concentrations from left to right approximately 1, 2, 4, 10, 42, 130, 400 and 1200 μM. (e) Effects of manganese toxicity on root growth of cv M Aus 3. Healthy plant on left, manganese toxic plant on right. (f) Plant of cv M Aus 10 showing both manganese toxicity (lower and middle leaves) and manganese-induced iron deficiency (chlorotic upper leaf at right).

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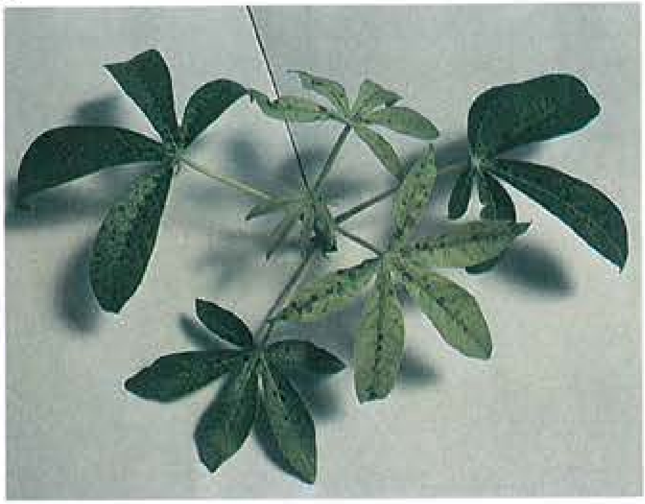

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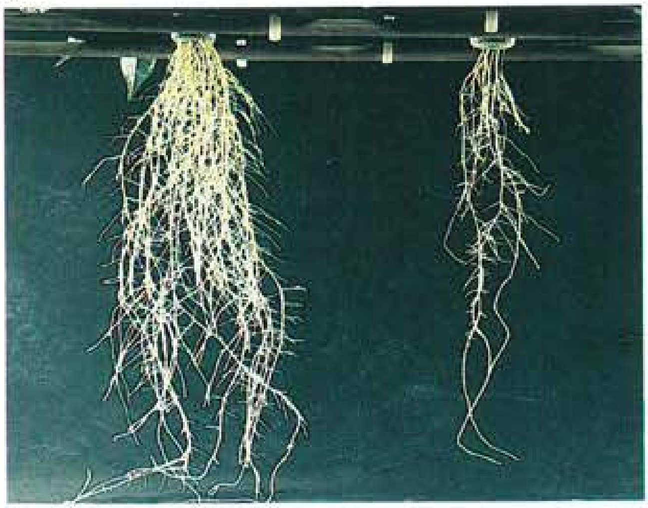

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Edwards (in press) has reported critical levels for manganese toxicity to range from 250 to 1450 μg/g in whole tops of young cassava plants. Howeler (1978) found toxicity symptoms to be associated with manganese concentrations in excess of 1000 μg/g in the lower leaves. The concentration in older leaves of affected plants was higher than in younger leaves.

Edwards and Asher (unpublished) found that the three cassava cultivars Nina, M Aus 7 and M Aus 10 were moderately resistant to manganese toxicity when grown in flowing nutrient solutions maintained at a range of constant manganese concentrations. All three cultivars reached maximum whole plant dry matter yields at 1.7 μM Mn. At 42 μM Mn, dry matter yields of cassava ranged from 61% of maximum (Nina) to 89% (M Aus 7), while those of soybean and french bean were 51 and 33% of maximum respectively. Among 12 other species studied in that experiment, three (sunflower, centro and pigeon pea) were more tolerant of manganese toxicity, two (siratro, safflower) had similar tolerance and the remaining seven species were less tolerant than cassava. Under field conditions, high yields of cassava (38 t/ha) have been obtained on a soil in which soybean and french bean *(Phaseolus vulgaris)* died of manganese toxicity (CIAT 1978).

Manganese toxicity is nearly always associated with acid soils. It is common on volcanic ash soils in Colombia (CIAT 1978). Since higher oxides of manganese are reduced to Mn^{2+} during waterlogging, manganese toxicity is most severe in poorly drained soils during the wet season. It can be corrected by application of lime which increases soil pH and reduces the solubility of manganese, and by improvement of drainage.

Aluminium toxicity

Aluminium toxicity forms an important component of the acid soil infertility complex in many acid tropical soils. However it is often difficult to separate the specific effects of high soil solution aluminium concentrations from other acid soil factors. Thus aluminium solubility is low in neutral to slightly acidic soils but increases rapidly with decreasing pH below about 5.0. It is difficult to separate effects of aluminium ions from those due to hydrogen ions at these low pH values. In addition phosphate solubility is low in the presence of high aluminium concentrations, so that phosphorus deficiency is often associated with aluminium toxicity. Also, acid soils are often low in available calcium, and aluminium has been shown to be a powerful inhibitor of calcium uptake (cf Awad and Edwards 1977). Hence calcium deficiency symptoms may also be associated with aluminium toxicity. The problem of distin-

Plate 6. *Aluminium toxicity.* (a) Close-up of leaf of aluminium toxic plant (cv M Aus 3) grown in solution culture. (b) Plant grown on an acid, aluminium toxic soil at Carimagua, Colombia. Note chlorotic lower leaves. Plant also shows deformities (arrowed) of the younger leaves probably due to aluminium-induced calcium deficiency. (c) Close-up of leaf showing interveinal chlorosis and necrosis. (d) Comparison of 8 cultivars grown in nutrient solutions to which aluminium had been added at 3 or 30 mg/1. Note the differential response among cultivars to high levels of A1 in solution.

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30 ppm Al
3 ppm Al
MCol 70
MCol 17
MCol 80
MCol 1
MCol 31
MCol 81
MCol 262
MCol 53
MCol 70
MCol 17
MCol 80
MCol 1
MCol 31
MCol 81

guishing between direct and indirect effects of aluminium is further complicated by the fact that liming to reduce aluminium solubility increases the supply of plant available calcium.

Solution culture experiments conducted with an adequate supply of phosphorus and calcium have shown that aluminium toxicity produces an interveinal chlorosis of the lower leaves. The intensity of this chlorosis decreases from the tip to the base of each lobe (Plates 6a, b). Sometimes light coloured necrotic spots develop within the chlorotic areas (Plate 6c). Aluminium toxicity also adversely affects root growth, some cultivars being much more susceptible to root injury than others (Plate 6d). Results of both glasshouse and field experiments suggest that in general cassava is more tolerant of aluminium toxicity than a number of other crops including maize, sorghum, rice, soybean and *Phaseolus* bean (CIAT 1976, 1977, Gunatilaka 1977). Gunatilaka (1977) found that plant response to aluminium was not well correlated with aluminium concentrations in the plant tissues. However, his data suggest critical aluminium concentrations of 60-100 μg/g in tops and 2000-14000 μg/g in roots of four weeks old cassava plants. Research at CIAT (1978) suggests that cassava will tolerate up to 80% aluminium saturation of the cation exchange complex of the soil whereas many other crops are severely affected at aluminium saturations below 50%.

Aluminium toxicity is common on acid ($pH<5.0$) oxisols and inceptisols. The problem is generally controlled by the incorporation of calcitic or dolomitic lime, which also serve as sources of calcium and/or magnesium. High rates of liming are rarely necessary to alleviate aluminium toxicity in cassava and may actually be detrimental by inducing micronutrient deficiencies, especially zinc deficiency (Howeler *et al.* 1977, Edwards and Kang 1978).

Since some cultivars are much more resistant to high levels of aluminium than others, the selection of aluminium tolerant cultivars may provide a long term solution to the problem of aluminium toxicity.

Boron toxicity

Two rather different symptoms of boron toxicity have been observed and further research is needed to establish the relationship between them. In solution culture and sand culture experiments (Forno *et al.* 1979, Howell 1974) boron toxicity has been associated with the development of whitish or brownish necrotic spots on the lower leaves. Usually these spots have a halo of darker tissue around them (Plates 7a, b, c). Later the tissue becomes necrotic and may break away giving a ragged edge to the affected leaf. The leaf spotting symptom has not yet been reported from the field. Instead, plants growing on alkaline soils to which a toxic excess of boron had been added showed stunting and a rather diffuse chlorosis of the lower leaves. The intensity of this chlorosis was greatest at the tips of the lobes (Plate 7d). Where boron toxicity has been caused by excessive boron application plants often recover.

Boron toxicity in the field has been observed only following heavy application of boron fertilizer or treatment of planting stakes with boron (Plate 7d). Experience with other crops suggests boron toxicity in cassava would most likely occur on alkaline soils of high boron status. Forno *et al.* (1979) reported a critical boron concentration for toxicity of 140 μg/g in whole tops of young plants.

Plate 7. *Boron toxicity.* (a) Boron toxicity symptoms on lower leaves of cv M Aus 10 grown in solution culture. (b) Close up of boron toxic leaf of cv Seda. (c) Close up of boron toxic leaf of cv Mameya. (d) Appearance of plant grown from boron-treated stake in an alkaline soil at CIAT, Colombia.

Disorders producing symptoms on either upper or lower leaves

Sulphur deficiency

Sulphur is usually classified as a phloem mobile element. However, in many crops sulphur deficiency symptoms appear less confined to the lower leaves than for most other phloem mobile elements, suggesting a somewhat lower phloem mobility.

In cassava, there is some doubt concerning the degree of phloem mobility of sulphur. Krochmal and Samuels (1968) made no mention of the position of affected leaves in their description of sulphur deficiency symptoms. Since they commented on leaf position in relation to all other disorders which produced definite deficiency symptoms (N, K, Mg, Mn, Fe, Ca and B) it may be inferred that the leaf chlorosis they described was not confined to leaves in any particular position. Solution culture experiments at the University of Queensland have consistently shown that sulphur deficiency symptoms occur first on, and are confined to the younger leaves (Plates 8a, b). In the field, however, Ngongi (1976) found sulphur deficiency symptoms largely on the lower leaves (Plate 8c). In view of these conflicting reports further research on sulphur deficiency in cassava appears warranted.

All authors are in agreement that sulphur deficient leaves are pale green to yellow in colour and very similar in appearance to nitrogen deficient leaves.

Field-grown plants generally have sulphur concentrations of 0.3-0.4% in the upper fully expanded leaf blades; Howeler (1978) has determined a critical concentration of 0.32%. Petioles have lower sulphur concentrations (0.13-0.15%) than leaf blades (Ngongi 1976), while roots of both sulphur deficient and healthy plants were found to contain 0.05-0.06% S (Ngongi *et al.* 1977).

Ngongi *et al.* (1977) observed sulphur deficiency symptoms and depression in root yield of cv Llanera grown with high rates of KCl at a sulphur deficient site in Colombia. Leaf symptoms were most prominent during the dry season. Addition of elemental sulphur or substitution of K_2SC_4 for KCl eliminated the symptoms and increased root yields by about 30%. Sulphur deficiency symptoms were associated with concentrations less than 0.30% S in young fully expanded leaf blades of 12-week old plants. The failure of other crops to show sulphur deficiency symptoms at this site suggests that cassava may be more susceptible to sulphur deficiency.

Sulphur deficiency has been reported on many oxisols and ultisols in Latin America (McClung *et al.* 1959, Ngongi *et al.* 1977) as well as in Australia (Probert 1978). In industrial areas much of the plant's sulphur requirement can be met from high sulphur contents in the atmosphere. Thus, sulphur deficiency is more likely in soils far removed from industrial areas. Sulphur deficiency can be controlled by application of 10-20 kg S/ha as elemental sulphur or gypsum, or by the use of sulphur containing fertilizers, such as ammonium sulphate, single superphosphate or potassium sulphate.

Plate 8. *Sulphur deficiency.* (a) Sulphur deficiency in a young plant of cv Mameya grown in solution culture. Note symptoms on upper leaves. (b) Sulphur deficiency on cv M Aus 3 grown in solution culture. (c) Sulphur deficiency of 3 months old cassava cv Llanera at Carimagua, Colombia. Note symptoms on lower leaves.

Disorders producing symptoms mainly on the younger leaves

Calcium deficiency

Calcium is an element of low phloem mobility (Epstein 1972). The development of calcium deficiency symptoms in young actively growing tissues is a consequence of the poor redistribution of previously absorbed calcium within the plant. Cassava root systems have been shown to be particularly sensitive to calcium deficiency (Plates 9a, b). Thus, unless adequate calcium is applied in the culture medium, cuttings will not establish a healthy root system and existing roots will become necrotic and start to decompose (Forno *et al.* 1976). Calcium deficiency is sometimes characterised by burning and curling of the tips of the younger leaves (Plate 9c), although this has not been observed in some cultivars even at very low calcium concentrations which reduced plant growth to less than 25% of that of plants supplied with adequate calcium. In the field calcium deficiency has not been recognized as an important field problem, although some responses to liming of acid soils may be due wholly or in part to the correction of calcium deficiency (see also comment regarding aluminium induced calcium deficiency under "aluminium toxicity").

Normal calcium levels of upper fully expanded leaves range from 0.6 to 1.5%, while the petioles of the corresponding leaves have calcium contents of 1.5 to 3%. As might be expected for an element of low phloem mobility, calcium levels tend to be higher in lower leaves than upper leaves (Cours *et al.* 1961, Spear *et al.* 1978c).

Cassava appears to tolerate low calcium levels better than many other crop species. Thus in flowing culture studies at the University of Queensland two cultivars achieved a relative yield of 26% at a very low calcium concentration (0.5 μM) whereas sunflower, sorghum, maize and soybean achieved relative yields of less than 3% at the same solution concentration (Edwards *et al.* 1977). In a very calcium deficient soil in Nigeria, two cassava cultivars did not show any deficiency symptoms, while soybean, lima bean and maize became grossly calcium deficient (Edwards and Kang 1978).

Plate 9. *Calcium deficiency.* (a) Response of cv M Aus 3 to increasing levels of calcium in nutrient solution. (b) Effect of inadequate supply of nitrogen, phosphorus, potassium and calcium on root growth of cv Mameya. Note the detrimental effect of calcium deficiency on root growth. (c) Tip burn and deformation of upper leaves of cv M Aus 3 due to calcium deficiency.

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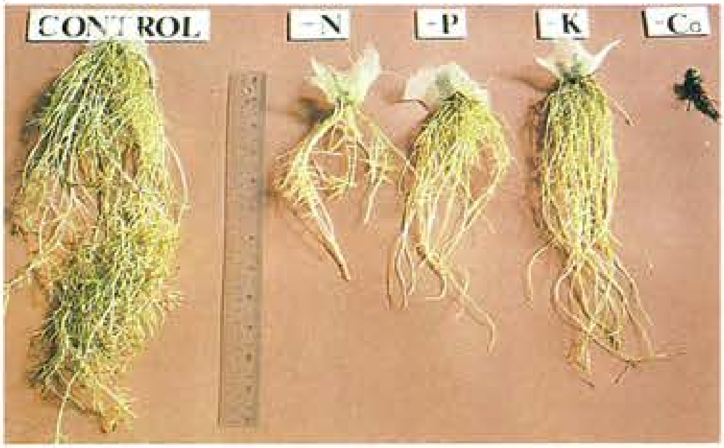

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Calcium deficiency is most likely to occur on sandy soils or oxisols and ultisols low in exchangeable bases and high in exchangeable aluminium. On some acid soils beneficial effects of small applications of lime (500-1000 kg/ha) are probably due to correction of aluminium induced calcium deficiency rather than to a lowering of soluble aluminium levels in the soil. Calcium oxide or hydroxide may be used in place of lime. These calcium sources are best broadcast and incorporated into the soil prior to planting. Where calcium deficiency is not associated with low pH, gypsum may be used as a calcium source. The use of single superphosphate (which contains 20% Ca) may contribute to the low incidence of calcium deficiency under field conditions.

Excessive use of lime may lead to the induction of deficiencies of potassium, magnesium, iron, manganese, zinc or copper.

Boron deficiency

Attempts to produce boron deficiency in sand culture have met with only limited success. Thus, Krochmal and Samuels (1968) reported that boron deficiency caused dwarfing of young plants and slight chlorosis of the younger leaves. However, the plants later recovered being similar in height and weight to the control plants when harvested after 12 weeks growth. Howell (1974) was unable to produce boron deficiency symptoms in cv Llanera or CMC 39 under sand culture conditions. However, boron deficiency has been easily induced in solution culture using good quality deionized water and analytical grade nutrient salts in studies at the University of Queensland.

Plate 10. *Boron deficiency.* (a) Boron deficient root showing stubby necrotic laterals and root tip. (b) Boron deficient root system showing swollen tips on laterals. (c) Effect of boron supply on plant height of cv M Aus 10 (boron levels increase from left to right). (d) Close-up of boron deficient plant of cv M Aus 10 showing short internodes, small deformed leaves at shoot apex and gummy stem lesions (arrowed). (e) Fine chlorotic spotting on leaf of boron deficient plant of cv Amarillo. (f) Close-up of top of shoot showing small deformed leaves, short petioles and gummy petiole lesions.

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Like calcium, boron is an element of low phloem mobility and hence the symptoms of boron deficiency occur on young actively growing tissues. The first symptoms are usually seen on the roots which show suppressed lateral root development and sometimes death of the root tip (Plate 10a). Often death of the root tip is followed by the emergence of short lateral roots with swollen ends (Plate 10b). However not all cultivars show this symptom. Boron deficient plants tend to be short due to a reduction in internode length (Plates 10c, d), and mildly affected leaves develop a chlorosis consisting of numerous minute light grey or brown spots concentrated mainly at the tips and margins of the leaf lobes (Plate 10e). More severely affected leaves are reduced in size, deformed and carried on short petioles. A distinctive symptom of boron deficiency is the development of lesions, from which a brown gummy substance exudes, on upper petioles and stems (Plates 10d, f). The stem lesions may later develop into cankers.

Boron concentrations in the upper leaves of healthy plants normally fall within the range 20-100 $\mu g/g$. Forno *et al.* (1979) have suggested a critical boron concentration of about 17 $\mu g/g$ in plant tops.

Up to the present time, boron deficiency symptoms have not been reported in field-grown cassava. However, a significant boron response has been obtained with cassava growing on a lateritic soil in Southern India (CTCRI, 1973). Boron deficiency has not been observed in cassava grown at CIAT on a soil in which yields of maize and *Phaseolus* beans were drastically reduced by boron deficiency (Howeler *et al.* 1978). However, Forno *et al.* (1979) have produced evidence indicating that boron uptake is highly dependent on root temperature. Thus a nutrient solution that provided adequate boron for cassava plants grown at a root temperature of 26°C was boron deficient for cassava at a root temperature of 19°C. These results suggest that the risk of boron deficiency may be increased in areas where sub-optimal soil temperatures are encountered during part of the growing season. Based on experience with other crops, borax or other sodium borates at 1-2 kg B/ha should be effective in controlling boron deficiency. Stakes may also be soaked for 15 minutes in 0.5 to 1% borax solutions, but higher concentrations are phytotoxic.

Iron deficiency

Iron deficiency is characterized by chlorosis of the younger leaves. Initially only the interveinal tissue is chlorotic, the veins remaining green (Plate 11a), but in a more severe state the veins lose their green colour and the whole leaf, including the petioles, becomes yellow and later almost white (Plate 11b). Iron deficiency can usually be distinguished from manganese deficiency, which also produces interveinal chlorosis of the young leaves, by the absence of a zone of green interveinal tissue adjacent to the veins, i.e., with iron deficiency the green veins tend to stand out on a yellow background whereas with manganese deficiency the boundary between green and chlorotic tissue is more diffuse. Plant height is severely reduced (Plate 11c). Under less severe conditions, plants may be a uniformly light green in colour, somewhat similar to the leaf colour due to nitrogen deficiency (Plate 11d). Iron deficient leaves are smaller than normal, but not deformed, the lobes having the same length to width ratio as those of normal leaves. High levels of manganese (Plate 5f), zinc

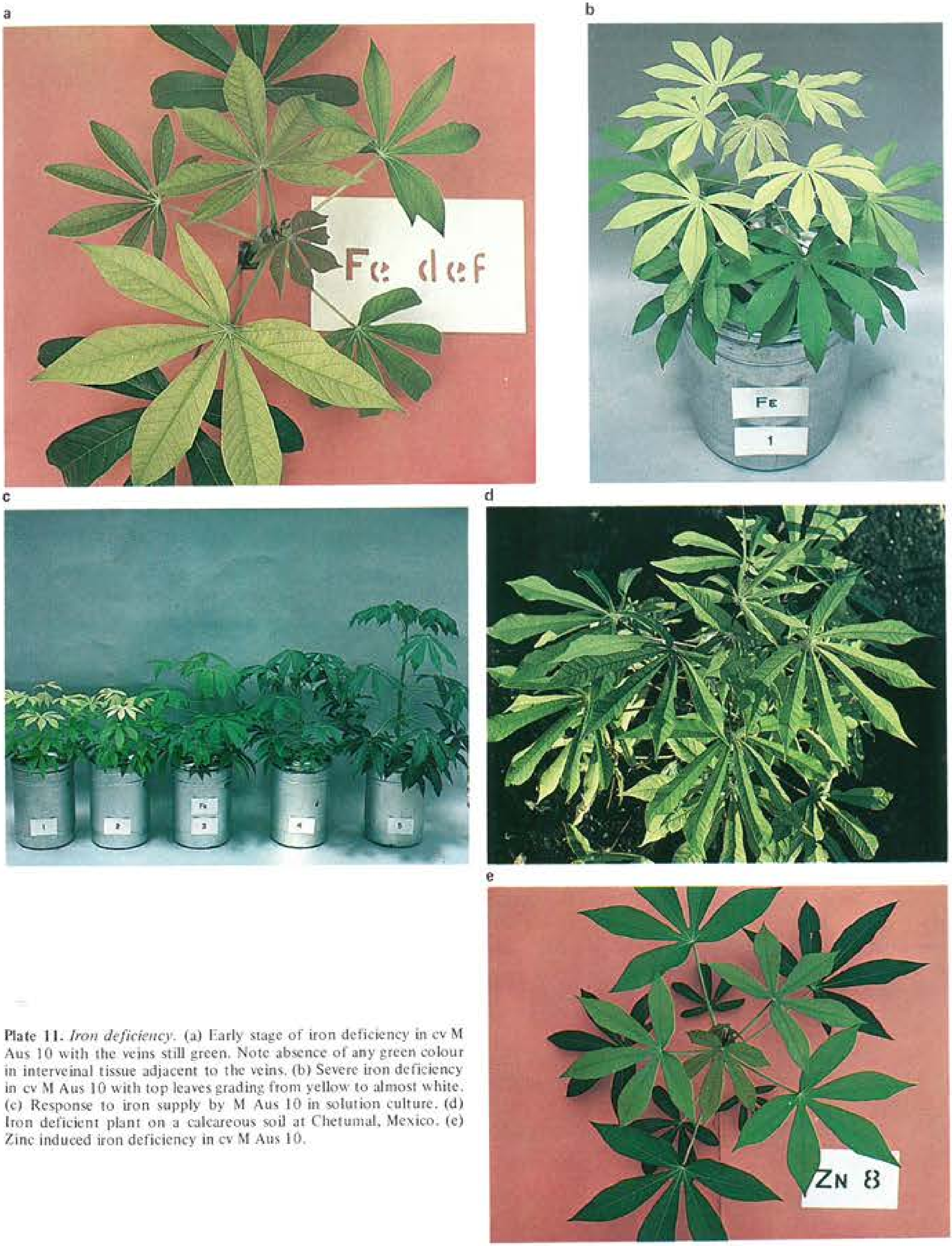

Plate 11. *Iron deficiency.* (a) Early stage of iron deficiency in cv M Aus 10 with the veins still green. Note absence of any green colour in interveinal tissue adjacent to the veins. (b) Severe iron deficiency in cv M Aus 10 with top leaves grading from yellow to almost white. (c) Response to iron supply by M Aus 10 in solution culture. (d) Iron deficient plant on a calcareous soil at Chetumal, Mexico. (e) Zinc induced iron deficiency in cv M Aus 10.

(Plate 11e) or copper in solution may induce iron deficiency symptoms, which disappear when iron levels are increased.

Normal plants have iron contents of 60-200 $\mu g/g$ in upper fully expanded leaves. Solution culture experiments at the University of Queensland indicate a critical concentration for deficiency of 122 $\mu g/g$ in the youngest fully expanded leaf.

Iron deficiency is rare in cassava, but it has been observed on calcareous soils of the Yucatan peninsula of Mexico (Plate 11d) and on an alkaline soil (pH >8.0) in the Salem district of Southern India (CTCRI 1973). In the latter soil it is accompanied by deficiencies of zinc and manganese. Iron deficiency may also be expected in sandy soils, organic soils, or soils having excessively high levels of manganese. Excessive liming or high phosphorus fertilization may also induce iron deficiency. The deficiency is best controlled by a foliar spray of iron chelate or 1-2% ferrous sulphate solution. The chelate may also be applied to the soil, but is effective only at rather high concentrations. A stake dip in 5% ferrous sulphate solution for 5 minutes before planting had no adverse effect on germination.

Manganese deficiency

Manganese deficiency produces an interveinal chlorosis of young recently expanded leaves (Plate 12a). This chlorosis can be distinguished from that due to iron deficiency by two characteristics. Firstly, the boundary between the green and chlorotic tissue tends to be rather diffuse, the veins being surrounded by a definite zone of non-chlorotic interveinal tissue (Plate 12b). Secondly, the symptoms are not usually seen on the youngest leaves, but on leaves that are fully expanded or nearly so. However with very severe manganese deficiency these distinctions may disappear, the affected leaves becoming completely chlorotic and even the youngest leaves being affected (Plate 12c).

Oxidation of plant available Mn^{2+} to insoluble higher oxides of manganese is favoured in well-aerated soils. Consequently, manganese deficiency tends to be most severe during dry seasons or in better drained parts of the field. Where cyclical changes in manganese availability occur, manganese deficient leaves will tend to be produced during each dry period. Under these circumstances manganese deficiency symptoms may be found in almost any position on the plant (Plate 12d).

Manganese contents of upper fully expanded leaves of normal plants range from about 50 to 250 $\mu g/g$. Lower leaves tend to have higher concentrations than upper leaves, especially under conditions of excess manganese supply. In solution culture, the critical concentration in the youngest fully expanded leaf was found to be 60 $\mu g/g$ (Howeler, unpublished).

Manganese deficiency in cassava has been observed on calcareous soils in Mexico, and on high-pH, sandy soils in Colombia and north-east Brazil. A significant response to manganese has been reported from Southern India (CTCRI, 1974). Manganese deficiency may also be expected on organic soils. Manganese deficiency may be corrected by soil application of manganese oxide or sulphate, or by foliar sprays of manganese sulphate or chelate. A stake dip in 5% manganese sulphate for 5 minutes before planting had no adverse effect on germination.

Plate 12. *Manganese deficiency.* (a) Plant of cv CMC 39 showing chlorosis of recently matured leaves due to manganese deficiency. (b) Leaves of cv M Aus 10 ranging from severely manganese deficient (lower left) to healthy (lower right). (c) Response to manganese in solution culture by cv M Aus 10 (left, deficient, centre adequate, right toxic levels of manganese). (d) Manganese deficiency symptoms on middle and lower leaves with healthy leaves formed above with the onset of the rainy season at CIAT, Colombia.

Zinc deficiency

Zinc deficiency causes a characteristic interveinal chlorosis of the younger leaves. Initially the leaves are a healthy green colour. Small white or light-yellow chlorotic patches then develop between the veins (Plates 13a, b). The colour and shape of these patches vary among cultivars. Each successive leaf produced is smaller, and more chlorotic, the leaf lobes becoming very narrow, light green to white in colour and with the margins curled upward. Leaf tips are necrotic under severe deficiency conditions. In a healthy leaf the two basal lobes normally point back towards the stem. However with zinc deficient leaves the basal lobes often tend to point away from the stem (Plates 13b, c). Although zinc deficiency affects mostly the younger leaves, in some cultivars the older leaves develop necrotic spots (Plate 13d, plant on right), rather similar to boron toxicity or infection by *Cercospora caribaea* . Because the growing point is most affected, zinc deficiency can drastically reduce plant growth and yield. Often, plants show symptoms of zinc deficiency very shortly after emergence. If the deficiency is not severe, plants may recover once they have a established a good root system. In this case healthy leaves will appear above the zinc deficient leaves so that zinc deficiency symptoms then appear on older instead of younger leaves.

Cassava seems to be exceptionally susceptible to zinc deficiency. The problem has been observed throughout the world on both acid soils (Plate 13c) and soils of high pH. Howeler *et al.* (1977) and Edwards and Kang (1978) found that moderate rates of lime (2-3 t/ha) caused yield reductions and appearance of zinc deficiency symptoms on acid soils in Colombia and Nigeria respectively. In the study of Edwards and Kang (1978) excessive liming (5 t/ha) severely restricted shoot growth (Plate 13f) and reduced tuber yields to zero. Significant responses to zinc fertilizer have been observed in Southern India (CTCRI, 1972, 1973, 1974). Large differences in susceptibility among cultivars have been observed, and it may be possible to select tolerant cultivars for low-zinc soils.

Zinc concentrations in upper fully expanded leaves of healthy plants are normally about 40 to 100 $\mu g/g$ critical zone concentrations ranging from about 35-50 $\mu g/g$ have been determined for various cultivars (Howeler 1978). In a recent solution culture experiment at the University of Queensland, the critical zinc concentration in the youngest fully expanded leaf blades of cv M Aust 10 was found to be 37 $\mu g/g$

Plate 13. *Zinc deficiency.* (a) Leaf of cv Seda showing linear chlorotic bands between the veins. (b) and (c) Chlorotic upper leaves of plants of cv M Mex 23 growing on zinc deficient soil. Note tendency for basal lobes of affected leaves to point away from the stem. (d) Two zinc deficient plants of cv M Aus 10 in solution culture. Less severely affected plant at right shows spotting of lower leaves. (e) Zinc deficiency in cv M Mex 23 at Carimagua, Colombia. (f) Lime induced zinc deficiency in cv Apuwuru. Lime levels were 0, 0.5, and 5 t/ha from left to right. Plants also show symptoms of cassava mosaic disease.

a

b

c

d

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f

(Howeler, unpublished). Edwards and Kang (1978) observed deficiency symptoms in cvs Ojukaniye and Apuwuru when the zinc concentration in a composite sample of the three youngest fully expanded leaves fell below 45 $\mu g/g$.

The critical content of soils, extracted with 0.05 M HC1 + 0.0125 M H_2SO_4 is about 0.7 $\mu g/g$, and extracted with bicarbonate-EDTA about 0.8 $\mu g/g$ (Howeler, 1978).

Zinc deficiency can be controlled by band application of 5-10 kg Zn/ha as zinc sulphate at planting or by incorporation of ZnO before planting. Under less severe conditions a foliar application of 1-2% zinc sulphate may be effective. To prevent zinc deficiency during early growth it is recommended that planting stakes be dipped in 2-4% zinc sulphate solution for 15 minutes prior to planting. Concentrations of zinc sulphate as high as 10% can be used without adversely affecting germination as long as the immersion time is not greatly extended. The stake dip can be mixed with fungicides and/or insecticides to improve germination and permit a longer stake storage time (CIAT 1977).

Copper deficiency

The main symptoms of copper deficiency are chlorosis and deformity of the young leaves. Often the leaf tips become necrotic (Plate 14a) and the leaves are either cupped upwards (Plate 14a) or curled downwards (Plate 14b). In addition, the number of lobes per leaf may be reduced to three or in extreme cases to one (Plate 14c). Stem internode lengths are not greatly reduced so that plant height may be approximately normal even under conditions of moderately severe copper deficiency (Plate 14d). However with severe copper deficiency, Chew *et al.* (1978) observed that plants died back from stem apices and grew again from the base producing a bushy plant with one or more dead stems projecting from the top. Often leaves in the middle of the plant are carried on abnormally long, drooping petioles (Plates 14b, e). Severe copper deficiency can markedly reduce root development (Plate 14f), rendering copper deficient plants susceptible to water stress even when grown in aerated solution culture.

Normal copper levels range from 7 to 15 $\mu g/g$ in upper fully expanded leaves and from 2 to 10 $\mu g/g$ in roots. Chew *et al.* (1978) found a copper content of 14 $\mu g/g$ in plants adequately supplied with copper and 7 $\mu g/g$ in copper deficient plants. Solution culture experiments at the University of Queensland indicate a critical concentration of 7 $\mu g/g$ in the youngest fully expanded leaf (Howeler, unpublished).

Plate 14. *Copper deficiency.* (a) Chlorotic upper leaves of copper deficient plant of cv M Aus 10 grown in solution culture. Note necrotic leaf tips and upward cupping of leaves. (b) Chlorotic upper leaves of copper deficient plant of cv Black Twig grown on Malaysian peat. Note downwards curling of younger leaves and long drooping petioles of older leaves. (c) Copper deficient leaves of cv Mameya showing necrotic tips, cupping, and reduction in number of lobes per leaf. (d) Response to copper supply in solution culture in cv M Aus 10 (severe copper deficiency at left, control at right). (e) Copper deficient plant of cv M Aus 10. Note symptoms on upper leaves, long internodes and long droopy petioles of older leaves. (f) Effect of severe copper deficiency on root growth of cv Nina.

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Copper deficiency tends to occur on acid sandy soils of low total copper content and on alkaline or organic soils in which copper availability is low. However copper deficiency of cassava has so far been reported only on peat soils. Chew *et al.* (1978) reported that copper deficiency reduced yields from 15 to 4 t/ha on Malaysian peat. On this soil copper deficiency can be corrected by soil application of 2.5-3.5 kg Cu/ha as copper sulphate. Excess copper is highly toxic and lower rates of application would be appropriate on sandy soils. A stake dip of 1% copper sulphate seriously impaired germination.

Heavy metal toxicities

Toxicities of heavy metals are rare, but may be observed near industrial centres due to pollution, in areas where sewage sludge is used on agricultural land, and on soils derived from certain parent materials. Excessive applications of zinc or copper fertilizer to sandy soils could also lead to the development of such a problem. So far there have been no reports of heavy metal toxicities from the field apart from manganese toxicity (see page 24).

Copper toxicity leads to severely reduced plant growth and may induce iron deficiency symptoms. Plants having leaves with more than 20 μg/g copper might be suspected of suffering from copper toxicity. Copper toxic soils have been reported in abandoned banana plantations in Honduras, where frequent foliar sprays with copper sulphate rendered the soils unproductive due to copper toxicity. Liming (to reduce copper availability) in combination with applications of iron and zinc may prove effective.

Nickel toxicity. At first the upper leaves show symptoms similar to iron deficiency. However, irregular brown necrotic spots later develop on affected leaves (Plate 15a). Nickel toxicity has not been reported on field-grown cassava but has been found on other crops in restricted areas, often on soils derived from serpentine rocks.

Chromium toxicity results in a chlorosis of the younger leaves with the intensity changing from a light green chlorosis through yellow to a yellowish-orange colour on the youngest leaves. The chlorosis is general rather than interveinal in appearance (Plate 15b).

Plate 15. (a) *Nickel toxicity.* (b) *Chromium toxicity* on cv Mameya. Note gradation of symptoms from older to younger leaves.

a

b

Salinity-alkalinity

Cassava grown on saline-alkaline soils may suffer from a complex of problems involving high pH, high sodium content, excess salts, poor drainage and sometimes micro-nutrient deficiencies. Under severe conditions the young plants become uniformly chlorotic, symptoms starting at the top but soon affecting the entire plant. The young leaves show tip and marginal chlorosis and fall off. Eventually the growing point dies, followed by die-back and death of the plant (Plate 16a). Under less severe conditions the plant becomes uniformly chlorotic and plant growth and yield are reduced. The problem is often very localized in "salt-spots", in which plants may die (Plate 16b, area on right), while only a few metres away plant growth may be completely normal.

While cassava is relatively tolerant of acid soils (Edwards *et al.* 1977), it is quite susceptible to high pH and related salinity-alkalinity problems (CIAT 1976). For most cultivars yield reductions can be expected at soil pH values above 7.8-8.0, at conductivity values above 0.05 S/m, and at sodium saturation values above 2.5%. Cassava was more susceptible to these salinity-alkalinity factors than *Phaseolus* beans (CIAT 1977). It has been observed that maize, sorghum and rice are also less affected by salinity-alkalinity problems than cassava.

Salinity-alkalinity problems occur principally in coastal areas or in valleys with relatively low precipitation and high evaporation. Leaching of salts with water of good quality, improvement of drainage, and the application of sulphur or gypsum may alleviate the problem to some extent, but the most practical solution is to select tolerant species and cultivars. Plate 16c shows how a susceptible cultivar (on right) was severely affected, while a tolerant cultivar grew normally on the same soil. Research on resistance to salinity is being undertaken at CTCRI (CTCRI 1975).

Salinity is caused by high concentrations of salts in the soil solution, of which the chlorides and sulphates of sodium and magnesium are most damaging to plants. Symptoms associated with an excess of individual ions have not yet been described and there is scope for additional work in this area. However in nutrient solutions artificially salinized with sodium chloride the tips and margins of the lower leaves developed necrotic patches (Plate 16d). In the field, bottom leaves on high chloride soils turn yellow prematurely and fall off, while plant growth is seriously reduced. While normal levels of chloride in plant tissue range from 100-1000 μg/g, under toxic conditions plants may accumulate chloride to as much as 1-5% (10,000-50,000 μg/g). Chloride toxicity is reduced mainly by leaching of the soil.

Plate 16. *Salinity-alkalinity.* (a) Cassava plants, cv Llanera, suffering from severe salinity problems in high pH soil at CIAT, Colombia. (b) Plants of cv Llanera on right dying from salinity in "salt-spot", while on left, plants are healthy. (c) cv M Col 22 (left) showing tolerance and cv M Ven 290 (right) showing extreme susceptibility to salinity-alkalinity at CIAT, Colombia. (d) Leaf of cv M Aus 3 showing symptoms of sodium chloride toxicity.

a

b

c

d

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