Chapter 7

Cassava Mineral Nutrition and Fertilization

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Introduction

Cassava is generally grown by poor farmers living in marginal areas with adverse climatic and soil conditions. The crop is very suitable for these conditions because of its exceptional tolerance to drought and to acid, infertile soils. It is often grown on sloping land because of its minimal requirement for land preparation, and its ability to produce reasonably good yields on eroded and degraded soils, where other crops would fail. It has been shown (Quintiliano *et al.*, 1961; Margolis and Campos Filho, 1981; Putthacharoen *et al.*, 1998), however, that growing cassava on slopes can result in severe erosion, with high soil and nutrient losses. Thus cassava cultivation on slopes requires adequate cultural and soil conservation practices that minimize erosion (Howeler, 1994).

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

Effect of Cassava Production on Soil Fertility

Nutrient absorption, distribution and removal in harvested products

As cassava may grow well in poor and/or degraded soils and few other crops will grow well on those same soils after cassava, it is often believed that cassava is a ‘scavenger crop’, that is, highly efficient in nutrient absorption from a low-nutrient soil, leaving that soil even poorer than before. Thus it is often concluded that cassava extracts more nutrients from the soil than most other crops, resulting in nutrient depletion and a decline in soil fertility.

Table 7.1 shows the average removal of the major nutrients by cassava roots as compared to that for the harvested products of other crops (Howeler, 1991b). Nitrogen (N) and P removal

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Table 7.1. Average nutrient removal by cassava and various other crops, expressed in both kg ha^{-1} and kg t^{-1} harvested product, as reported in the literature.

	Yield (t ha^{-1})		(kg ha^{-1})			(kg t^{-1} DM produced)		
Crop/plant part	Fresh	Dry[a]	N	P	K	N	P	K
Cassava/fresh roots	35.7	13.53	55	13.2	112	4.5	0.83	6.6
Sweet potatoes/fresh roots	25.2	5.05	61	13.3	97	12.0	2.63	19.2
Maize/dry grain	6.5	5.56	96	17.4	26	17.3	3.13	4.7
Rice/dry grain	4.6	3.97	60	7.5	13	17.1	2.40	4.1
Wheat/dry grain	2.7	2.32	56	12.0	13	24.1	5.17	5.6
Sorghum/dry grain	3.6	3.10	134	29.0	29	43.3	9.40	9.4
Common beans[b]/dry grain	1.1	0.94	37	3.6	22	39.6	3.83	23.4
Soybeans/dry grain	1.0	0.86	60	15.3	67	69.8	17.79	77.9
Groundnuts/dry pod	1.5	1.29	105	6.5	35	81.4	5.04	27.1
Sugarcane/fresh cane	75.2	19.55	43	20.2	96	2.3	0.91	4.4
Tobacco/dry leaves	2.5	2.10	52	6.1	105	24.8	2.90	50.0

Source: Howeler (1991b).

[a] Assuming cassava to have 38% DM, grains 86%, sweet potatoes 20%, sugarcane 26%, dry tobacco leaves 84%.

[b] *Phaseolus vulgaris*.

DM, dry matter.

per tonne of dry matter (DM) in cassava roots was actually much lower than that removed by most other crops, while that of potassium (K) was similar or lower than that of other crops. When cassava root yield was very high, as in Table 7.1, the N and P removal per hectare was similar to that of other crops, while K removal was indeed higher than that of any other crop. Similar results were reported by Prevot and Ollagnier (1958) and Amarasiri and Perera (1975). Putthacharoen *et al.* (1998), however, reported that with an average root yield of 11 t ha^{-1} cassava roots removed much less N and P than other crops, while K removal was similar to that of other crops and much less than that removed by pineapple.

Nutrient absorption and distribution are closely related to plant growth rate, which depends on soil fertility and climatic conditions as well as on varietal characteristics. In poor soils fertilizers can markedly increase plant growth and nutrient absorption; while in areas with a long dry season, irrigation can do the same (Fig. 7.1). At 2–3 months after planting (MAP), the tuberous roots become the major sink of DM. At harvest DM is always highest in the roots, usually followed by stems, fallen leaves, leaf blades and petioles (Fig. 7.1). Table 7.2 shows the DM and nutrient distribution at time of harvest for fertilized and unfertilized plants in Carimagua, Colombia. Fertilization increased total DM production and root yield by about 30%, but nearly doubled the total absorption of P and K, and increased that of N by 61%. Total nutrient absorption was highest for N, followed by K, Ca, Mg, P and S; absorption of micronutrients was very low (Paula *et al.*, 1983). The roots generally accumulated more K than N, followed by P, Ca, Mg and S, while fallen leaves and stems were high in N and Ca. Similar results were reported by Nijholt (1935), Asher *et al.* (1980), CIAT (1980, 1985a,b), Howeler and Cadavid (1983), Paula *et al.* (1983) and Putthacharoen *et al.* (1998).

As indicated above, the amount of nutrients absorbed by the plant or that removed in the root harvest is highly dependent on growth rate and yield, which in turn depend on climate, soil-fertility conditions and variety. Table 7.3 shows the fresh and dry matter production, as well as the nutrient content in the roots and in the total plant from 15 experiments reported in the literature, with yields ranging from 6 to 65 t ha^{-1}. The amounts of nutrients in the roots or in the whole plant were quite variable, but tended to be very high when yields were high and quite low when yields were low. If nutrient removal were

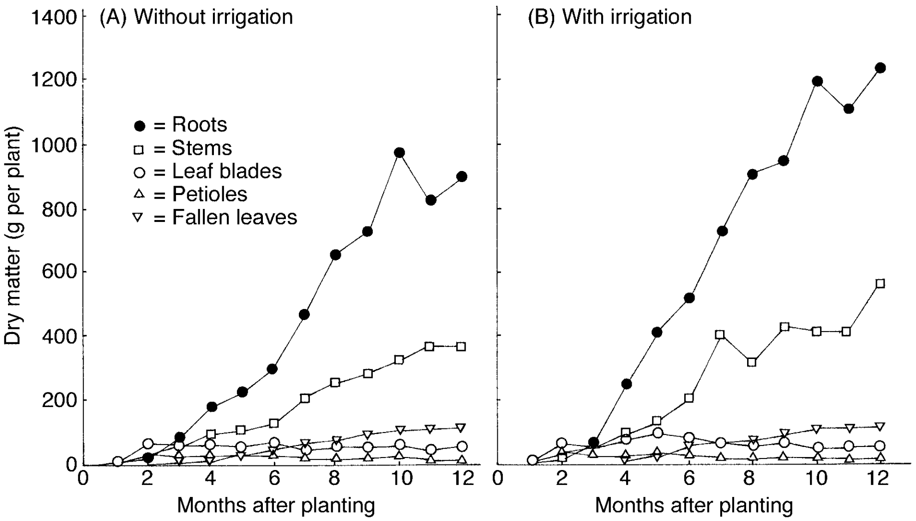

Fig. 7.1. Dry matter distribution among roots, stems, leaf blades, petioles and fallen leaves of fertilized cassava during a 12-month growth cycle in Carimagua (Colombian Eastern Plains), with (B) or without (A) irrigation. (Source: CIAT, 1985b.)

Table 7.2. Dry matter (DM) and nutrient distribution in 12-month-old cassava cv. M Ven 77, grown with and without fertilization in Carimagua, Colombia.

	(t ha^{-1})	(kg ha^{-1})										
	DM	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
Unfertilized												
Top	5.11	69.1	7.4	33.6	37.4	16.2	8.2	0.07	0.03	0.45	0.33	0.26
Roots	10.75	30.3	7.5	54.9	5.4	6.5	3.3	0.08	0.02	0.38	0.02	0.10
Fallen leaves	1.55	23.7	1.5	4.0	24.7	4.0	2.5	0.04	0.01	–	0.37	0.18
Total	17.41	123.1	16.4	92.5	67.5	26.7	14.0	0.19	0.06	–	0.72	0.54
Fertilized												
Tops	6.91	99.9	11.7	74.3	55.0	15.3	9.6	0.08	0.03	0.78	0.57	0.30
Roots	13.97	67.3	16.8	102.1	15.5	8.4	7.0	0.07	0.03	0.90	0.06	0.17
Fallen leaves	1.86	30.5	2.0	7.1	31.9	4.7	2.6	0.05	0.02	–	0.46	0.19
Total	22.74	197.7	30.5	183.5	102.4	28.4	19.3	0.20	0.08	–	1.09	0.66

Source: Howeler (1985a).

proportional to yield, an average root yield of 15 t ha^{-1} would remove about 35 kg N, 5.8 kg P, 46 kg K, 7.0 kg Ca and 4.1 kg Mg ha^{-1}. The relationship between dry root yield and root nutrient content is, however, not linear (Fig. 7.2) because high-yielding plants generally have higher nutrient concentrations in the roots than low-yielding plants. Thus at lower yield levels, nutrient removal is considerably lower than indicated above. Figure 7.2 shows that at a fresh root yield level of 15 t ha^{-1} the nutrients removed in the harvested roots would be about 30 kg N, 3.5 kg P and 20 kg K ha^{-1}, considerably lower for P and K than previously estimated (Howeler, 1981). This may be the reason why cassava yields of less than 10 t ha^{-1} (about 3.7 t ha^{-1} of dry roots) do not seriously deplete the nutrient level of the soil. Yields can be sustained at those levels for several cropping seasons, even when no fertilizers or manures are applied, as long as plant tops are re-incorporated into the soil. The rather close fit of the experimental data reported in the literature for the relationship between P and K removal with dry root yield (Fig. 7.2B and C) indicates that yields may be more closely associated with the concentrations of P and K in the roots than with that of N.

To prevent nutrient depletion of the soil, about 60 kg N, 10–20 kg P_2O_5 and 50 kg K_2O ha^{-1} should be applied if the expected yield level is 15 t ha^{-1} and all stems and leaves are returned to the soil. If leaves and stems are also removed, at least twice this much needs to be applied. Removal of P, Ca and Mg is quite low if only roots are harvested but increases considerably (especially Ca and Mg) if plant tops are also removed.

Nutrient losses by runoff and erosion

When cassava is grown on slopes, nutrient losses in eroded sediments and runoff can be substantial. The detachment of soil particles by the impact of raindrops and the subsequent movement down slope, together with runoff water, not only physically removes part of the top soil with the associated organic matter (OM), nutrients and microorganisms, but also fertilizers, plant litter and earthworm castings. This leaves a soil that is lighter in texture and lower in OM and nutrients. Given the reduced depth of the topsoil, a highly acid, infertile subsoil may be exposed. Consequently, cassava

Table 7.3. Fresh and dry yield, as well as nutrient content in cassava roots and in the whole plant at time of harvest, as reported in the literature.

	Yield (t ha^{-1})		Nutrient content (kg ha^{-1})					
Plant part	Fresh	Dry	N	P	K	Ca	Mg	Source/cultivar
Roots	64.7	26.59	45	28.2	317	51	18	Nijholt (1935)
Whole plant	110.6	39.99	124	45.3	487	155	43	São Pedro Preto
Roots	59.0	21.67	152	22.0	163	20	11	Howeler and Cadavid (1983)
Whole plant	–	30.08	315	37.0	238	77	32	M Col 22, fertilized
Roots	52.7	25.21	38	27.9	268	34	19	Nijholt (1935)
Whole plant	111.1	44.65	132	48.5	476	161	52	Mangi
Roots	37.5	13.97	67	17.0	102	16	8	Howeler (1985b)
Whole plant	–	22.74	198	31.0	184	102	28	M Col 22, unfertilized
Roots	~ 33.9	12.60	161	10.0	53	16	12	Paula *et al.* (1983)
Whole plant	–	20.92	330	20.5	100	88	30	Branco SC, fertilized
Roots	32.3	15.39	127	19.1	71	6	5	Cadavid (1988)
Whole plant	–	25.04	243	34.4	147	56	25	CM 523–7, fertilized
Roots	~ 27.6	10.28	100	8.7	107	15	13	Paula *et al.* (1983)
Whole plant	–	19.56	353	24.8	174	133	37	Riqueza, fertilized
Roots	26.6	12.81	91	11.3	47	5	6	Cadavid (1988)
Whole plant	–	19.10	167	19.1	76	32	19	CM 523–7, unfertilized
Roots	26.0	10.75	30	8.0	55	5	7	Howeler (1985a)
Whole plant	–	17.41	123	16.0	92	67	27	M Ven 77, unfertilized
Roots	18.3	5.52	32	3.6	35	5	4	Sittibusaya, unpublished
Whole plant	–	9.01	95	9.9	65	37	15	Rayong 1, fertilized
Roots	16.1	3.64	30	4.7	45	9	5	Putthacharoen *et al.* (1998)
Whole plant	–	10.55	193	27.0	137	122	27	Rayong 1, 1990/91
Roots	~ 15.0	5.58	66	2.7	17	8	5	Paula *et al.* (1983)
Whole plant	–	10.62	197	8.1	61	100	20	Riqueza, unfertilized
Roots	~ 8.7	3.24	37	1.5	23	4	2	Paula *et al.* (1983)
Whole plant	–	6.54	93	4.0	40	30	9	Branca SC, unfertilized
Roots	8.7	2.68	13	0.9	4	3	2	Sittibusaya, unpublished
Whole plant	–	4.23	39	3.2	10	21	8	Rayong 1, unfertilized
Roots	6.0	1.52	18	2.2	15	5	2	Putthacharoen *et al.* (1998)
Whole plant	–	4.37	91	12.2	55	46	15	Rayong 1, 1989/90

yields on eroded soils are substantially lower than on nearby non-eroded soil (Howeler, 1986, 1987).

Research has shown (Quintiliano *et al.*, 1961; Margolis and Campos Filho, 1981; Putthacharoen *et al.*, 1998; Wargiono *et al.*, 1998)

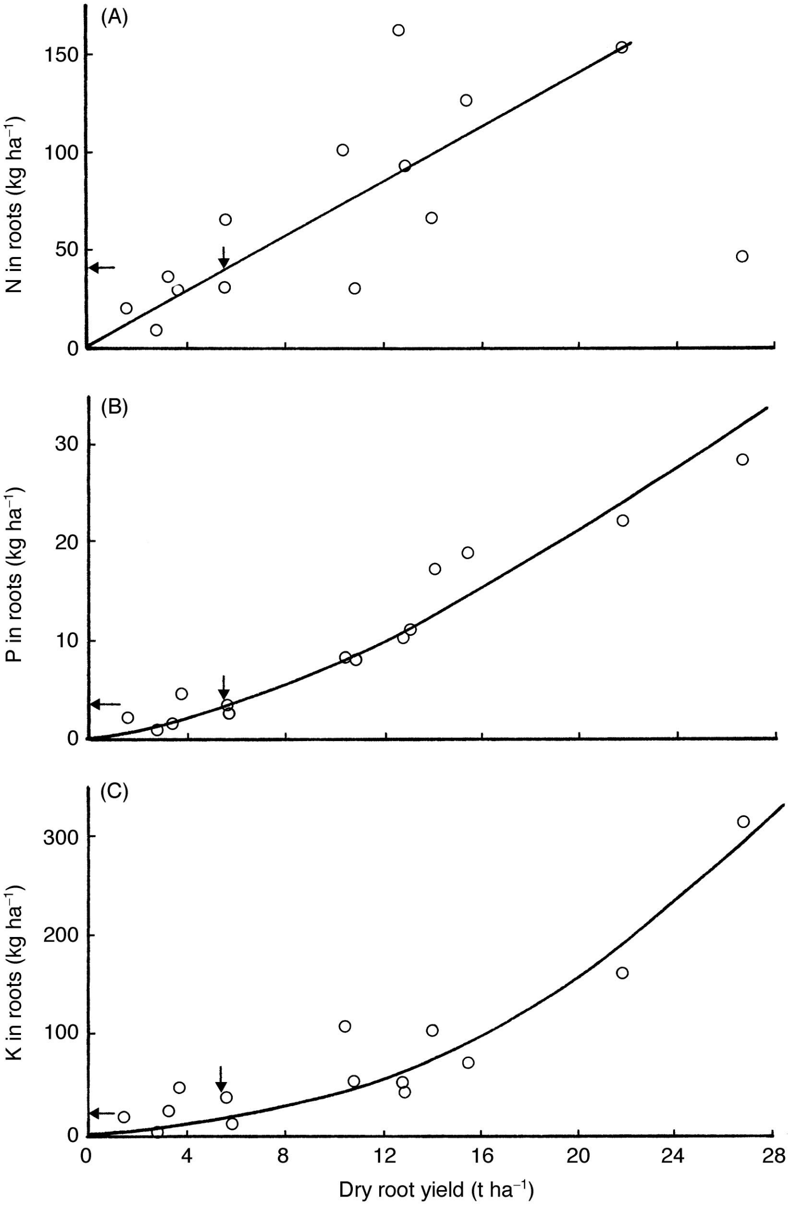

Fig. 7.2. Relation between the N, P and K contents of cassava roots and dry root yield, as reported in the literature (see Table 7.3); arrows indicate the approximate nutrient contents corresponding to a fresh root yield of 15 t ha^{-1}. (In Fig. 7.2A two points corresponding to data of Nijholt (1935) were not considered when drawing the line, as the reported levels of N removal were too low for the high yields obtained. This may have been due to faulty analytical procedures at the time. Data for P and K removal from the same author seem to be correct and are therefore included.)

that cultivating cassava on slopes results in more erosion than for most other crops. This is mainly due to the wide plant spacing used and the slow initial growth of cassava, which result in soil being exposed to the direct impact of rainfall during the first 3–4 MAP. Recent research has shown that erosion can be markedly reduced by simple agronomic practices such as selecting varieties with rapid initial growth, minimum tillage, closer plant spacing (0.8 × 0.8 m), vertical planting, intercropping, mulching, fertilizer application, planting at the end rather than the beginning of the rainy season, and the planting of contour hedgerows of grasses such as vetiver (*Vetiveria zizanioides*), leguminous trees or forage species (Howeler, 1998; Nguyen Huu Hy *et al.*, 1998; Tongglum *et al.*, 1998; Wargiono *et al.*, 1998).

Table 7.4 shows the soil and associated nutrient losses measured in cassava trials conducted in Thailand and Colombia. Nutrient losses were much higher in Thailand than in Colombia due to the higher soil losses, even on a ‘gentle’ slope of only 7%. Losses of P, K and Mg are in terms of available P and exchangeable K and Mg. If the unavailable or non-exchangeable fractions had been measured, these losses would have been about ten times higher. Thus annual N losses in eroded sediments in Thailand were almost twice as high as in the harvested roots (Putthacharoen *et al.*, 1998), while in Colombia N losses in sediments were one to two times as high as those estimated in the harvested roots (Ruppenthal, 1995; Ruppenthal *et al.*, 1997).

There is little quantitative information about nutrient losses from cassava fields in rainfall runoff. Naturally this depends on rainfall intensity, amount of runoff, fertilizers applied, etc. Data reported for upland rice grown on 25–35% slope in Luang Prabang, Laos, indicate that total N and P losses in runoff (3.6 kg N and 0.85 kg P ha^{-1} year^{-1}) were considerably lower than in the eroded sediments (35.5 kg N and 5.6 kg P ha^{-1} year^{-1}), but that total K losses were higher (52 kg ha^{-1} year^{-1}) in the runoff than in the sediment (33 kg ha^{-1} year^{-1}; Phommasack *et al.*, 1995, 1996).

Long-term effect of cassava production on soil productivity

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

Cong Doan Sat and Deturck (1998) compared the effect of long-term cultivation

Table 7.4. Nutrients in sediments eroded from cassava plots with various treatments in Thailand and Colombia.

Location and treatments	Dry soil loss (t ha^{-1} year^{-1})	(kg ha^{-1} year^{-1}) N[a]	P[b]	K[b]	Mg[b]
Cassava on 7% slope in Sriracha, Thailand[c]	71.4	37.1	2.18	5.15	5.35
Cassava on 7–13% slope in Quilichao, Colombia[d]	5.1	11.5	0.16	0.45	0.45
Cassava + leguminous cover crops in Quilichao, Colombia[d]	10.6	24.0	0.24	0.97	0.81
Cassava + grass hedgerows in Quilichao, Colombia[d]	2.7	5.8	0.06	0.22	0.24
Cassava on 12–20% slope in Mondomo, Colombia[d]	5.2	13.3	1.09	0.45	0.36
Cassava + leguminous cover crops in Mondomo, Colombia[d]	2.7	6.5	0.04	0.24	0.20
Cassava + grass hedgerows in Mondomo, Colombia[d]	1.5	3.5	0.02	0.13	0.10

[a] Total N.
[b] Available P and exchangeable K and Mg.
[c] Source: Putthacharoen *et al.* (1998).
[d] Source: Ruppenthal *et al.* (1997).

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

When cassava was grown for 8 consecutive years without fertilizers in Quilichao, Colombia, root yields declined from 22 t ha^{-1} in the first year to 13 t ha^{-1} in the last year (Fig. 7.3). With application of only N or P, yields declined from 27 and 29 t ha^{-1} in the first year to 20 and 15 t ha^{-1}, respectively, in the last year. This yield decline was due to the increasing intensity of K deficiency. When only K was applied (150 kg K_2O ha^{-1}) yields could be maintained at about 30 t ha^{-1}, while with the annual application of 100 kg N, 200 kg P_2O_5 and 150 kg K_2O ha^{-1}, yields actually increased from about 32 to nearly 40 t ha^{-1}. Without K application the exchangeable K content of the soil decreased in 2–3 years from 0.2 to about 0.1 meq 100 g^{-1} and remained at that level for the following five crop cycles. With application of 150 kg K_2O ha^{-1}, the soil K level remained constant at about 0.2 meq 100 g^{-1}, while with applications of 300 kg K_2O ha^{-1} it increased gradually to 0.45 meq 100 g^{-1}. Thus high yields and adequate levels of K could be maintained with annual applications of 150 kg K_2O ha^{-1} (Howeler and Cadavid, 1990; Howeler, 1991b).

On mineral soils in Malaysia, very high cassava yields of about 50 t ha^{-1} were maintained for 9 years with annual applications of 112 kg N, 156 kg P_2O_5 and 187 kg K_2O ha^{-1}, but without fertilizers yields declined from 32 t ha^{-1} in the first year to about 20 t ha^{-1} in the 9th year (Chan, 1980; Howeler, 1992). This was also attributed mainly to increasing K deficiency. In Kerala, India, continuous cropping for 10 years also resulted in declining yields when no K was applied, while annual applications of 100 kg K_2O ha^{-1} maintained high yields of 20–30 t ha^{-1} (Kabeerathumma *et al.*, 1990).

Figure 7.4 shows similar results for a long-term (> 20 year) fertility trial conducted in Khon Kaen, Thailand. Without K application yields declined from 28 t ha^{-1} in the first year to 10 t ha^{-1} in the second, and then slowly declined to about 5 t ha^{-1} during the subsequent 17 cropping cycles. With application of NK or NPK, yields could be maintained at a level of 20 t ha^{-1} for the entire period. Figure 7.4B also shows that when plant tops were re-incorporated into the soil, the yield decline without fertilizer application was much slower. After 19 years the yield was still about 10 t ha^{-1}, i.e. twice as high as when all plant parts were removed. Thus, when plant tops were returned to the soil, yields of about 10 t ha^{-1} could be maintained, even in a very poor soil and without any application of fertilizers. With adequate fertilization high yields of at least 20 t ha^{-1} could be maintained for 19 years of continuous cropping.

Diagnosis of Nutritional Disorders

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

Observation of deficiency and toxicity symptoms

Cassava plants do not readily translocate nutrients from the lower to the upper leaves; instead, when certain nutrients are in deficient supply, plants respond by slowing the growth rate, producing fewer and smaller leaves and sometimes shorter internodes. Leaf life is also

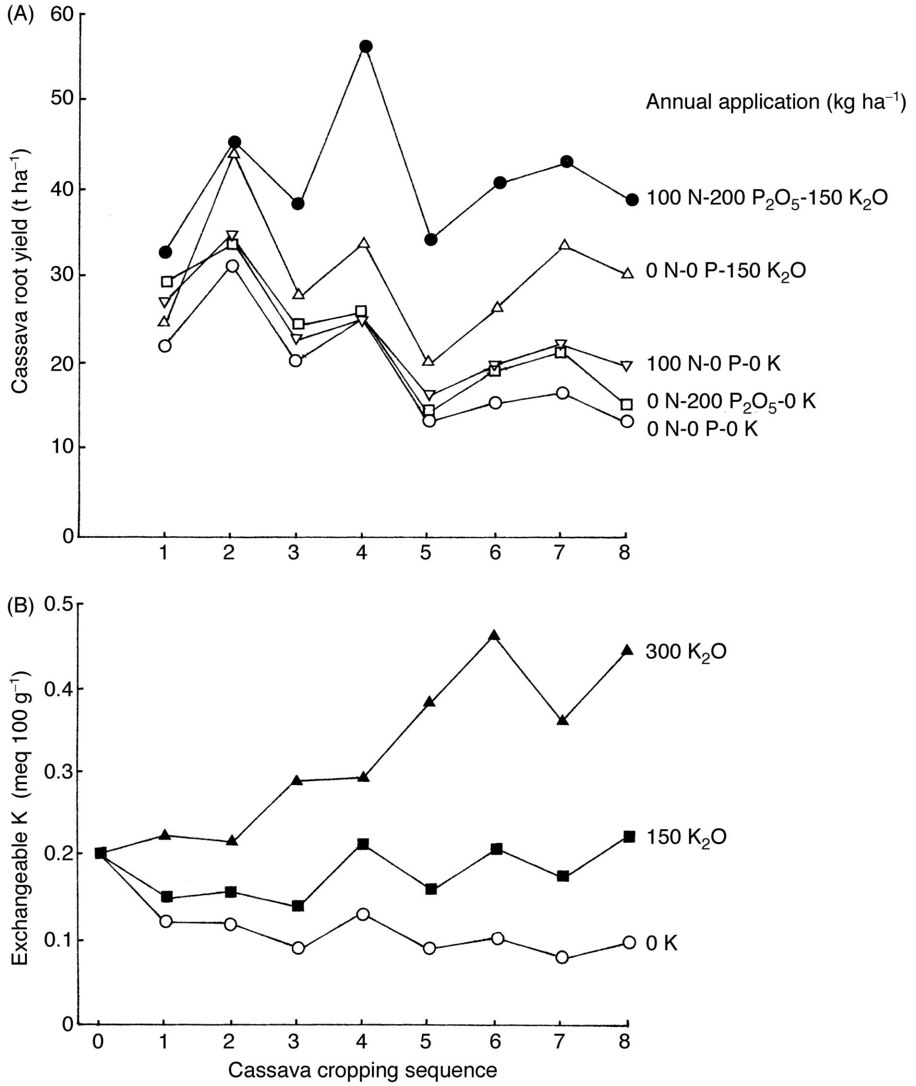

Fig. 7.3. Effect of various levels of annual applications of N, P and K on cassava root yield (A), and on the exchangeable K content of the soil (B) during eight consecutive cropping cycles in a long-term NPK trial conducted at CIAT-Quilichao, Colombia.

reduced. As nutrients are not readily mobilized to the growing point, symptoms for NPK deficiencies, normally found in the lower leaves, tend to be less pronounced in cassava than in other crops. For that reason farmers may not be aware that plant growth is reduced because of nutritional deficiencies. The initial diagnosis based on deficiency or toxicity symptoms needs to be confirmed by soil or plant tissue analyses or from experiments. Nevertheless, visual identification is a quick, easy method to diagnose many nutritional problems. Symptoms have been described and colour photos have been included in several publications (Asher *et al.*, 1980; Howeler, 1981, 1989, 1996a,b; Lozano *et al.*, 1981; Howeler and Fernandez, 1985). The symptoms of nutrient deficiencies and toxicities are summarized in Table 7.5.

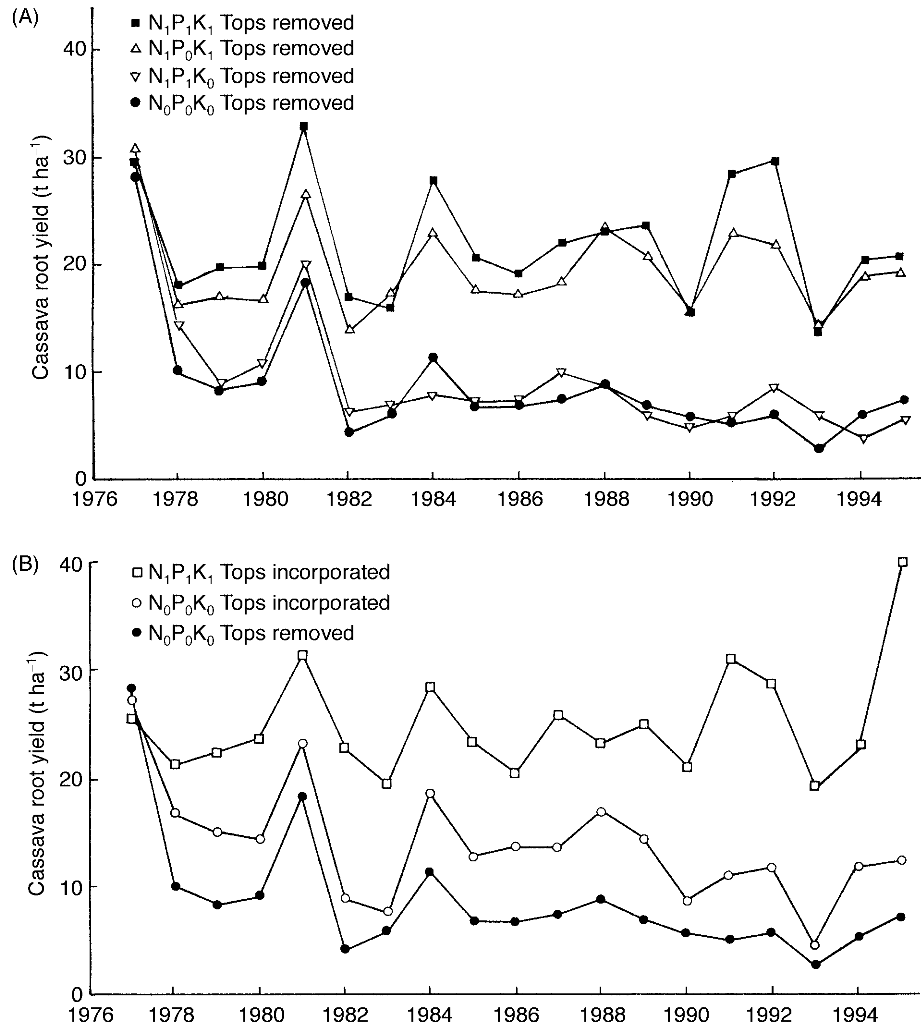

Fig. 7.4. Effect of annual applications of various combinations of N, P and K (A) and crop residue management (B) on cassava yield during 19 consecutive crops grown in Khon Kaen, Thailand, from 1977–1995. (Source: Howeler, 2000.)

Soil analysis

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

Soil analyses usually determine the amount of available or exchangeable nutrient as this part of the total soil nutrient is best correlated with plant uptake. These ‘available’ fractions are usually determined by shaking the soil sample with certain extracting solutions and determining the amount of nutrient in the extract. Different laboratories may use different extracting agents as there is no one method that is optimal for all soil types; thus results from one laboratory may

Table 7.5. Symptoms of nutrient deficiencies and toxicities in cassava.

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

Toxicities	Symptoms
Aluminium (Al) (only in very acid mineral soils)	Reduced root and shoot growth Under very severe conditions yellowing of lower leaves
Boron (B) (only observed after excessive B application)	Necrotic spotting of lower leaves, especially along leaf margins
Manganese (Mn) (mainly in acid soils and when plant growth stagnates)	Yellowing or oranging of lower leaves with purple-brown spots along veins Leaves become flaccid and drop off
Salinity (observed only in saline/ alkaline soils)	Uniform yellowing of leaves, starting at bottom of plant but soon spreading throughout Symptoms very similar to Fe deficiency Under severe conditions border necrosis of lower leaves, poor plant growth and death of young plants

differ from those of another. In interpreting the results, therefore, it is important to consider the methodology used.

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

Results of the soil analysis can be compared with published data obtained from correlation studies, which indicate either the 'critical level' of the nutrient, as determined with a specific extracting agent or the nutrient ranges according to the particular nutritional conditions of the crop. Table 7.6 gives the ranges corresponding to the nutritional requirements of cassava determined with particular methodologies.

These data were determined from many fertilizer experiments conducted in Colombia and in various Asian countries by relating the relative yield in the absence of N, P or K fertilizers (yield without the nutrient over the highest yield obtained with the nutrient) with the OM, available P and exchangeable K content of the soil, respectively. Figure 7.5 gives an example from nine locations in four Asian countries. A line was drawn visually through the points to show the relationship and to estimate the 'critical level' of the nutrient or soil parameter. This critical level is interpreted as the concentration of the nutrient in the soil or plant tissue above which there is no further significant response to application of the nutrient (usually defined as corresponding to 95% of maximum yield). Critical levels are 3.2% for OM, 7 $\mu g\ g^{-1}$ for P (Bray II) and 0.14 meq 100 g^{-1} for exchangeable K. The critical levels for P and K are close to those reported earlier in the literature (Table 7.7). Those for available soil-P reported for cassava (4–10 $\mu g\ g^{-1}$) are much lower than for most other crops (10–18 $\mu g\ g^{-1}$), indicating that cassava will grow well in soils that are low in P and where other crops would suffer from P deficiency. This is due to the effective association between cassava roots and vesicular–arbuscular mycorrhizas (VAM) occurring naturally in the soil (Howeler, 1990).

The critical levels for exchangeable K for cassava (0.08–0.18 meq K 100 g^{-1}; Table 7.7) are also lower than for most other crops

Table 7.6. Approximate classification of soil chemical characteristics according to the nutritional requirements of cassava.

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

[a] pH in H_2O.

[b] OM = Walkley and Black method.

[c] Al saturation = 100 × Al (Al + Ca + Mg + K) in meq 100 g^{-1}.

[d] P in Bray II; K, Ca, Mg and Na in 1N NH_4-acetate; S in Ca phosphate.

[e] B in hot water; and Cu, Mn, Fe and Zn in 0.05 N HCl + 0.025 N H_2SO_4.

Source: Howeler (1996a,b).

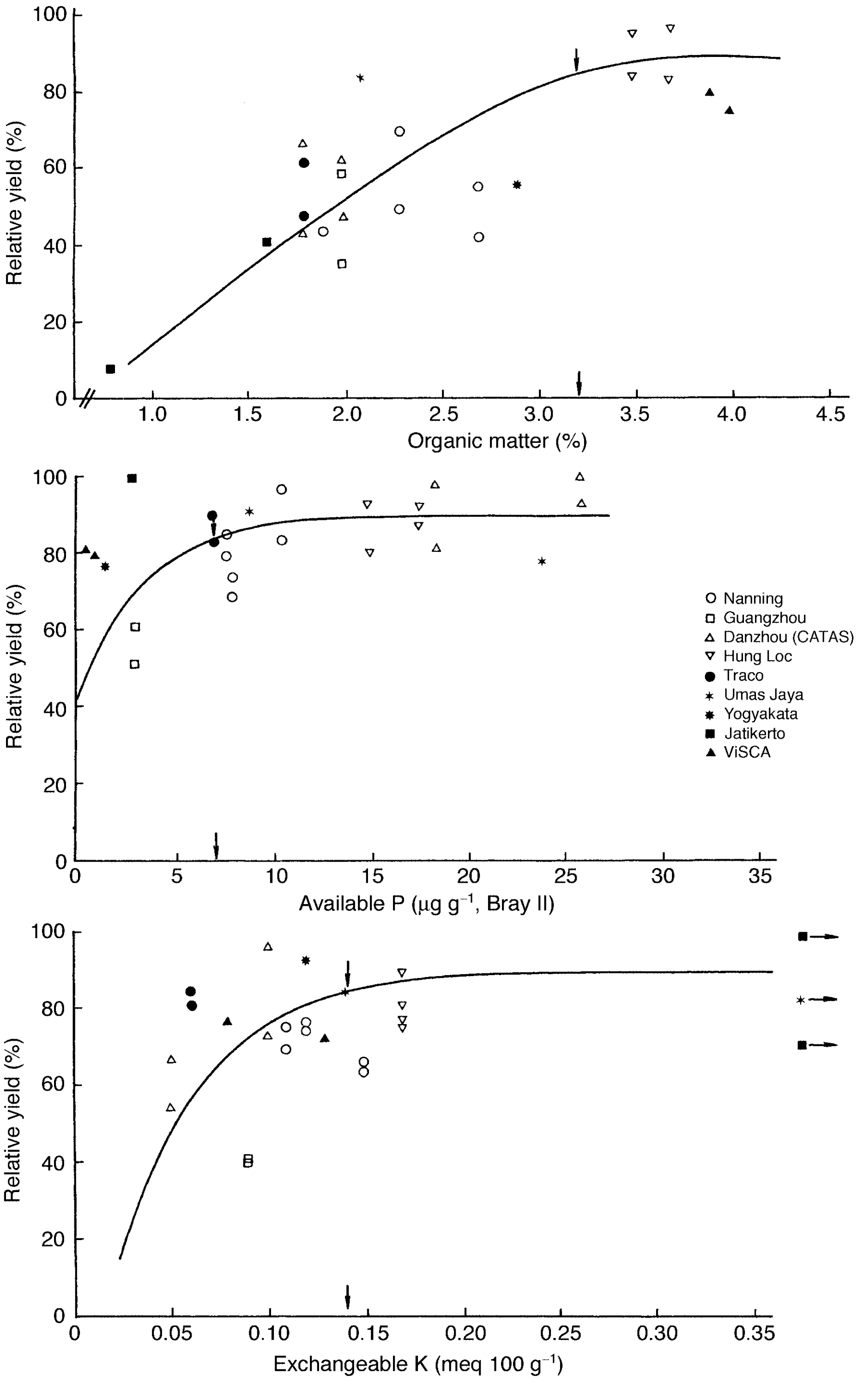

Fig. 7.5. Relationship between relative yield of cassava (i.e. without nutrient as % of highest yield with nutrient) and organic matter available P and exch. K content of the soil in nine NPK trials conducted in Asia (1993–1996). (Source: Howeler, 1998.)

Table 7.7. Critical levels[a] of nutrients for cassava and other crops according to various methods of soil analysis, as reported in the literature.

Soil parameter	Method[c]	Crop	Critical level	Source
Organic matter (%)	Walkley and Black	Cassava	3.1	Howeler (1998)
P ($\mu g\ g^{-1}$)	Bray I	Cassava	7	Howeler (1978)
		Cassava	8[b]	Kang *et al.* (1980)
		Cassava	4.2	Cadavid (1988)
		Cassava	7	Howeler (1989)
		Maize	14	Kang *et al.* (1980)
		Soybeans	15	Kang *et al.* (1980)
	Bray II	Cassava	8	CIAT (1982)
		Cassava	4	Howeler (1985a)
		Cassava	6	CIAT (1985a)
		Cassava	5.8[b]	Cadavid (1988)
		Cassava	10	Howeler (1989)
		Cassava	10	Hagens and Sittibusaya (1990)
		Cassava	4	Howeler and Cadavid (1990)
		Cassava	4.5	Howeler (1995)
		Cassava	7	Howeler (1998)
		Common beans[d]	10–15	Howeler and Medina (1978)
	Olsen-EDTA	Cassava	3	van der Zaag *et al.* (1979)
		Cassava	7.5[b]	Cadavid (1988)
		Cassava	8	Howeler (1989)
	North Carolina	Cassava	5.0[b]	Cadavid (1988)
		Cassava	9	Howeler (1989)
		Common beans	18	Goepfert (1972)
K (meq 100 g^{-1})	NH_4-acetate	Cassava	0.09–0.15	Obigbesan (1977)
		Cassava	< 0.15	Kang (1984)
		Cassava	< 0.15	Kang and Okeke (1984)
		Cassava	0.18	Howeler (1985b)
		Cassava	0.175[b]	Cadavid (1988)
		Cassava	0.15	Howeler (1989)
		Cassava	0.18	Howeler and Cadavid (1990)
		Cassava	0.08–0.10	Hagens and Sittibusaya (1990)
		Rice	0.21	Jones *et al.* (1982)
		Potatoes	0.20–1.00	Roberts and McDole (1985)
		Sugarcane	0.16–0.51	Orlando Filho (1985)
	Bray II	Cassava	0.15	CIAT (1985a)
		Cassava	0.17	Howeler (1985b)
		Cassava	0.16	CIAT (1988b)
		Cassava	0.175[b]	Cadavid (1988)
		Cassava	0.17	Howeler and Cadavid (1990)
		Cassava	0.12	Howeler (1995)
		Cassava	0.14	Howeler (1998)
	North Carolina	Cassava	0.15	Howeler (1989)
Ca (meq 100 g^{-1})	NH_4-acetate	Cassava	0.25	CIAT (1979)
		Common beans	4.5	Howeler and Medina (1978)
Mg (meq 100 $^{-1}$)	NH_4-acetate	Cassava	< 0.20	Kang (1984)
pH	1 : 1 in water	Cassava	4.6 and 7.8	CIAT (1977, 1979)
		Common beans	4.9	Abruña *et al.* (1974)
Al (% sat.)	KCl	Cassava	80	CIAT (1979)
		Common beans	10–20	Abruña *et al.* (1974)

footnote on next page

(0.16–0.51 meq K 100 g^{-1}), indicating that despite the crop's relatively high K requirement, it will still grow well on soils with only intermediate levels of K.

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

Using data from 20 NPK cassava trials conducted in Colombia to compare different methods of extracting available P, Cadavid (1988) reported the highest correlation between relative cassava yields and available soil P using Bray I, followed by Bray II, North Carolina and Olsen-EDTA extractants. For determining exchangeable K, Cadavid (1988) found no significant difference between the use of Bray II and NH_4-acetate; both resulted in a critical level of 0.175 meq K 100 g^{-1}.

Plant tissue analysis

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

Given that nutrient concentrations vary among different tissues, it is imperative to use an 'indicator' tissue, the nutrient concentration of which is best related to plant growth or yield. For cassava, the best 'indicator' tissue is the blade of the youngest fully expanded leaf (YFEL), i.e. normally about the fourth to fifth leaf from the top. Blades without petioles are analysed as nutrient concentrations are quite different in these two tissues (Table 7.8). Nutrient concentrations also change during the growth cycle, depending on the rate of plant growth (Howeler and Cadavid, 1983; CIAT, 1985a,b). As they tend to stabilize after about 4 months, leaf samples should be taken at about 4 MAP.

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

To diagnose nutritional problems, the results are compared with the nutrient ranges corresponding to the various nutritional states of the plant (Table 7.9), or with critical levels reported in the literature (Table 7.10). While the numbers may vary somewhat given the different varieties, soil and climatic conditions (Howeler, 1983), the data in these tables can be used as a general guide for interpreting plant tissue analyses.

Footnote for Table 7.7.

[a] Critical level defined as 95% of maximum yield.

[b] Critical level defined as 90% of maximum yield.

[c] Methods:

Bray I = 0.025 N HCl + 0.03 N NH_4F.
Bray II = 0.10 N HCl + 0.03 N NH_4F.
Olsen-EDTA = 0.5 N $NaHCO_3$ + 0.01N 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.

[d] *Phaseolus vulgaris*.

Table 7.8. Nutrient concentration in various plant parts of fertilized and unfertilized cassava cv. M Ven 77 at 3–4 MAP in Carimagua, Colombia.

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

[a] Fallen leaves and rootlets were probably contaminated with micronutrients from the soil.
Source: Howeler (1985a).

Greenhouse and field experiments

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

Table 7.9. Nutrient concentrations in youngest fully expanded leaf (YFEL) blades of cassava at 3–4 MAP, corresponding to various nutritional states of the plants; data are averages of various greenhouse and field trials.

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

[a] Very deficient, < 40% maximum yield.
Deficient, 40–80% maximum yield.
Low, 80–90% maximum yield.
Sufficient, 90–100% maximum yield.
High, 100–90% maximum yield.
Toxic, < 90% maximum yield.

[b] – = no data available.

Source: Howeler (1996a,b).

For pot experiments it is recommended not to sterilize or fumigate the soil, in order not to kill the native mycorrhizas. Rooted plant shoots rather than stakes should be used as the stakes have high nutrient reserves and their use would therefore delay responses to nutrient additions. In pot experiments cassava plants are generally harvested 3–4 MAP, and dry weights of top growth are used as indicators of nutrient response.

Correcting Nutritional Disorders

Chemical fertilizers

While cassava performs better than most crops on infertile soils, the crop is highly responsive to fertilizer applications. High yields can be obtained and maintained only when adequate amounts of fertilizers and/or manures are applied. Thousands of fertilizer experiments conducted by FAO worldwide indicate that cassava is as responsive to fertilizer applications as other crops, with yield increases of 49% (West Africa) to 110% (Latin America) versus increases of 43% (yams and rice in West Africa) to 102% (rice in Latin America) for other crops. In West Africa (Ghana) cassava responded mainly to K, in Latin America (Brazil) to P, and in Asia (Indonesia and Thailand) to N (Richards, 1979; Hagens and Sittibusaya, 1990).

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

Table 7.10. Critical nutrient concentrations for deficiencies and toxicities in cassava plant tissue.

Element	Method	Plant tissue	Critical level[a]	Source
N deficiency	Field	YFEL blades	5.1%	Fox *et al*. (1975)
	Field	YFEL blades	5.7%	Howeler (1978)
	Field	YFEL blades	4.6%	Howeler (1995)
	Field	YFEL blades	5.7%	Howeler (1998)
	Nutrient solution	Shoots	4.2%	Forno (1977)
P deficiency	Field	YFEL blades	0.41%	CIAT (1985a)
	Field	YFEL blades	0.33–0.35%	Nair *et al*. (1988)
	Nutrient solution	Shoots	0.47–0.66%	Jintakanon *et al*. (1982)
K deficiency	Nutrient solution	YFEL blades	1.1%	Spear *et al*. (1978a)
	Field	YFEL blades	1.2%	Howeler (1978)
	Field	YFEL blades	1.4%	CIAT (1982)
	Field	YFEL blades	1.5%	CIAT (1982)
	Field	YFEL blades	< 1.1%	Kang (1984)
	Field	YFEL blades	1.5%	CIAT (1985a)
	Field	YFEL blades	1.7%	Howeler (1995)
	Field	YFEL blades	1.9%	Nayar *et al*. (1995)
	Field	YFEL blades	1.9%	Howeler (1998)
	Nutrient solution	Petioles	0.8%	Spear *et al*. (1978a)
	Field	Petioles	2.5%	Howeler (1978)
	Nutrient solution	Stems	0.6%	Spear *et al*. (1978a)
	Nutrient solution	Shoots and roots	0.8%	Spear *et al*. (1978a)
Ca deficiency	Nutrient solution	YFEL blades	0.46%	CIAT (1985a)
	Field	YFEL blades	0.60–0.64%	CIAT (1985a)
	Nutrient solution	Shoots	0.4%	Forno (1977)
Mg deficiency	Nutrient solution	YFEL blades	0.29%	Edwards and Asher (unpublished)
	Field	YFEL blades	< 0.33%	Kang (1984)
	Field	YFEL blades	0.29%	Howeler (1985a)
	Nutrient solution	YFEL blades	0.24%	CIAT (1985a)
	Nutrient solution	Shoots	0.26%	Edwards and Asher (unpublished)
S deficiency	Field	YFEL blades	0.32%	Howeler (1978)
	Nutrient solution	YFEL blades	0.27%	CIAT (1982)
	Field	YFEL blades	0.27–0.33%	Howeler, unpublished
Zn deficiency	Field	YFEL blades	37–51 µg g^{-1}	CIAT (1978)
	Nutrient solution	YFEL blades	43–60 µg g^{-1}	Edwards and Asher (unpublished)
	Nutrient solution	YFEL blades	30 µg g^{-1}	Howeler *et al*. (1982c)
	Field	YFEL blades	33 µg g^{-1}	CIAT (1985a)
Zn toxicity	Nutrient solution	YFEL blades	120 µg g^{-1}	Howeler *et al*. (1982c)
B deficiency	Nutrient solution	YFEL blades	35 µg g^{-1}	Howeler *et al*. (1982c)
	Nutrient solution	Shoots	17 µg g^{-1}	Forno (1977)
B toxicity	Nutrient solution	YFEL blades	100 µg g^{-1}	Howeler *et al*. (1982c)
	Nutrient solution	Shoot	140 µg g^{-1}	Forno (1977)
Cu deficiency	Nutrient solution	YFEL blades	6 µg g^{-1}	Howeler *et al*. (1982c)
Cu toxicity	Nutrient solution	YFEL blades	15 µg g^{-1}	Howeler *et al*. (1982c)
Mn deficiency	Nutrient solution	YFEL blades	50 µg g^{-1}	Howeler *et al*. (1982c)
	Nutrient solution	Shoots	100–120 µg g^{-1}	Edwards and Asher (unpublished)
Mn toxicity	Nutrient solution	YFEL blades	250 µg g^{-1}	Howeler *et al*. (1982c)
	Nutrient solution	Shoots	250–1450 µg g^{-1}	Edwards and Asher (unpublished)
Al toxicity	Nutrient solution	Shoots	70–97 µg g^{-1}	Gunatilaka (1977)
	Nutrient solution	Roots	2000–14,000 µg g^{-1}	Gunatilaka (1977)

[a] Range corresponds to values obtained in different varieties.
YFEL, youngest fully expanded leaf.

absorption of Ca and especially Mg, leading to Mg deficiency. However, in both nutrient solution and field experiments with varying rates of applications of K, Ca and Mg, Howeler (1985b) did not find a significant effect of increasing K on the Ca concentration in the leaves. The Mg concentration decreased slightly in the field, but increased in the nutrient solution experiment. Increasing Mg supply markedly decreased the concentrations of K and Ca. Similarly, Ngongi *et al.* (1977) reported that high applications of KCl induced S deficiency in a low-S soil in Colombia, while Nair *et al.* (1988) found that high rates of P application induced Zn deficiency. Hence, it is important not only to apply the right amount of each nutrient, but also the right balance among the various nutrients.

Nitrogen

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

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

On a very sandy soil (89% sand, 0.7% OM) in Jaguaruna, Santa Catarina, Brazil, two local varieties showed a nearly linear response up to 150 kg N ha^{-1}. For both varieties highest yields were obtained with a split application of N, with one-third applied at 30, 60 and 90 days after planting (Moraes *et al.*, 1981). A similarly spectacular response to N was also observed in a clay soil with 1.2% OM in Jatikerto, East Java, Indonesia (Fig. 7.6). In this case, cassava was intercropped with maize, which competed strongly for the limited supply of N in the soil (Wargiono *et al.*, 1998). In Nanning, Guangxi, China, there was also a highly significant response to N (Zhang Weite *et al.*, 1998), up to 200 kg N ha^{-1} in one cultivar (SC205), but only up to 50 kg N ha^{-1} in the other (SC201). As the latter cultivar is extremely vigorous, high N levels produced too much top growth at the expense of root production. Similar negative responses to high N applications have been reported by Acosta and Perez (1954), Vijayan and Aiyer (1969), Fox *et al.* (1975) and Obigbesan and Fayemi (1976). Krochmal and Samuels (1970) reported a root yield reduction of 41% and top growth increase of 11% due to high N applications. These high rates also stimulate production of N-containing compounds, such as protein and HCN, and may result in a decrease in root starch content. High

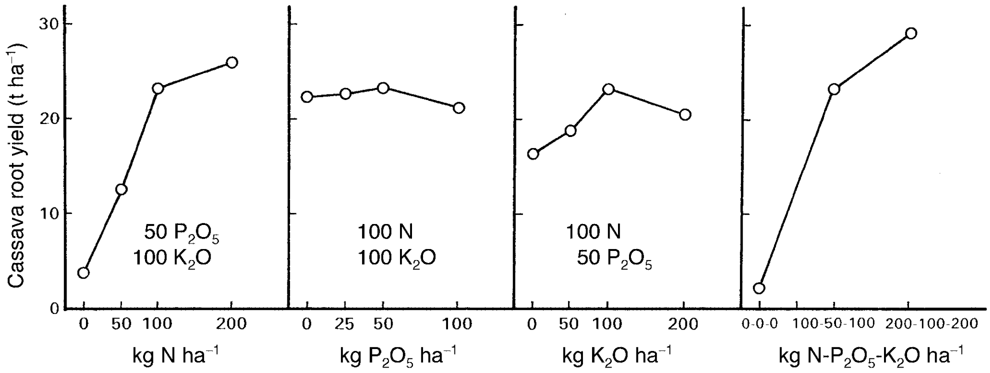

Fig. 7.6. Response of cassava cv. Faroka to the annual application of different levels of N, P and K during the seventh cycle in Jatikerto, East Java, Indonesia in 1994/95. (Source: Wargiono *et al.*, 1998.)

rates of N application may also increase the intensity of diseases such as cassava bacterial blight (Kang and Okeke, 1984). Thus N rates must not only be adjusted to a particular soil but also tailored to the needs of a particular cultivar.

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

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

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

Phosphorus

Cassava's tolerance to low P concentrations in soil solution is not due to the efficient uptake of P by the root system; in fact, cassava grown in flowing nutrient solution required a much higher P concentration for maximum growth than rice, maize, cowpeas or common beans (Howeler *et al.*, 1981; Jintakanon *et al.*, 1982; Howeler 1990). When inoculated with endotrophic VAM, the growth of cassava in nutrient solution improved significantly (Howeler *et al.*, 1982a). Masses of mycorrhizal hyphae growing in and around the fibrous roots of cassava markedly increased the plant's ability to absorb P from the surrounding medium (Fig. 7.7). When planted in natural soil, the crop's fibrous roots soon become infected with native soil mycorrhizas. The resulting hyphae grow into the surrounding soil and help in the uptake and transport of P to the cassava roots. Through this highly effective symbiosis, cassava is able to absorb P from soils with low levels of available P, mainly by extending the soil volume from which P can be absorbed through the associated mycorrhizal hyphae.

Responses of cassava to P application depend on the available-P level of the soil, the mycorrhizal population and the variety used. van der Zaag *et al.* (1979) reported high yields of 42 t ha^{-1} in an oxisol in Hawaii with only 3 μg P g^{-1} ($NaHCO_3$-extractant) using the cultivar Ceiba. CIAT (1988a) similarly reported that some varieties produced yields of 40–50 t ha^{-1} without P application in a soil with only 4.6 μg P g^{-1} (Bray II). In other soils with equally low levels of available P but with a less-efficient mycorrhizal population, cassava responded very markedly to P applications. Thus in the oxisols of the Eastern Plains of Colombia, with only 1.0 μg P g^{-1} (Bray II), cassava responded markedly to applications of 200–400 kg P_2O_5 ha^{-1} (Fig. 7.8). Of the seven P sources tested, banding of triple superphosphate (TSP) or broadcast applications of basic slag were most effective.

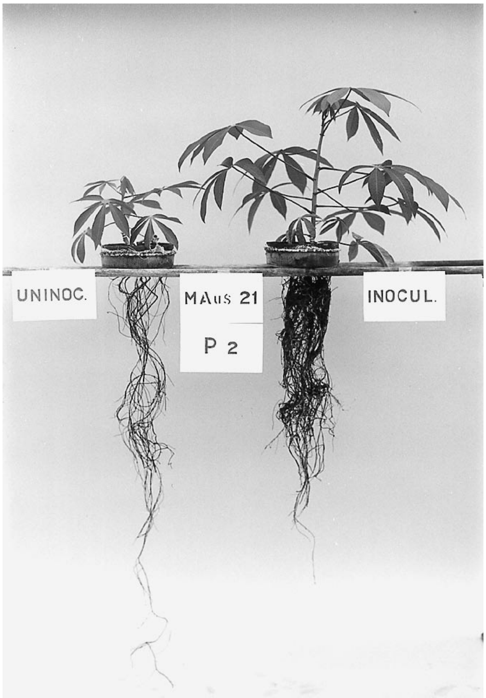

Fig. 7.7. Comparison of a vesicular–arbuscular mycorrhizas (VAM)-inoculated plant (right) with a non-inoculated plant grown in a phosphorus-deficient nutrient solution.

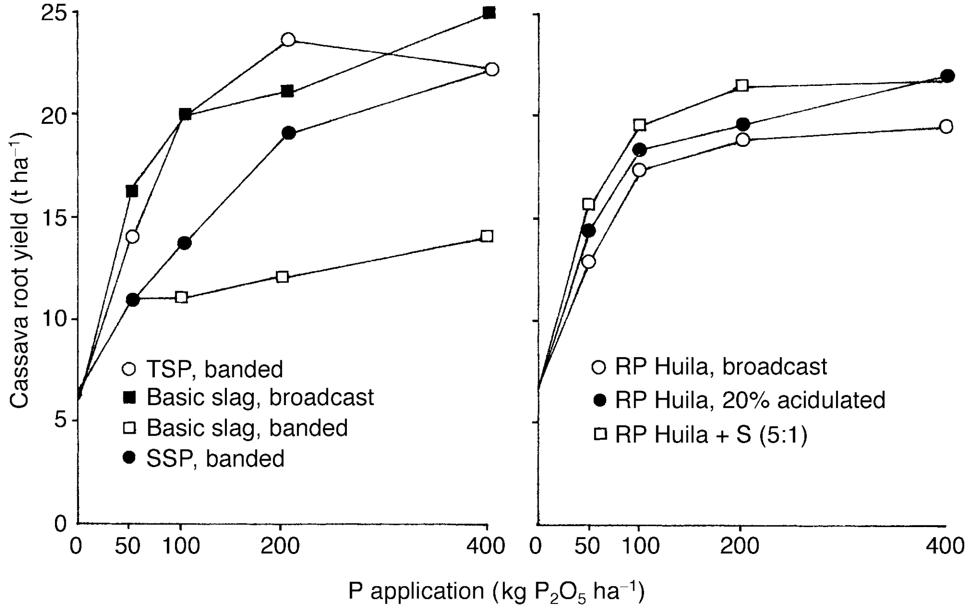

Fig. 7.8. Response of cassava cv. Llanera to application of different levels and sources of P in Carimagua, Colombia. RP, rock phosphate; TSP, triple super-phosphate; SSP, single super-phosphate. (Source: CIAT, 1977.)

Partially acidulated rock phosphate (RP) or RP mixed with elemental sulphur (S) were also quite effective in these acid soils (CIAT, 1978). Locally produced simple super phosphate (SSP) was less effective, except at high rates of application. Similarly, Santos and Tupinamba (1981) reported significant responses to 60 or 120 kg P_2O_5 ha^{-1} in three soils of Sergipe, Brazil, with TSP and hyperphosphate being more effective than two local sources of RP. Soluble-P sources like TSP, SSP, mono- or di-ammonium phosphate should be band applied near the stakes, while less-soluble sources such as basic slag and RPs should be broadcast and incorporated. All P should be applied at or shortly after planting as fractionation of P had no significant effect on yield. Alternative methods of P application, such as stake treatments or foliar sprays, are not as effective as soil application in increasing yields (Howeler, 1985a).

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

In Asia P deficiency is seldom the principal limiting factor for cassava production because most cassava is grown on soils with more than 4 μg g^{-1} of available P and/or that have been previously fertilized with P. Nevertheless, significant responses to P application have been observed in Guangzhou (Guangdong), Nanning (Guangxi) and on Hainan Island of China; in northern and southern Vietnam; and on Leyte Island of the Philippines. In low-P soils in Kerala State, India, significant initial responses to 100 kg P_2O_5 ha^{-1} were reported, but these declined over time. Nair *et al.* (1988) determined an optimum economic rate of 45 kg P_2O_5 ha^{-1}.

In Africa few P experiments have been conducted with cassava. Responses to P application have been reported mainly in Ghana (Stephens, 1960; Takyi, 1972) and Madagascar (Cours *et al.*, 1961). Ofori (1973) reported a negative effect of P application on cassava yields on a forest ochrosol in Ghana.

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

Potassium

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

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

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

Long-term experiments in Asia and Colombia have shown that K deficiency invariably becomes the main limiting factor when cassava is grown continuously on the same soil without adequate K fertilization. Figure 7.9 shows that, without K application, yields declined from 22.4 to 6.3 t ha^{-1} during 10 years of continuous cropping in Trivandrum, Kerala, India (Kabeerathumma *et al.*, 1990). During that time, exchangeable K of the soil gradually declined from 0.18 to 0.064 meq 100 g^{-1}. High yields of 20–30 t ha^{-1} could be maintained with annual applications of 100 kg N, 100 P_2O_5 and 100 K_2O ha^{-1}. The high rate of P used led to a buildup of soil P to excessive levels (~100 μg P g^{-1}). There was also a slight buildup of exchangeable K to a level of 0.25 meq 100 g^{-1}. This contrasts with reports by Howeler and Cadavid (1990), which show that 8 years of continuous cropping with annual applications of 150 kg K_2O ha^{-1} in Quilichao, Colombia, maintained the exchangeable K content at only 0.2 meq 100 g^{-1}. In a very poor sandy soil near the Atlantic Coast of Colombia, Cadavid *et al.* (1998) also found that annual applications of 50 kg N, 50 P_2O_5 and 50 K_2O ha^{-1} increased yields during 8 years of continuous cropping, but had no effect on soil K, which remained at a low level (0.06 meq 100 g^{-1}).

Long-term NPK trials were conducted in four Asian countries. After 4–10 years of continuous cropping, there was a significant response to N in eight out of 11 sites, to P in four and to K in seven. Responses to K increased most markedly with time (Nguyen Huu Hy *et al.*, 1998; Howeler, 2000), but in Malang, Indonesia, responses to N increased more markedly than elsewhere (Wargiono *et al.*, 1998).

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

In Africa, significant responses to K have been found on strongly acid soils of eastern Nigeria (Okeke, unpublished) and on slightly acid soils (0.23 meq K 100 g^{-1}) of southwestern Nigeria (Kang and Okeke, 1984). No significant response to K was observed in field experiments conducted in Nigeria (Obigbesan, 1977) nor in Ghana (Takyi, 1972). In Madagascar, however, Roche *et al.* (1957) and Cours *et al.* (1961) found that K was the main limiting nutrient, and applications of 110 kg K_2O ha^{-1} were recommended (Anon, 1952, 1953).

Experiments on different sources of K have generally shown no significant differences between the use of KCl, K_2SO_4 or Sulphomag (CIAT, 1985a), while in southern India the use of syngenite and schoenite (extracted from seawater) were also found to be equally effective (Central Tuber Crops Research Institute; CTCRI, 1974, 1975). In low-S soils in the Eastern Plains

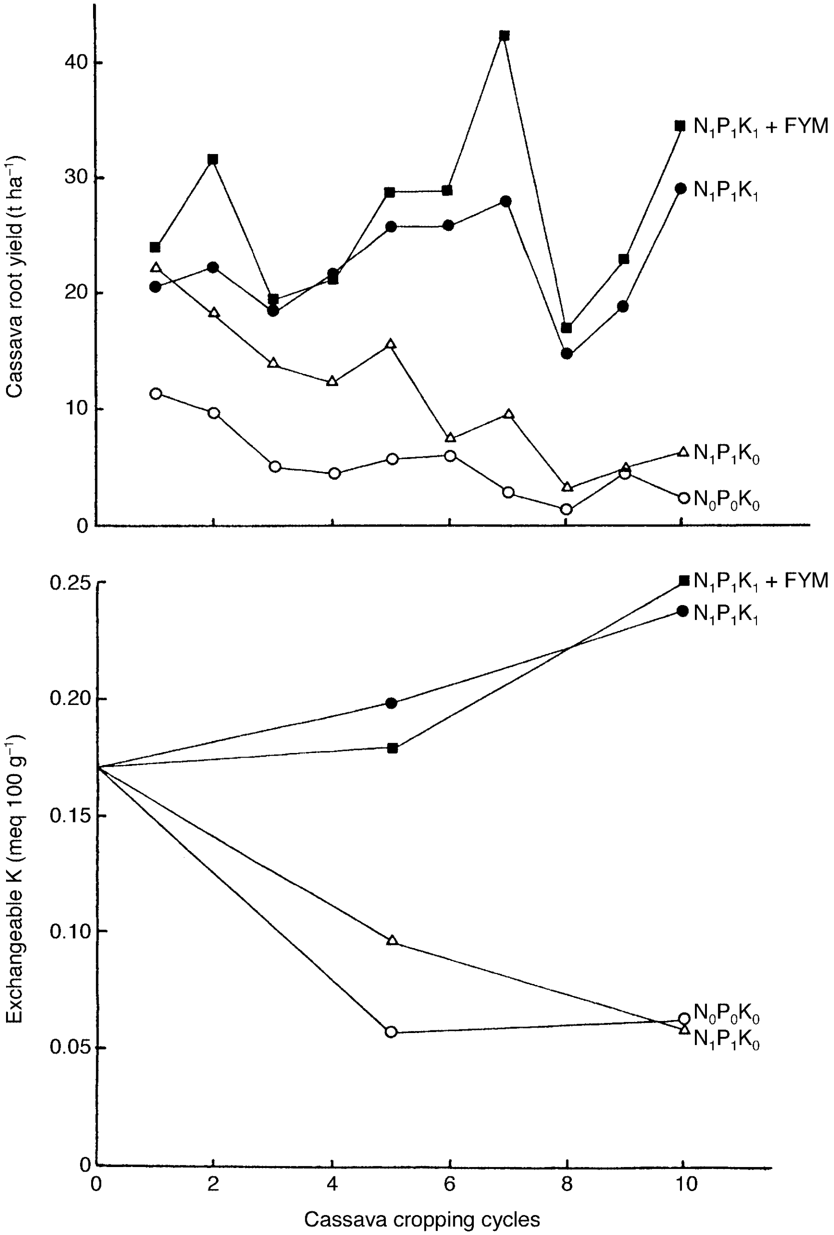

Fig. 7.9. Cassava yield (top) and the exchangeable K content of the soil (bottom) during 10 years of continuous cropping with various NPK treatments in Trivandrum, Kerala, India. (Source: Kabeerathumma *et al.*, 1990.)

of Colombia, Ngongi *et al.* (1977) obtained much better yields with application of K_2SO_4 or KCl + S than with KCl. However, this was mainly a response to S; the same experiment conducted in Jamundí, Colombia, did not show any difference between K sources.

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

Calcium and magnesium

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

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

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

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

Sulphur

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

Micronutrients

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

Zinc

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

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

Copper

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

Iron and manganese

Deficiency symptoms of Fe are often observed in calcareous soils such as in the Yucatan peninsula of Mexico, parts of northern Colombia, southeast Java of Indonesia and western Nakorn Rachasima province of Thailand. Mn deficiency has been observed in sandy soils along the coast in northeast Brazil, in alkaline soils at CIAT, Colombia, and in northern Vietnam, near houses where lime had been used for their construction. A practical solution is probably a stake treatment with 2–4% $FeSO_4.H_2O$ or $MnSO_4.4H_2O$ before planting, or foliar sprays with sulphates or chelates.

Boron

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

Soil Amendments

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

Acid soils

Very acid soils present a complex of problems for plant growth, including low pH, high concentrations of Al and/or Mn, low levels of Ca, Mg and K, and sometimes low P and N. Cassava as a species is particularly tolerant of soil acidity and high levels of Al (Gunatilaka, 1977; CIAT, 1979; Islam *et al.*, 1980), but some varietal differences in acid soil tolerance have also been observed (CIAT, 1982, 1985a; Howeler, 1991a). In very acid ($pH < 4.5$) and high Al (> 80% Al saturation) soils, lime application may increase cassava yields, mainly by supplying Ca and Mg as nutrients. High rates of lime may, however, induce micronutrient deficiencies, particularly Zn, resulting in decreased yield (Spain *et al.*, 1975; Edwards and Kang, 1978). Field trails (CIAT, 1976) showed that without Zn, cassava responded to lime applications only up to 2 t ha^{-1}, but with applied Zn there was a positive response up to 6 t ha^{-1} of lime. Analysis of cassava leaves confirmed that liming reduced Zn uptake and that with 6 t ha^{-1} of lime without Zn, the Zn concentrating in YFEL blades dropped below the critical level of 40–50 µg g^{-1}. Large varietal differences have been found for both high-Al and low-Zn tolerance (Spain *et al.*, 1975).

Saline–alkaline soils

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

Animal manures and compost

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

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

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

In Bahia, Brazil, Gomes *et al.* (1983) obtained very high yields with a system called '*parcagem*', which is basically *in situ* application of cattle manure, where a large number of cattle are enclosed overnight on a small piece of land. It was calculated that 30 animals kept overnight on 1 ha for 60 days will produce about 8 t of dry manure containing 40 kg N (plus the N in the urine). At an equal dosage of 40 kg N ha^{-1}, cassava yields with the *parcagem* system (combined with additional P and K) increased 30–90% as compared to application of only chemical fertilizers. This system may be economically viable in areas with large cattle populations. Good results were also obtained in Bahia when applying 5 t ha^{-1} of cattle manure combined with 10 kg P_2O_5 ha^{-1} (Diniz *et al.*, 1994).

Little information is available on the effectiveness of applying compost, which is considerably lower in nutrients than animal manures (Howeler *et al.*, 2002); but when applied in large quantities (10–15 t ha^{-1}), they may supply considerable amounts of nutrients as well as improving the soil's physical condition and water-holding capacity. Application of 6–10 t ha^{-1} of compost made from cassava peel residues in starch factories has given promising results in Thailand. In Brazil the application of 5 t ha^{-1} of *vinhoto* (a by-product of alcohol production) increased yields, especially when fortified with 60 kg P_2O_5 and 1 t lime (Souza *et al.*, 1992).

Green manures, cover crops and mulch

Planting of green manures and their subsequent mulching or incorporation into the soil have been practised traditionally as a form of ‘improved fallow’ to maintain soil fertility. Research on the use of green manures and cover crops to maintain soil fertility in cassava fields was recently reviewed (Howeler *et al*., 2002a, b). In the absence of chemical fertilizers, green manures increased yields slightly in Quilichao, Colombia, but significantly on sandy soils in Media Luna, Colombia. In the presence of fertilizers the effect was minimal. Most effective were kudzu (*Puerarea phaseoloides*), Zornia (*Zornia latifolium*) and groundnuts (*Arachis hypogea*) in Quilichao, and local weeds and *Canavalia ensiformis* in Media Luna. In Thailand, *Crotalaria juncea* was the most productive and effective in increasing yields. The growing of green manures before planting cassava was found to be impractical, however, as cassava yields were markedly reduced by planting too late in the wet season (Howeler, 1992, 1995).

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

Planting intercrops such as maize, groundnut, cowpea, common bean, mungbean or soybean and incorporating the residue after harvest may improve soil fertility (especially if the intercrops are fertilized), help reduce erosion and provide the farmer with additional food or income, without reducing cassava yields too seriously (Leihner, 1983).

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

Inoculation with mycorrhizas

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

Soils, however, differ in both quantity and quality of native mycorrhizae and, thus, in the crop’s responses to P application (Sieverding and Howeler, 1985; Howeler *et al*., 1987). Of many VAM species tested, *Glomus manihotis* was one of the most effective species for increasing cassava growth and yield in acid soils. *G. manihotis* was also found to compete strongly with other VAM species in the range of 50–200 kg ha^{-1} of applied P. Inoculation with *G. manihotis* markedly increased cassava growth in greenhouse experiments using sterilized soils. The effect was significant but less dramatic in non-sterilized soil. When plots in the field were sterilized with methyl bromide to kill the native VAM in the topsoil, re-inoculation of the soil with VAM markedly improved initial plant growth (Fig. 7.10). Non-inoculated plants grew poorly, showing clear symptoms of P deficiency. Once the roots of these non-inoculated plants reached the non-sterilized subsoil, however, they soon became infected with VAM and recuperated. In Quilichao, Colombia, which has a highly effective native VAM population dominated by *G.*

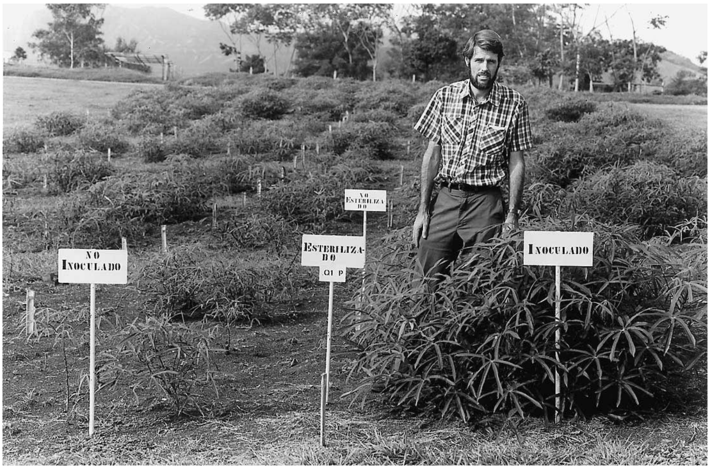

Fig. 7.10. Comparison of plants inoculated with vesicular–arbuscular mycorrhizas (VAM); (right) and non-inoculated plants in plots previously sterilized with methyl bromide.

manihotis, non-inoculated plants in the sterilized plots attained as high yields as those in the unsterilized soil. Inoculated plants growing in the sterilized soil produced 40% higher yields (Howeler *et al*., 1982b). In other experiments at Quilichao, soil sterilization markedly reduced yields, but inoculation of plants growing in unsterilized soil did not increase yields because of the highly effective native VAM population.

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

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

References

Abruña, F., Perez-Escolar, R., Vicente-Chandler, J., Figarella, J. and Silva, S. (1974) Response of green beans to acidity factors in six tropical soils. *Journal of Agriculture* (University of Puerto Rico) 58(1), 44–58.

Acosta, J.R. and Perez, G.J. (1954) Abonamiento en yuca. *Suelo Tico* (*Costa Rica*) 7, 300–308.

Amarasiri, S.L. and Perera, W.R. (1975) Nutrient removal by crops growing in the dry zone of Sri Lanka. *Tropical Agriculturist* 131, 61–70.

Anon. (1952) Le manioc. *Recherche Agronomique de Madagascar* 1, 49–52.

Anon. (1953) Essais de fumure du manioc. *Recherche Agronomique de Madagascar. Compte Rendu* 2, 85–88.

Asher, C.J., Edwards, D.G. and Howeler, R.H. (1980) *Nutritional Disorders of Cassava (*Manihot esculenta *Crantz)*. University of Queensland, St Lucia, Queensland, Australia.

Ashokan, P.K. and Sreedharan, C. (1980) Effect of potash on growth; yield and quality of tapioca variety H. 97. In: *Proceedings National Seminar on Tuber Crops Production Technology*, Tamil Nadu

Agricultural University, Coimbatore, Tamil Nadu, India, pp. 78–80.

Blin, H. (1905) La fumure du manioc. *Bulletin Economique de Madagascar* 3, 419–421.

Cadavid, L.F. (1988) *Respuesta de la yuca (*Manihot esculenta *Crantz) a la aplicacion de NPK en suelos con diferentes características*. Monograph, Universidad Nacional de Colombia, Palmira, Colombia.

Cadavid, L.F., El-Sharkawy, M.A., Acosta, A. and Sanchez, T. (1998) Long-term effects of mulch, fertilization and tillage on cassava grown in sandy soils of northern Colombia. *Field Crops Research* 57, 45–56.

CTCRI (1972) *Annual Report 1971*. CTCRI, Trivandrum, India.

CTCRI (1974) *Annual Report 1973*. CTCRI, Trivandrum, India.

CTCRI (1975) *Annual Report 1974*. CTCRI, Trivandrum, India.

CIAT (1976) *Annual Report for 1975*. CIAT, Cali, Colombia.

CIAT (1977) *Annual Report for 1976*. CIAT, Cali, Colombia.

CIAT (1978) *Annual Report for 1977*. CIAT, Cali, Colombia.

CIAT (1979) *Annual Report for 1978*. CIAT, Cassava program. Cali, Colombia, pp. A76–84.

CIAT (1980) Cassava program. *Annual Report for 1979*. CIAT, Cali, Colombia.

CIAT (1982) Cassava program. *Annual Report for 1981*. CIAT, Cali, Colombia.

CIAT (1985a) Cassava program. *Annual Report for 1982 and 1983*. CIAT, Cali, Colombia.

CIAT (1985b) Cassava program. *Annual Report for 1984*. Working Document No. 1. CIAT, Cali, Colombia.

CIAT (1988a) Cassava program. *Annual Report for 1985*. Working Document No. 38. CIAT, Cali, Colombia.

CIAT (1988b) Cassava program. *Annual Report for 1986*. Working Document No. 43. CIAT, Cali, Colombia.

CIAT (1998) *Improving Agricultural Sustainability in Asia. Integrated Crop-Soil Management for Sustainable Cassava-Based Production Systems.* End-of-Project Report, 1994–1998 submitted to the Nippon Foundation. CIAT, Cali, Colombia.

Chan, S.K. (1980) Long-term fertility considerations in cassava production. In: Weber, E.J., Toro, J.C. and Graham, M. (eds) *Workshop on Cassava Cultural Practices*, Salvador, Bahia, Brazil, 18–21 March, IDRC-151e, pp. 82–92.

Chew, W.Y. (1971) The performance of tapioca, sweet potato and ginger on peat at the Federal Experiment Station, Jalan Kebun, Selangor. Agronomy Branch, Division of Agriculture, Kuala Lumpur, Malaysia.

Chew, W.Y., Ramli, K. and Joseph, K.T. (1978) Copper deficiency of cassava (*Manihot esculenta* Crantz) on Malaysian peat soil. *MARDI Research Bulletin* 6(2), 208–213.

Cock, J.H. (1975) Fisiología de la planta y desarrollo. In: *Curso sobre Produccion de Yuca*. Instituto Colombiano Agropecuario, Regional 4, Medellín, Colombia.

Cong Doan Sat and Deturck, P. (1998) Cassava soils and nutrient management in South Vietnam. In: Howeler, R.H. (ed.) *Cassava Breeding, Agronomy and Farmer Participatory Research in Asia*, Proceedings 5th Regional Workshop, Danzhou, Hainan, China, 3–8 November 1996, pp. 257–267.

Cours, G., Fritz, J. and Ramahadimby, G. (1961) El diagnóstico felodérmico de la mandioca. *Fertilité* 12, 3–20.

Diniz, M. de S., Gomes C. J. de and Caldas, R.C. (1994) Sistemas de adubação na cultura da mandioca. *Revista Brasileira de Mandioca* (Cruz das Almas, Bahia, Brazil) 13, 157–160.

Edwards, D.G. and Kang, B.T. (1978) Tolerance of cassava (*Manihot esculenta* Crantz) to high soil acidity. *Field Crops Research* 1, 337–346.

EMBRAPA, CNPMF (1981) *Relatória Técnico Annual. Projecto de Mandioca*. Cruz das Almas, Bahia, Brazil, pp. 119–167.

EMBRAPA, CNPMF (1984) *Relatória Técnico Annual do CNPMF 1983*. Cruz das Almas, Bahia, Brazil.

FAO (1980) *Review of Data on Responses of Tropical Crops to Fertilizers, 1961–1977*. FAO, Rome, Italy.

Forno, D.A. (1977) The mineral nutrition of cassava (*Manihot esculenta* Crantz) with particular reference to nitrogen. PhD thesis. University of Queensland, St Lucia, Queensland, Australia.

Fox, R.H., Talleyrand, H. and Scott, T.W. (1975) Effect of nitrogen fertilization on yields and nitrogen content of cassava, Llanera cultivar. *Journal of Agriculture* (University of Puerto Rico) 56, 115–124.

Goepfert, C.F. (1972) Experimento sobre o efeito residual da adubação fosfatada em feijoeiro (*Phaseolus vulgaris*). *Agronomia Sulriograndense* 8, 41–47.

Gomes, C.J. de (1998) *Adubação de mandioca*. Curso Internacional de Mandioca para Países Africanos de Lingua Portuguesa. Cruz das Almas, Bahia, Brazil, 13–30 April.

Gomes, C.J. de and Ezeta, F.N. (1982) Nutrição e adubação potássica da mandioca no Brasil. In: *Anais de Simpósio Sobre Potássio na Agricultura Brasileira*, Londrina, Paraná. Instituto da Potassa/IAPAR, Piracicaba, SP, Brazil, pp. 487–502.

Gomes, C.J. de, Souza, R.F., Rezende, J. de O. and Lemos, L.B. (1973) Efeitos de N, P, K, S, micronutrientes e calagem na cultura de mandioca. *Boletim Técnico 20*. Instituto de Pesquisa Agropecuária do Leste (IPEAL). Cruz das Almas, Bahia, Brazil, pp. 49–67.

Gomes, C.J. de, Carvalho, P.C.L. de, Carvalho, F.L.C. and Rodrigues, E.M. (1983) Adubação orgânico na recuperação de solos de baixa fertilidade com o cultivo da mandioca. *Revista Brasileira de Mandioca* (Cruz das Almas, Bahia, Brazil) 2(2), 63–76.

Gunatilaka, A. (1977) Effects of aluminium concentration on the growth of corn, soybean, and four tropical root crops. MSc thesis. University of Queensland, St. Lucia, Queensland, Australia.

Hagens, P. and Sittibusaya, C. (1990) Short and long term aspects of fertilizer applications on cassava in Thailand. In: Howeler, R.H. (ed.) *Proceedings 8th Symposium International Society of Tropical Root Crops*, Bangkok, Thailand, 30 October–5 November, 1988, pp. 244–259.

Howeler, R.H. (1978) The mineral nutrition and fertilization of cassava. In: *Cassava Production Course*. CIAT, Cali, Colombia, pp. 247–292.

Howeler, R.H. (1980a) The effect of mycorrhizal inoculation on the phosphorus nutrition of cassava. In: Weber, E.J., Toro, J.C. and Graham, M. (eds) *Cassava Cultural Practices*, Proceedings Workshop, Salvador, Bahia, Brazil, 18–21 March, International Development Research Centre (IDRC) 151e, Ottawa, Canada, pp. 131–137.

Howeler, R.H. (1980b) Soil-related cultural practices for cassava. In: Weber, E.J., Toro, J.C. and Graham, M. (eds) *Cassava Cultural Practices*, Proceedings Workshop, Salvador, Bahia, Brazil, 18–21 March, IDRC 151e, Ottawa, Canada, pp. 59–69.

Howeler, R.H. (1981) *Mineral Nutrition and Fertilization of Cassava*. Series 09EC-4, CIAT, Cali, Colombia.

Howeler, R.H. (1983) *Análisis del Tejido Vegetal en el Diagnóstico de Problemas Nutricionales: Algunos Cultivos Tropicales*. CIAT, Cali, Colombia.

Howeler, R.H. (1985a) Mineral nutrition and fertilization of cassava. In: *Cassava; Research, Production and Utilization*. UNDP-CIAT Cassava Program, Cali, Colombia, pp. 249–320.

Howeler, R.H. (1985b) Potassium nutrition of cassava. In: *Potassium in Agriculture*. International Symposium, Atlanta, GA, 7–10 July. ASA, CSSA, SSSA, Madison, Wisconsin, USA, pp. 819–841.

Howeler, R.H. (1986) El control de la erosión con prácticas agronómicas sencillas. *Suelos Ecuatoriales* 16, 70–84.

Howeler, R.H. (1987) Soil conservation practices in cassava-based cropping systems. In: Tay, T.H., Mokhtaruddin, A.M. and Zahari, A.B. (eds) *Proceedings International Conference Steepland Agriculture in the Humid Tropics*, Kuala Lumpur, Malaysia, 17–21 August, pp. 490–517.

Howeler, R.H. (1989) Cassava. In: Plucknett, D.L. and Sprague, H.B. (eds) *Detecting Mineral Deficiencies in Tropical and Temperate Crops*. Westview Press. Boulder, Colorado, pp. 167–177.

Howeler, R.H. (1990) Phosphorus requirements and management of tropical root and tuber crops. In: *Proceedings Symposium on Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania*. IRRI, Los Baños, Philippines. 6–10 March, 1989, pp. 427–444.

Howeler, R.H. (1991a) Identifying plants adaptable to low pH conditions. In: Wright, R.J., Baligar, V.C. and Murrmann, R.P. (eds) *Plant-Soil Interactions at Low pH*. Kluwer Academic, The Netherlands, pp. 885–904.

Howeler, R.H. (1991b) Long-term effect of cassava cultivation on soil productivity. *Field Crops Research* 26, 1–18.

Howeler, R.H. (1992) Agronomic research in the Asian Cassava Network – an overview, 1987–1990. In: Howeler, R.H. (ed.) *Cassava Breeding, Agronomy and Utilization Research in Asia*, Proceedings 3rd Regional Workshop, Malang, Indonesia, 22–27 October 1990, pp. 260–285.

Howeler, R.H. (1994) Integrated soil and crop management to prevent environmental degradation in cassava-based cropping systems in Asia. In: Bottema, J.W.T. and Stoltz, D.R. (eds) *Upland Agriculture in Asia*, Proceedings Workshop, Bogor, Indonesia, 6–8 April 1993, pp. 195–224.

Howeler, R.H. (1995) Agronomy research in the Asian Cassava Network – towards better production without soil degradation. In: Howeler, R.H. (ed.) *Cassava Breeding, Agronomy Research and Technology Transfer in Asia*. Proceedings 4th Regional Workshop, Trivandrum, Kerala, India, 2–6 November 1993, pp. 368–409.

Howeler, R.H. (1996a) Diagnosis of nutritional disorders and soil fertility maintenance of cassava. In: Kurup, G.T., Polaniswami, M.S., Potty, V.P., Padmaja, G., Kabeerathumma, S. and Pillai, S.V. (eds) *Tropical Tuber Crops: Problems, Prospects and Future Strategies*. Oxford and IBH Publishing Co., New Delhi, India, pp. 181–193.

Howeler, R.H. (1996b) Mineral nutrition of cassava. In: Craswell, E.T., Asher, C.J. and O'Sullivan, J.N. (eds) *Mineral Nutrient Disorders of Root Crops in the Pacific*. Proceedings Workshop, Nuku'alofa, Kingdom of Tonga, 17–20 April 1995, ACIAR Proceedings no. 5, Canberra, Australia, pp. 110–116.

Howeler, R.H. (1998) Cassava agronomy research in Asia – an overview, 1993–1996. In: Howeler, R.H. (ed.) *Cassava Breeding, Agronomy and Farmer Participatory Research in Asia*. Proceedings 5th Regional Workshop, Danzhou, Hainan, China, 3–8 November 1996, pp. 355–375.

Howeler, R.H. (2000) Cassava production practices – can they maintain soil productivity? In: Howeler, R.H., Oates, C.G. and O'Brien, G.M. (eds) *Cassava, Starch and Starch Derivatives*, Proceedings of an International Symposium, Nanning, Guangxi, China, 11–15 November 1996. pp. 101–117.

Howeler, R.H. and Cadavid, L.F. (1983) Accumulation and distribution of dry matter and nutrients during a 12-month growth cycle of cassava. *Field Crops Research* 7, 123–139.

Howeler, R.H. and Cadavid, L.F. (1990) Short- and long-term fertility trials in Colombia to determine the nutrient requirements of cassava. *Fertilizer Research* 26, 61–80.

Howeler, R.H. and Fernandez, F. (1985) *Nutritional Disorders of the Cassava Plant. Study Guide*. CIAT, Cali, Colombia.

Howeler, R.H. and Medina, C.J. (1978) *La fertilización en el frijol* Phaseolus vulgaris*: elementos mayores y secundarios*. Revisión de la literatura para el Curso de Producción de Frijol. CIAT, Cali, Colombia.

Howeler, R.H. and Sieverding, E. (1983) Potentials and limitations of mycorrhizal inoculation illustrated by experiments with field grown cassava. *Plant and Soil* 75, 245–261.

Howeler, R.H., Cadavid, L.F. and Calvo, F.A. (1977) The interaction of lime with minor elements and phosphorus in cassava production. In: *Proceedings 4th Symposium International Society of Tropical Root Crops*, Cali, Colombia. IDRC, Ottawa, Canada, pp. 113–117.

Howeler, R.H., Edwards, D.G. and Asher, C.J. (1981) Application of the flowing solution culture techniques to studies involving mycorrhizas. *Plant and Soil* 59, 179–183.

Howeler, R.H., Asher, C.J. and Edwards, D.G. (1982a) Establishment of an effective endomycorrhizal association in cassava in flowing solution culture and its effect on phosphorus nutrition. *New Phytologist* 90, 229–238.

Howeler, R.H., Cadavid, L.F. and Burckhardt, E. (1982b) Response of cassava to VA mycorrhizal inoculation and phosphorus application in greenhouse and field experiments. *Plant and Soil* 69, 327–339.

Howeler, R.H., Edwards, D.G. and Asher, C.J. (1982c) Micronutrient deficiencies and toxicities of cassava plants grown in nutrient solutions. I. Critical tissue concentrations. *Journal of Plant Nutrition* 5, 1059–1076.

Howeler, R.H., Sieverding, E. and Saif, S. (1987) Practical aspects of mycorrhizal technology in some tropical crops and pastures. *Plant and Soil* 100, 249–283.

Howeler, R.H., El-Sharkawy, M.A. and Cadavid, L.F. (2002a) The use of grain and forage legumes for soil fertility maintenance and erosion control in cassava in Colombia (in press).

Howeler, R.H., Oates, C.G. and Costa Allem, A.C. (2002b) *Strategic Assessment on the Impact of Small-holder Cassava Production and Processing on the Environment and Biodiversity*. International Fund for Agricultural Development (IFAD), Rome, Italy (in press).

Howeler, R.H., Thai Phien and Nguyen the Dang (2002) Sustainable cassava production on sloping lands in Vietnam. *Proceedings of International Workshop on Sustainable Land Management in the Northern Mountainous Region of Vietnam.* Hanoi, Vietnam (in press).

Hulugalle, N.R., Lal, R. and Gichuru, M. (1991) Effect of five years of no-tillage and mulch on soil properties and tuber yield of cassava on an acid ultisol in southeastern Nigeria. *IITA Research* 1, 13–16.

Islam, A.K.M.S., Edwards, D.G. and Asher, C.J. (1980) pH optima for crop growth: results of flowing culture experiment with six species. *Plant and Soil* 54(3), 339–357.

Jintakanon, S., Edwards, D.G. and Asher, C.J. (1982) An anomalous, high external phosphorus requirement for young cassava plants in solution culture. In: *Proceedings 5th International Symposium Tropical Root Crops*, Manila, Philippines, 17–21 September 1979, pp. 507–518.

Jones, U.S., Katyal, J.C., Mamaril, C.P. and Park, C.S. (1982) Wetland-rice nutrient deficiencies other than nitrogen. In: *Rice Research Strategies for the Future*. IRRI, Los Baños, Philippines, pp. 327–378.

Kabeerathumma, S., Mohankumar, B., Mohankumar, C.R., Nair, G.M., Prabhakar, M. and Pillai, N.G. (1990) Long range effect of continuous cropping and manuring on cassava production and fertility status of soil. In: Howeler, R.H. (ed.) *Proceedings 8th Symposium International Society of Tropical Root Crops*, Bangkok, Thailand, 30 October–5 November 1988, pp. 259–269.

Kang, B.T. (1984) Potassium and magnesium responses of cassava grown in ultisol in southern Nigeria. *Fertilizer Research* 5, 403–410.

Kang, B.T. and Okeke, J.E. (1984) Nitrogen and potassium responses of two cassava varieties grown on an alfisol in southern Nigeria. In: *Proceedings 6th Symposium International Society of Tropical Root Crops*, Lima, Peru, 21–26 February 1983, pp. 231–237.

Kang, B.T., Islam, R., Sanders, F.E. and Ayanaba, A. (1980) Effect of phosphate fertilization and inoculation with VA-mycorrhizal fungi on performance of cassava (*Manihot esculenta*, Crantz) grown on an alfisol. *Field Crops Research* 3, 83–94.

Kasele, I.N. (1980) Investigation on the efffect of shading, potassium and nitrogen and drought on the development of cassava tuber at the early stage of plant growth. MSc thesis, University of Ibadan. Ibadan, Nigeria.

Krochmal, A. and Samuels, G. (1970) The influence of NPK levels on the growth and tuber development of cassava in tanks. *CEIBA* 16, 35–43.

Leihner, D. (1983) *Management and Evaluation of Intercropping Systems with Cassava*. CIAT, Cali, Colombia.

Lozano, J.C., Bellotti, A., Reyes, J.A., Howeler, R., Leihner, D. and Doll, J. (1981) *Field Problems in Cassava*. CIAT Series No. 07EC-1, Cali, Colombia.

Margolis, E. and Campos Filho, O.R. (1981) Determinação dos fatores da equação universal de perdas de solo num podzólico vermelho amarelo de Glória do Goitá. In: *Anais do 3rd Encontro Nacional de Pesquisa Sobre Conservação do Solo*, Rengife, Pernambuco, Brazil, 28 July–1 August 1980, pp. 239–250.

Moraes, O. de, Mondardo, E., Vizzotto, J. and Machado, M.O. (1981) *Adubação quimica e calagem da mandioca*. Boletim Técnico No.8. Empresa Catarinense de Pesquisa Agropecuâria. Florianopolis, Santa Catarina, Brazil.

Muhr, L., Leihner, D.E., Hilger, T.H. and Müller-Sämann, K.M. (1995) Intercropping of cassava with herbaceous legumes. II. Yields as affected by below-ground competition. *Angewandte Botanik* 69, 22–26.

Nair, P.G., Mohankumar, B., Prabhakar, M. and Kabeerathumma, S. (1988) Response of cassava to graded doses of phosphorus in acid lateritic soils of high and low P status. *Journal of Root Crops* 14(2), 1–9.

Nayar, T.V.R., Kabeerathumma, S., Potty, V.P. and Mohankumar, C.R. (1995) Recent progress in cassava agronomy in India. In: Howeler, R.H. (ed.) *Cassava Breeding, Agronomy Research and Technology Transfer in Asia*. Proceedings 4th Regional Workshop, Trivandrum, Kerala, India, 2–6 November 1993, pp. 61–83.

Ngongi, A.G.N., Howeler, R.H. and MacDonald, H.A. (1977) Effect of potassium and sulphur on growth, yield, and composition of cassava. In: *Proceedings 4th Symposium International Society of Tropical Root Crops*, Cali, Colombia, 1–7 August 1976. IDRC, Ottawa, Canada, pp. 107–113.

Nguyen Huu Hy, Pham Van Bien, Nguyen The Dang and Thai Phien (1998) Recent progress in cassava agronomy research in Vietnam. In: Howeler, R.H. (ed.) *Cassava Breeding, Agronomy and Farmer Participatory Research in Asia*. Proceedings 5th Regional Workshop, Danzhou, Hainan, China, 3–8 November 1996, pp. 235–256.

Nguyen Tu Siem (1992) Organic matter recycling for soil improvement in Vietnam. In: *Proceedings 4th Annual Meeting*, IBSRAM Asialand Network.

Nijholt, J.A. (1935) *Opname van voedingsstoffen uit den bodem bij cassave* [Absorption of nutrients from the soil by a cassava-crop]. Buitenzorg. Algemeen Proefstation voor den Landbouw. Korte Mededeelingen No. 15.

Normanha, E.S. and Pereira, A.S. (1950) Aspectos agronômicos da cultura da mandioca (*Manihot utilissima* Pohl). *Bragantia* (Campinas, SP, Brazil) 10, 179–202.

Nunes, W.O., de, Brito, D.P.P.S., de, Meneguelli, C.A., Arruda, N.B. de and Oliveira, A.B. de (1974) Resposta da mandioca a adubação mineral e métodos de aplicação do potássio em solos de baixa fertilidade. *Pesquisa Agropecuária Brasileira* (*Série Agronomia*) (Rio de Janeiro, Brazil) No. 9, pp. 1–9.

Obigbesan, G.O. (1973) The influence of potassium nutrition on the yield and chemical composition of some tropical root and tuber crops. In: *10th Coloquium International Potash Institute*, Abidjan, Ivory Coast, pp. 439–451.

Obigbesan, G.O. (1977) Investigations on Nigerian root and tuber crops: effect of potassium on starch yield, HCN content and nutrient uptake of cassava cultivars (*Manihot esculenta*). *Journal of Agricultural Science* 89, 29–34.

Obigbesan, G.O. and Fayemi, A.A.A. (1976) Investigations on Nigerian root and tuber crops: influence of nitrogen fertilization on the yield and chemical composition of two cassava cultivars (*Manihot esculenta*). *Journal of Agricultural Science* 86, 401–406.

Ofori, C.S. (1973) Decline in fertility status of a tropical forest ochrosol under continuous cropping. *Experimental Agriculture* 9, 15–22.

Okogun, J.A., Sanginga, N. and Adeola, E.O. (1999) *Soil Fertility Maintenance and Strategies for Cassava Production in West and Central Africa*. IITA, Ibadan, Nigeria (mimeograph).

Orlando Filho, J. (1985) Potassium nutrition of sugarcane. In: Bishop, W.D. *et al*. (eds) *Potassium in Agriculture*. ASA-CSSA-SSSA, Madison, Wisconsin, pp. 1045–1062.

Paula, M.B. de, Nogueira, F.D. and Tanaka, R.T. (1983) Nutrição mineral da mandioca: absorção de nutrientes e produção de materia seca por duas cultivares de mandioca. *Revista Brasileira de Mandioca, Cruz das Almas*, 31–50.

Payne, H. and Webster, D.C. (1956) The toxicity of cassava varieties on two Jamaican soil types of differing K status. Ministry of Agriculture and Fisheries. Crop Agronomy Division, Kingston, Jamaica.

Pellet, D. and El-Sharkawy, M.A. (1993a) Cassava varietal response to phosphorus fertilization. I. Yield, biomass and gas exchange. *Field Crops Research* 35, 1–11.

Pellet, D. and El-Sharkawy, M.A. (1993b) Cassava varietal response to phosphorus fertilization. II. Phosphorus uptake and use efficiency. *Field Crops Research* 35, 13–20.

Phommasack, T., Sengtaheuanghung, O. and Phanthaboon, K. (1995) The management of sloping lands for sustainable agriculture in Laos. In: Sajjapongse, A. and Elliot, C.R. (eds) *The Management of Sloping Lands for Sustainable Agriculture in Asia*, (Phase 2, 1992–1994). IBSRAM/Asialand Network Doc. no. 12. IBSRAM, Bangkok, Thailand, pp. 87–101.

Phommasack, T., Sengtaheuanghung, O. and Phanthaboon, K. (1996) The management of sloping lands for sustainable agriculture in Laos. In: Sajjapongse, A. and Leslie, R.N. (eds) *The Management of Sloping Lands in Asia.* IBSRAM/Asialand Network Doc. no. 20. IBSRAM, Bangkok, Thailand, pp. 109–136

Prevot, P. and Ollagnier, M. (1958) La fumure potassique dans les regions tropicales et subtropicales. In: *Potassium Symposium*, Berne, Switzerland, pp. 277–318.

Putthacharoen, S., Howeler, R.H., Jantawat, S. and Vichukit, V. (1998) Nutrient uptake and soil erosion losses in cassava and six other crops in a Psamment in eastern Thailand. *Field Crops Research* 57, 113–126.

Queiroz, G.M. de and Pinho, J.L.N. de (1981) Resultados do experimento efeito da fertilização com macronutrientes NPK em mandioca no Estado do Ceará. EPACE. Pacajús, Ceará, Brazil.

Queiroz, G.M. de, Pinho, J.L.N. de, Lima, A.R.C. da and Verde, N.G.L. (1980) Efeito da fertilização com macronutrientes NPK em mandioca (*Manihot esculenta* Crantz) no Estado do Ceará. In: EPACE, *Relatório Annual de Pesquisa Fitotécnica*. Fortaleza, Ceará, Brazil, pp. 83–96.

Quintiliano, J., Margues, A., Bertoni, J. and Barreto, G.B. (1961) Perdas por erosão no estado de São Paulo. *Brigantia* 20(2), 1143–1182.

Richards, I.R. (1979) Response of tropical crops to fertilizer under farmers conditions – analysis of results of the FAO Fertilizer Programme. *Phosphorus in Agriculture* 76, 147–156.

Rio Grande do Norte (1976) Pesquisa e experimentação com culturas alimentares: mandioca, 1971–1975. *Secretaria da Agricultura.* Rio Grande do Norte, Brazil.

Roberts, S. and McDole, R.E. (1985) Potassium nutrition of potatoes. In: Bishop, W.D. *et al.* (eds) *Potassium in Agriculture*. International Symposium, Atlanta, Georgia, 7–10 July. ASA-CSSA-SSSA, Madison, Wisconsin, pp. 800–818.

Roche, P., Velly, J. and Joliet, B. (1957) Essai de determination des seuils de carence en potasse dans le sol et dans les plantes. *Revue de la Potasse* 1957, 1–5.

Ruppenthal, M. (1995) *Soil Conservation in Andean Cropping Systems*. Hohenheim Tropical Agriculture Series no. 3, Hohenheim University, Germany.

Ruppenthal, M., Leihner, D.E., Steinmuller, N. and El-Sharkawy, M.A. (1997) Losses of organic matter and nutrients by water erosion in cassava-based cropping systems. *Experimental Agriculture* 33, 487–498.

Santos, Z.G. dos and Tupinamba, E.A. (1981) Resultados do experimento de niveis e fontes de fósforo na produção de mandioca (*Manihot esculenta* Crantz). EMBRAPA-UEPAE, Aracaju, Sergipe, Brazil.

Sieverding, E. and Howeler, R.H. (1985) Influence of species of VA mycorrhizal fungi on cassava yield response to phosphorus fertilization. *Plant and Soil* 88, 213–222.

Silva, J.R. da and Freire, E.S. (1968) Efeitos de doses crescentes de nitrogênio, fósforo e potássio sobre a produção de mandioca em solos de baixa e alta fertilidade. *Brigantia* (*Campinas, SP, Brazil*) 27 (29), 357–364.

Silva, L.G. (1970) Adubação NPK na cultura da mandioca em Tabuleiró Costeiro no estado da Paraiba. *Pesquisas Agropecuárias no Nordeste* 2(1), 73–75.

Silva, L.G., Souza, J.B. de, Silva, J.C. da and Lucas, A.P. de (1969) Ação de macronutrientes e manganês na cultura da mandioca em solos de tabuleiros costeiros do Nordeste. SUDENE, Recife. Pernambuco, Brazil.

Sittibusaya, C. (1993) [*Progress report of soil research on fertilization of field crops, 1992*]. Annual Cassava Program Review, Rayong, Thailand, 19–20 January 1993 [in Thai].

Sobral, L.F., Barreto, A.C., Siqueira, L.A., Santos, Z.G. dos, Souza, R.F., Rezende, J.O. de and Ribeiro, J.V. (1976) Efeitos de macro e micronutrientes em produção da mandioca (*Manihot esculenta* Crantz). *Comunicado Técnico, 1.* EMBRAPA-Rep. No Estado de Sergipe, Aracaju, Sergipe, Brazil.

Souza, L.D., Gomes C.J. de and Caldas, R.C. (1992) Interação vinhoto, calage, e fósforo na cultura da mandioca no Norte de Mato Grosso. *Revista Brasileira de Mandioca* 11(2), 148–155.

Spain, J.M., Francis, C.A., Howeler, R.H. and Calvo, F. (1975) Differential species and varietal tolerance to soil acidity in tropical crops and pastures. In: Bosnemisza, E. and Alvarado, A. (eds) *Soil*

Management in Tropical America. North Carolina State University, Raleigh, North Carolina, pp. 308–329.

Spear, S.N., Asher, C.J. and Edwards, D.G. (1978a) Response of cassava, sunflower, and maize to potassium concentration in solution. I. Growth and plant potassium concentration. *Field Crops Research* 1, 347–361.

Spear, S.N., Edwards, D.G. and Asher, C.J. (1978b) Response of cassava, sunflower, and maize to potassium concentration in solution. III. Interactions between potassium, calcium, and magnesium. *Field Crops Research* 1, 375–389.

Stephens, D. (1960) Fertilizer trials on peasant farms in Ghana. *Empire Journal of Experimental Agriculture* 109, 1–22.

Takyi, S.K. (1972) Effects of potassium, lime and spacing on yields of cassava (*Manihot esculenta* Crantz). *Ghana Journal of Agricultural Science* 5(1), 39–42.

Tongglum, A., Vichukit, V., Jantawat, S., Sittibusaya, C., Tiraporn, C., Sinthuprama, S. and Howeler, R.H. (1992) In: Howeler, R.H. (ed.) *Cassava Breeding, Agronomy and Utilization Research in Asia*. Proceedings 3rd Regional Workshop, Malang, Indonesia, 22–27 October 1990, pp. 199–223.

Tongglum, A., Pornpromprathan, V., Paisarncharoen, K., Wongwitchai, C., Sittibusaya, C., Jantawat, S., Nual-on, T. and Howeler, R.H. (1998) Recent progress in cassava agronomy research in Thailand. In: Howeler, R.H. (ed.) *Cassava Breeding, Agronomy and Farmer Participatory Research in Asia*. Proceedings 5th Regional Workshop, Danzhou, Hainan, China, 3–8 November 1996, pp. 211–234.

Vijayan, M.R. and Aiyer, R.S. (1969) Effect of nitrogen and phophorus on the yield and quality of cassava. *Agricultural Research Journal of Kerala* 7, 84–90.

Vinod, G.S. and Nair, V.M. (1992) Effect of slow-release nitrogenous fertilizers on the growth and yield of cassava. *Journal of Root Crops* 18, 124–125.

Wargiono, J., Kushartoyo, Suyamto, H. and Guritno, B. (1998) Recent progress in cassava agronomy research in Indonesia. In: Howeler, R.H. (ed.) *Cassava Breeding, Agronomy and Farmer Participatory Research in Asia*. Proceedings 5th Regional Workshop, Danzhou, Hainan, China, 3–8 November 1996, pp. 307–330.

Zaag, P. van der (1979) The phosphorus requirements of root crops. PhD thesis, University of Hawaii, Hawaii.

Zangrande, M.B. (1981) Resultados do experimento estudo de níveis de NPK para a cultura da mandioca (*Manihot esculenta* Crantz) no Estado do Espírito Santo, EMCAPA. Cariacica, ES, Brazil.

Zhang Weite, Lin Xiong, Li Kaimian, Huang Jie, Tian Yinong, Lee Jun and Fu Quohui (1998) Cassava agronomy research in China. In: Howeler, R.H. (ed.) *Cassava Breeding, Agronomy and Farmer Participatory Research in Asia*. Proceedings 5th Regional Workshop, Danzhou, Hainan, China, 3–8 November 1996, pp. 191–210.