Nutrient Cycling in Agroecosystems **71**: 151–162, 2005.
DOI 10.1007/s10705-004-1803-9

Identification of nutrients limiting cassava yield maintenance on a sedimentary soil in southern Benin, West Africa

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Received 19 December 2003; accepted in revised form 29 July 2004

Key words: Fertilizer response, Marginal rate of return, Nutrient balance calculation, Soil properties

Abstract

Market opportunities will drive intensification of cassava production and fertilizer will play a role in this. A trial was initiated on 15 farmers' fields (replications) in one village territory in Benin on a relatively fertile sedimentary soil site to identify nutrients limiting cassava yield using nutrient omission plots over three cropping years. There was no response to fertilizer in the first year when fresh root yields in the unamended control averaged 19.1 t ha^{-1}. In the second year, the control yield was 16 t ha^{-1} and there were significant reductions from withholding P (3.5 t ha^{-1}) and K (2 t ha^{-1}) from a complete fertilizer regime. Nutrient balance after 1 and 2 years (cumulative) showed substantial P and K deficits in unamended plots. In the third year, the control yield was 12.9 t ha^{-1} and effects of withholding K (5.3 t ha^{-1}), P (5.0 t ha^{-1}) and N (3.0 t ha^{-1}) were statistically significant. Soil K was a significant source of variation in yield in the third year. In the third year of annual nutrient additions soil P and K in the top 0.3 m were increased by 37 and 40%, respectively. Based on the cumulative nutrient balance calculation, the annual application needed to compensate nutrient depletion was 13 kg N, 10 kg P, and 60 kg K ha^{-1}. Partial budget analysis based on these amounts of fertilizer suggested that investment was clearly justified in the third year of continuous cropping at current low cassava prices.

Introduction

Cassava (*Manihot esculenta* Crantz) is an important commodity for income generation and food security in Africa. Recently it has been recognized that cassava has considerable commercial potential both domestically and internationally (Nweke et al. 2002). In addition to the usual root flours and meals, domestic products include snacks, starch, green leaves for human and livestock feed. Possible world market products include alcohol, starch, gari, tapioca, and dried chips (FAO/IFAD 2001). Benin has recognized the potential benefit of increased cassava production for food security and income generation and has initiated several large development projects.

While increased production of cassava in response to commercialization is an opportunity, there are accompanying threats to ecological sustainability. As land use intensifies, there are increased risks of nutrient mining and soil degradation. At the farm level the restoration of soil fertility has become the most pressing issue and fertilizer has an important role to play (Carr 2001).

While cassava is regarded as a crop that does not demand fertile soil, it still depletes the soil of nutrients. A nutrient balance study conducted in the Mono Division of southern Benin, for example, showed that land under cassava on sedimentary soil plateau sites was undergoing a net loss of 11 kg N, 6 kg K, and 4 kg Ca ha^{-1} an^{-1} (Van der Pol et al. 1993[1]). The sedimentary soil plateaus occupy approximately 5320 km^2 in southern Benin (INRAB 1997) and a similar area in southern Togo and southwestern Nigeria. But their importance is disproportional because they support higher human population densities than other physiographic zones. Densities of 250 to 300 inhabitants km^{-2} are common (Van der Pol et al. 1993). In southern Benin and Togo, these soils, locally called *terre de barre*, have good physical properties but are known to be naturally low in exchangeable K; an element known to be critical for cassava production (Howeler 1985).

Current yield levels of cassava in West Africa are low, averaging approximately 10 t ha^{-1} of fresh roots (FAOSTAT 2003) with 30 to 35% dry matter while cassava varieties with a fresh yield potential of 25 t ha^{-1} (INRAB 1995) and higher (IITA 2001) are available. Such a root yield would export approximately 50 kg of N, 12 kg of P, and 100 kg of K ha^{-1} according to Howeler (1985). Additional amounts are exported in stem cuttings to be used as planting material. A recent review by Howeler (2002) indicated that few fertilizer trials have been conducted with cassava, mainly because very few cassava farmers apply fertilizers. Nweke (1996) estimated that inorganic fertilizers are used on 15 and 28% of cassava fields in Ghana and Nigeria, respectively, but much less in other countries. His multi-country survey and regression analysis indicated that yield on farmers' fields was increased from 11.6 to 15.2 t ha^{-1} by use of fertilizer. Although the cost of fertilizer at village level is relatively high in Africa, Nweke and Spencer (1995) in a study of 285 villages in six African countries showed that fertilizer use on cassava increases as market access improves.

[1]Estimates based on area planted to cassava in the Division, its production, and estimates of relevant terms in the nutrient balance (i.e. losses by exportation, leaching, and erosion; gains through weathering of soil, biological nitrogen fixation, and atmospheric deposition).

In order to increase yields of cassava to realize the potential of the crop without depleting soil stocks, nutrient inputs are needed. But farmers need realistic recommendations and they need to know if their investment will pay off. The first objective of this study was to identify the most probable limiting nutrients over time and to relate these to soil properties. A second objective was to measure the amounts of nutrients exported by the crop, supporting the fertilizer response study with nutrient balance calculations.

Materials and methods

Trials were conducted on farmers' fields in the village of Hayakpa (2°08′ E, 6°33′ N; approx. 150 m above sea level) with typical rainfed agriculture based on maize and cassava with maize being preferred. The rainfall pattern is bimodal with very little rain from 15 November to 15 April and again from 15 July to 15 August. The soil is typical of low-lying plateaus in southern Benin and Togo formed on Quarternary sediments. They are classified as Ferrali-Haplic Acrisols (Stahr et al. 1996) or *sols ferrallitiques moyennement désaturés appauvris* (Raunet 1977). They are deep, and contain no coarse fraction. Surface texture is sandy loam and subsoil is clay loam or clay. They are slightly acid in the surface layer and acid in the subsoil. Floquet and Mongbo (1998) characterised the Hayakpa area as being representative of *terre de barre* plateaus with good agricultural potential as indicated by the presence of some fallow land and higher maize yields (0.76 t ha^{-1} without fertilizer) compared with other plateaus in southern Benin. At the same time, they found indications that soil fertility in the village territory is degrading as indicated by a shift from maize to cassava, decreasing size of land holdings for newer occupants of the zone, and adoption of *Acacia auriculiformis* woodlots. Another stimulus for the shift to cassava is the opportunity to transform and sell *gari* and other products in urban markets (Floquet and Mongbo 1998).

Soil properties to 0.3 m depth were characterized at the beginning of the trial using a composite of at least 12 cores for each field. Initial organic carbon of the 15 fields ranged from 8 to 12 g kg^{-1} and clay content was 100 to 180 g kg^{-1}. Mean Bray-1 P was 6.1 mg kg^{-1} (s.d. 1.6) and mean exchangeable K was 0.13 $cmol_c$ kg^{-1} (s.d. 0.04). Exchangeable Ca was 3.1 $cmol_c$ kg^{-1} (s.d. 0.6). Rainfall was measured daily at two locations in the village within 5 km of each farmers' field.

The trials were established on 15 farmers' fields and managed by the research team. The same treatments were imposed on the same plots every year. Six plots of 10 × 10 m were marked out in each field. Fertilizer treatments were unamended control (0-0-0), fertilized control (N-P-K), missing N (0-P-K), missing P (N-0-K), missing K (N-P-0) and K only (0-0-K). The 0-0-K treatment was included because of the possibility that N application might reduce cassava yields as observed in Cameroon (John Wendt, IITA, personal communication, 1999) and thereby mask the effect of K application. Fertilizer application rates were 60 kg ha^{-1} N as urea, 16 kg ha^{-1} P as triple super phosphate (TSP) and 138 kg ha^{-1} K as muriate of potash (MOP). The amounts of P and K were chosen to exceed the replacement of the nutrients expected to be exported in a dry root yield of 10 t ha^{-1} and associated stems assuming approximately 7 g kg^{-1} N, 1 g kg^{-1} P and 7.5 g kg^{-1} K in the dry roots as summarized by Howeler and Cadavid (1983). Nitrogen application was limited to 60 kg ha^{-1} to avoid potential problems of excessive leaf formation at the expense of root growth (Howeler 2002). The TSP application also supplied 12 to 15 kg ha^{-1} of Ca.

Cassava was planted between mid-May and early June each year (1999, 2000, 2001) in a flat area and without ridges or mounds after a first weed control operation. The variety used – BEN 86052 – is erect and forms two sympodial branches at each fork (INRAB 1995). It is resistant to mosaic virus and green spider mite and tolerant to cassava bacterial blight. Stem cuttings of 0.2 to 0.25 m length were planted at an angle with half of the cutting underground at a spacing of 1.0 × 1.0 m. The TSP and half of the urea and MOP were applied at planting. The fertilizers were placed in 0.05 m deep holes about 0.15 m to each side of the cassava stand and covered with soil. The rest of the urea and MOP were applied in a similar manner 2 months after planting. Fertilizer was applied each year in the same way using the same sources and doses. Plots were kept weed-free throughout the cropping cycles. Pest and disease problems never reached damaging levels during the three seasons of continuous cassava, although there was some mosaic and some anthracnose disease observed in the third season. There was some apparent competition between cassava and surrounding fallow vegetation and this was avoided by shifting harvest areas away from the affected rows, maintaining the minimum number of harvested cassava stands at 24 per plot.

Harvest of cassava is normally done at 11 to 12 months after planting (MAP) at the beginning of the wet season because the early rains loosen the soil for easy harvest. Sampling for nutrient concentrations was done at 9 months after planting, *i.e.*, before the rains, so that potassium would not be leached from leaves as this element is known to be easily leached from vegetation (Norgrove et al. 2000). Three plants from the unamended and fertilized controls (0-0-0 and N-P-K) were harvested and separated into tuberous root, stem and leaf portions. This was done for ten fields in 1999–2000 and 15 fields in 2000–2001 and 2001–2002. Samples of each portion were oven-dried at 65 °C. Nitrogen concentration was determined in 25–50 mg of sample by the micro-Kjeldahl method and P and K concentrations were determined using wet ashing as described by IITA (1979). At harvest (12 MAP in 1999–2000 and 11 MAP in other years) between 24 and 48 cassava plants were sampled in each plot. All tuberous roots, stems and leaves were separated and weighed. Subsamples of each were weighed before and after oven drying for at least three days for conversion to dry matter.

Soils were sampled in November, 2001 to assess the effect of three annual fertilizer applications on soil chemical properties. Composites of 18 cores per plot were made from the top 0.3 m of all experimental units except for the 0-0-K plots. The soil was analysed for organic carbon using the Walkley Black method, total N with the Macro Kjeldahl method (5–10 g of soil), pH in 1:1 soil: water suspension, plant available P using Bray 1 solution, and exchangeable K using 1N Ammonium Acetate at pH 7 (all described in IITA 1979).

Data treatment and statistical analyses

Yield data were subjected to ANOVA over all years using the six fertilizer treatments to test the main effect of fertilizer using Proc GLM in SAS (SAS Institute 1985). The farmers' field (experimental block) and the year of experimentation were treated as random factors. The global effect of fertilizer was estimated each year by combining all fertilizer treatments and comparing them to the control in a single degree of freedom contrast using the 'estimate' statement of Proc GLM. ANOVA was also calculated for each year separately by treating N, P and K application as separate factors, each with two levels, in an incomplete factorial design (using dummy variables of 0 for absence of the nutrient and 1 for presence of the nutrient).

The relationship of initial soil parameters and yield was studied by including initial soil fertility classes for organic carbon (<10; 10–11; and >11 g kg^{-1}), Bray 1 P (<4.6; 4.6–6.0; and >6.0 mg kg^{-1}) and exchangeable K (<0.12; 0.12–0.16; >0.16 cmol$_c$ kg^{-1}) in the ANOVA as sources of variation in fresh tuber yield for the first two cropping years using Proc GLM. The classes were chosen to obtain similar numbers of members per class. A single df contrast was used to compare fresh yields associated with plant available P greater than and less than 5.4 mg kg^{-1}. The effect of three fertilizer applications over 2.5 years on soil parameters (C, N, pH, available P and exchangeable K) was tested using ANOVA. Soil C, P and K in late 2001 were tested as predictors of fresh root yield in 2002 using Proc REG in SAS (SAS Institute 1985). Then Proc GLM was used to test N, P and K treatment factors with and without soil K.

ANOVA was calculated for nutrient concentrations in roots, stems, and leaves at 9 MAP, testing the effects of years and fertilizer application. Loss of sample resulted in various numbers of missing observations (two for N, nine for P, and three for K). In each year nutrient uptake was calculated using the nutrient concentrations for roots, stems and leaves measured at 9 MAP and the dry matter at harvest and ANOVA was calculated for years combined.

Nutrient balance estimation

The nutrient balance (B) was estimated as the difference between inputs to and exports from the soil-plant system and did not include changes in soil nutrient levels. Nitrogen inputs by non-symbiotic biological nitrogen fixation were assumed to be negligible as were losses by denitrification and volatilisation, as fertilizer was covered with soil. Inputs included fertilizer (F), stem cuttings (S), atmospheric deposition (A), weathering (W) and mineralization (M). Exports included leaching (L), runoff/erosion (E), and harvest (H). Thus:

$$B = F + S + A + W + M - (L + E + H)$$

The individual terms were estimated as follows: Fertilizer input was based on nutrients applied each year, 60 kg N/ha as urea, 16 kg P ha^{-1} as TSP, and 138 kg K ha^{-1} as MOP. Nutrient input through stem cuttings was based on 10,000 planting stakes weighing 0.02 kg dry matter per stake, multiplied by nutrient concentration in stems in the previous year at 9 MAP (for the first year, the nutrient concentrations of 1999–2000 was used). Atmospheric deposition used estimates for southern Benin (3 kg N, 1 kg P, and 5 kg K ha^{-1}) from a study by Herrmann (1996). The estimates of nutrient inputs from weathering for *terre de barre* plateau soils were the most conservative ones available (0 kg N, 0.5 kg P and 1 kg K ha^{-1}) from Van der Pol et al. (1993) because these soils are low in weatherable minerals. Mineralization of organic N was estimated based on the initial organic C measured to 0.3 m depth (10 g kg^{-1}), a C/N of 12, bulk density of 1.4 Mg m^{-3} (Akondé et al. 1997; Agbo 1999), and annual N mineralization rate of 3% per year (de Ridder and van Keulen 1990). This gave N release of 105 kg ha^{-1} in year 1, 102 kg ha^{-1} in year 2 and 99 kg ha^{-1} in year 3. Mineralization of organic P was estimated with same assumptions as above and the C/P of the soil organic matter is 240. This gave P release of 5.3 kg ha^{-1} in the first year, 5.1 kg ha^{-1} in the second, and 4.9 kg ha^{-1} in the third. Litterfall was not included as part of the organic N and P pool because the nutrients are cycled within the soil-plant system.

Leaching losses for unamended *terre de barre* plateau soils are 10 kg N, 0.1 kg P, and 4 kg K ha^{-1} from Van der Pol et al. (1993). When N fertilizer is applied, Van der Pol et al. (1993) assumed that 20% of the N would be lost due to leaching. For K applied as fertilizer, Poss et al. (1997) found 2% of applied K at 1.8 m depth under a maize crop in similar soils in Togo. We assumed that loss would be 5% under a cassava crop because of greater spacing between plants than a maize crop. Runoff/erosion estimates for *terre de barre* plateau soils are 3 kg N, 0.5 kg P and 1 kg K ha^{-1} (Van der Pol et al. 1993). Harvest estimates are based on root and stem yield at harvest and multiplied by nutrient concentrations at 9 MAP and varied according to year and fertilizer application. Nutrient concentrations in 2000–2001 were assumed to be the mean of 1999–2000 and 2001–2002.

Financial analysis

Based on the nutrient balance calculations, the amount of N-P-K formula needed to compensate nutrient deficits was calculated. Farmers are likely to buy a formulated fertilizer rather than use several single element sources as we did in this trial. A partial budget was simulated for a locally available formula designed for root and tuber crops called Hydrochem Root and Tuber (HRT) formulated and blended by Hydrochem-Benin. Its formula is 13N–4P–22.4K–5S–4MgO and its purchase price was 8800 FCFA per 50 kg bag in 2001. The rate was based on provision of 60 kg ha^{-1} of K in this formula, which would require approximately 5.5 bags. It was assumed that the yield with HRT would be the same as the N-P-K treatment each year and that it would be applied once at planting. A partial budget and marginal rate of return (MRR) were calculated according to CIMMYT (1988). Total costs that vary (TCV) were based on a fertilizer purchase cost of 9000 FCFA per 50 kg bag (regardless of fertilizer type). Transport was 500 FCFA per bag and application cost was assumed to be 3000 FCFA ha^{-1} per application. The gross revenue used a price of 16 FCFA kg^{-1} for fresh cassava roots at the field border. Dominated treatments were identified as those whose TCV is larger than the previous treatment but whose net return is equal or smaller. The dominated treatments were eliminated before calculating the MRR.

Results

Yield response

In 1999, there was no significant response of fresh root yield to N, P, or K individually on the 15 farmers' fields but the effect of all fertilizer treatments combined was significant (Table 1). The overall mean fresh root yield without fertilizer was 19.1 t ha^{-1} and the block means ranged from 14.3 to 24.4 t ha^{-1}, which translated in a highly significant block effect. In the second cassava cropping year, control yields decreased to 16.0 t ha^{-1} and the yield with NPK was maintained at 19.8 t ha^{-1}

Table 1. Cassava fresh root yield (t ha^{-1}) and dry root yield (in brackets) on 15 farmers' fields over 3 years in Hayakpa, southern Benin.

Treatment	1999–2000	2000–2001	2001–2002	Mean
0-0-0	19.6 (6.2)	16.0 (5.5)	12.9 (4.0)	16.0
0-0-K	21.4 (6.7)	16.7 (5.7)	16.7 (4.9)	18.3
0-P-K	20.4 (6.7)	18.6 (6.5)	18.9 (5.8)	19.3
N-0-K	20.9 (6.2)	16.1 (5.2)	16.9 (5.0)	18.0
N-P-0	21.5 (6.8)	17.8 (6.1)	16.6 (5.3)	18.5
N-P-K	21.0 (6.5)	19.8 (6.6)	21.9 (6.4)	20.9
Mean	20.7 (6.5)	17.5 (5.9)	17.3 (5.1)	
SE (Year)	0.31			
SE (Treatment)	0.43			
SE (Interaction)	0.75			
Nutrient factor	Type III Prob > F^{a}			
N	n.s.	n.s.	n.s.	0.089
P	n.s.	< 0.0001	0.0006	< 0.0001
K	n.s.	0.090	< 0.0001	< 0.0001
NPK effect (t ha^{-1})[b]	1.95	1.79	5.27	3.00
Pr > $\|t\|$	0.0012	0.0092	0.0001	0.0001

[a]Probability of a larger *F*-value using Type III (partial) sums of squares.
[b]All fertilizer treatments compared with the unamended control.

(Table 1). There was a significant response of cassava yield to P and to K. The yield loss was 3.7 t ha^{-1} of fresh roots due to withholding P and 2.0 t ha^{-1} due to withholding K (Table 1). In the third year, the average yield was 12.9 t ha^{-1} without fertilizer and 21.9 t ha^{-1} with NPK (Table 1). Foregone yields from not using N (3.0 t ha^{-1}), P (5.0 t ha^{-1}) and K (5.3 t ha^{-1}) were all statistically significant, but the overall effect of the N treatment factor was never significant. In the third season, we observed that plants in some of the N-P-0 plots at 5 MAP were shorter with numerous branches and small, pale leaves. These symptoms, as well as some necrosis where the petiole joins the leaf, suggest K deficiency (Howeler 1981).

Relationships with soil properties

Organic C classes were associated with a significant portion of the yield variation in 1999–2000 but the trend was negative while a positive trend was expected. K classes were significantly related to yield in 2000–2001 but the trend was not linear (data not shown). Plant available soil P was positively related to yield in 1999–2000 and again in 2000–2001 (Table 2). The mean yield of fields with Bray P greater than 5.4 mg kg^{-1} was 3.3 t ha^{-1} higher than the fields with Bray P below that level in 1999–2000 and 1.5 t ha^{-1} higher in 2000–2001.

Analysis of soils in the third year of cropping shows that exchangeable K and plant available P were significantly higher in plots where these nutrients were applied (Table 3). Plots without K application had less than 0.1 S_c kg^{-1} and those with K applied had approximately 0.13 $cmol_c$ kg^{-1}, a difference of 40%. Plant available P was likewise 37% higher with a mean of 2.76 mg kg^{-1} in the plots without P applied (0-0-0 and N-0-K) and 3.78 mg kg^{-1} in those with P applied (0-P-K, N-P-0, and N-P-K). Although fertilizer was spot-placed and difficult to detect with a soil probe, cassava leaf litter production was substantial (Carsky and Toukourou 2004) and deposited nutrients in a uniform manner. Soil carbon and total N were not affected by fertilizer treatments.

Table 2. Mean fresh yield of cassava roots (t ha^{-1}) as a function of three equal initial Bray-1 P classes in the first 2 years of the study.

Bray 1 P classes (mg kg^{-1})	No. of fields	1999–2000	2000–2001
< 5.4	5	18.4	16.8
5.4–6.4	5	22.3	19.1
> 6.4	5	21.1	17.6
Prob > *t* for contrast '> 5.4 vs. < 5.4'		0.0002	0.068

In the third year, fresh root yield was significantly ($p < 0.0001$) related to exchangeable soil K (data not shown). Regression of yield on soil K gave a highly significant regression coefficient of 66.4 t ha^{-1} (s.e. = 14.6 t ha^{-1}) per unit change in soil K. Thus, the yield increase due to increasing exchangeable K was estimated at 0.66 t ha^{-1} for each increase in exchangeable K of 0.01 $cmol_c$ kg^{-1}. Soil C and P were not related to yield. Soil K was also a highly significant ($p = 0.0005$) covariate in the ANOVA for fresh root yield in 2002. With soil K included, the K fertilizer factor was no longer significant.

Nutrient uptake and nutrient balances

Mean root concentrations (dry weight basis weighted for different numbers of samples in each year) for the 3 years were 7.9 g kg^{-1} N, 1.4 g kg^{-1}

Table 3. Mean soil properties (top 0.3 m) during the third cassava crop (November, 2001).

Treatment	Organic C (g kg^{-1})	Total N (g kg^{-1})	pH	Exch. K ($cmol_c$ kg^{-1})	Bray 1 P (mg kg^{-1})
0-0-0	6.71	0.73	5.29	0.098	2.99
0-P-K	6.40	0.76	5.40	0.139	4.01
N-0-K	6.50	0.75	5.37	0.128	2.52
N-P-0	6.38	0.77	5.25	0.090	3.95
N-P-K	6.21	0.76	5.36	0.129	3.39
SE means	0.17	0.02	0.04	0.005	0.16
Prob > *F*[a]	n.s.	n.s.	0.03	< 0.0001	< 0.0001

[a]Probability of a larger *F*-value using Type III (partial) sums of squares.

Table 4. Nutrient concentrations (g kg^{-1}) at 9 MAP of dry roots and stems for two treatments during 3 years.

Part	Year	Fertilizer	N	P	K
Root	1999–2000	0-0-0	11.1	2.14	8.0
		N-P-K	11.8	2.28	7.9
		SE means	0.34	0.069	0.86
	2000–2001	0-0-0	5.7	1.28	4.7
		N-P-K	5.4	1.48	6.5
		SE means	0.30	0.089	0.59
	2001–2002	0-0-0	7.7	0.83	6.4
		N-P-K	7.6	1.00	9.5
		SE means	0.28	0.056	0.59
	Prob > F[a]	Year	< 0.0001	< 0.0001	0.0005
	Fertilizer	n.s.	0.0072	0.0065	
Stem	1999–2000	0-0-0	14.3	2.03	8.8
		N-P-K	14.1	2.08	7.6
		SE means	0.57	0.067	0.92
	2000–2001	0-0-0	14.8	1.47	5.6
		N-P-K	14.9	1.63	8.6
		SE means	0.50	0.086	0.63
	2001–2002	0-0-0	14.0	1.19	6.7
		N-P-K	14.0	0.23	10.0
		SE means	0.46	0.055	0.62
	Prob > F[a]	Year	n.s.	< 0.0001	n.s.
	Fertilizer	n.s.	n.s.	0.0069	

[a]Probability of a larger *F*-value using Type III (partial) sums of squares.

Table 5. Nutrient uptake[a] (kg ha^{-1}) in cassava roots, stems and leaves during 3 years on farmers' fields in a non-degraded *terre de barre* site in southern Benin.

Year	Fertilizer	N	P	K
1999–2000	0-0-0	176.6	26.9	108.1
	N-P-K	203.4	31.9	111.7
	SE means	8.45	1.18	10.0
	No. fields[b]	10	10	7
2000–2001	0-0-0	139.5	15.3	56.0
	N-P-K	160.9	19.6	92.0
	SE means	7.41	1.53	6.83
	No. fields[b]	13	6	15
2001–2002	0-0-0	75.1	6.7	45.6
	N-P-K	113.5	11.2	96.4
	SE means	6.9	0.97	6.83
	No. fields[b]	15	15	15
Prob > F	Year	< 0.0001	< 0.0001	< 0.0002
	Fertilizer	< 0.0001	< 0.0001	< 0.0001

[a]Uptake at harvest was calculated with dry matter at harvest (11 to 12 MAP) and nutrient concentrations at 9 MAP.
[b]No. fields = number of fields (replications).

P, and 7.0 g kg^{-1} K (Table 4). These are similar to those of Howeler and Cadavid (1983) who reported 7 g kg N^{-1}, 1 g kg^{-1} P and 7.5 g kg^{-1} K in roots at 12 MAP. Mean stem concentrations of N were higher than root concentrations while stem P and K were similar to root P and K. Root N decreased from the first to third year, while leaf N increased and stem N did not change. Root, stem and leaf P also decreased over time. Root and stem K decreased in the 0-0-0 plot but increased in the N-P-K plot. The interaction between fertilizer treatment and year was statistically significant for stem K.

Nutrient uptake by cassava roots, stems and leaves was influenced by the cropping year and by fertilizer application (Table 5). In 1999–2000, nutrient content of the crop excluding the litter was approximately 177 kg N, 27 kg P and 108 kg K ha^{-1} without fertilizer applied. Fertilizer application increased uptake of N and P but not K; only P uptake was increased significantly ($p < 0.05$). In 2002, nutrient content of the crop excluding the litter was 75 kg N, 7 kg P and 46 kg K ha^{-1} without fertilizer applied. Thus the supply of nutrients from the soil decreased by more than 50% between the first and third cropping year. Fertilizer application increased the uptake of N, P and K in 2002.

N and P balance in the N-P-K plots was slightly negative in the first year but positive after 3 years, while the K balance was positive throughout the period (Table 6). On the other hand, negative nutrient balances were recorded in the first year in all treatments in which nutrients were not applied. Compared to the amounts of fertilizer applied, the deficits in the 0-0-0 plots were approximately 68% for N, 100% for P and 66% for K. The cumulative P and K balances became more negative in the second year while the N balance did not. The cumulative K deficit in the N-P-0 treatment reached 137 kg ha^{-1} in the second year and 180 kg ha^{-1} in the third when all stems are exported from the field. If all stems are retained on the field, then the cumulative balance for the 0-0-0 treatment after 3 years is 153 kg N, −4.7 kg P and −94 kg K ha^{-1}. The annual amount of nutrient needed to compensate deficits can be calculated by dividing the deficit by the number of cropping years. Based on this calculation for the cumulative balances at the end of the third year in the omission plots, approximately 13 kg N, 10 kg P and 60 kg K ha^{-1} would be needed annually to compensate deficits.

Table 6. Cumulative nutrient balances (kg ha^{-1}) in cassava crops excluding changes in soil nutrient levels for two fertilizer treatments in three cropping years.

Year	Treatment	1999–2000	2000–2001	2001–2002
N	0-0-0	−41	−27	14
	N-P-K	−17	27	187
	0-P-K	−52	−56	−39
P	0-0-0	−17	−22	−21
	N-P-K	−5	0	13
	N-0-K	−18	−25	−29
K	0-0-0	−90	−132	−165
	N-P-K	36	90	140
	N-P-0	−93	−137	−180

Calculation assumes all stems exported from the field. If all stems are retained on the field, then the cumulative balance for the 0-0-0 treatment after 3 years is approximately 174 kg N, 4.7 kg P and −100 kg K ha^{-1}.

Financial analysis

Application of N-P-K in a complete formula (HRT) sufficient to offset the average annual nutrient deficit had a variable cost of 54,150 FCFA ha^{-1} (Table 7). Costs related to fertilizer technology might also be reduced through cooperative purchase and transport as well as broadcast (instead of spot) application. Fertilizer application was dominated by the unamended control in the first year but not in the second or third. N-P-K fertilizer based on provision of 60 kg ha^{-1} of K (268 kg or approx. 5.5 bags ha^{-1}) gave a MRR of 12% in the second year and 166% in the third. It should be kept in mind that the simulated effect may have been overestimated by assuming the same yields from 5.5 bags (50 kg each) ha^{-1} of complete fertilizer application in the second or third year as 9.9 bags ha^{-1} applied annually in the N-P-K treatment of the field trial.

Table 7. Partial budget, dominance analysis and marginal rate of return (MRR) in three cropping years (2000, 2001, and 2002 harvests) for a complete fertilizer formulation (HRT) on cassava on 15 farmers' fields on a non-degraded *terre de barre* site in southern Benin. All values in FCFA ha^{-1}.

Year	Fertilizer	Gross revenue	Net revenue dominance	MRR	
1999–2000	0-0-0	305,600	305,600		
	HRT	336,000	281,850	D	
2000–2001	0-0-0	256,000	256,000		
	HRT	316,800	262,650		0.12
2001–2002	0-0-0	206,400	206,400		
	HRT	350,400	296,250		1.66

HRT fertilizer formula is 13N–4P–22.4K–5S–4MgO. It is assumed that this formula is applied once in the season and that maximum yields are achieved. The amount of HRT applied is that which is needed to provide 62 kg ha^{-1} of K. Total costs that vary are 54,150 FCFA ha^{-1} for HRT each year.

Discussion

The fresh root yield without fertilizer was much higher than the average yield on farmers' fields in the same part of Benin (Hinvi 1992; Université Nationale du Bénin 1992). This is partly because cassava is sometimes intercropped with maize (resulting in lower cassava densities) and partly because the site was representative of a relatively high level of productivity. The Hayakpa village territory is at a relatively early stage of soil nutrient depletion as characterised by Floquet and Mongbo (1998) but is clearly in danger of serious soil nutrient depletion followed by chemical and physical degradation. Fertilizer can clearly play a role in slowing or reversing this process. Results of FAO fertilizer trials in Ghana and Nigeria (Howeler 1981) gave a mean response to N-P-K application to cassava of 68% and value cost ratios that were twice as high as for maize in both countries. Although cassava is considered to be a crop that degrades the soil (Howeler 2002; Nweke et al. 2002), this does not have to be. Cassava returns large amounts of leaf litter to the soil that can help maintain soil physical properties. Carsky and Toukourou (2004) estimated that 3.4 t ha^{-1} of litter was produced during the first year in the 0-0-0 plots of these same trials and that the amount was increased to 4.1 t ha^{-1} in the N-P-K plots.

Cassava yields were maintained over the period with repeated fertilizer applications. Howeler (1985, 2002) described several cases in which yield declined dramatically without nutrient application and yield was maintained with fertilizer application. The yield decrease without fertilizer during the trial period could be due to nutrient depletion, decreasing rainfall, and or pest and disease pressure. Rainfall during the cropping season decreased from 1400 mm during the first crop (1999–2000) to approximately 900 mm in 2000–2001 and less than 700 mm in 2001–2002. The constant yield with complete fertilizer suggests moisture may not have been a problem. However, fertilizer may have favoured root growth and made the plant better able to exploit soil moisture in the amended plots. In this case, the interaction of reduced rainfall and nutrient mining may have combined to reduce root yield over the period. Pest disease problems were not observed to be important and the variety used is resistant to major pests and diseases in the area.

Identification of limiting nutrients

This study confirmed the need for K in cassava production on sedimentary soils in southern Benin, but not necessarily in the first years of cropping. There was no yield response in the first year and fertilizer investment was not financially justified in the second year even though the yield response was statistically significant. A response to K could have been expected in the first year because the mean soil K concentration in the trial was below published critical levels, generally 0.15 to 0.18 $cmol_c\ kg^{-1}$ from other studies (Kang 1984; Howeler 1985). But it should be noted that soils were sampled to 0.3 m instead of the usual 0.15 m depth. The critical level of exchangeable K to 0.3 m depth can be expected to be lower than that for 0.15 m depth because exchangeable K concentration normally decreases with depth and these soils are not an exception (Saragoni et al. 1992). In addition, cassava yields of less than 22 t ha^{-1} would not require as much K as some of the higher yields on which critical levels are normally based. In the third year, yield was highly related to soil K, which was the most significant limiting factor. Howeler (2002) has found that K deficiency is always the main limiting factor when cassava is grown continuously on the same soil without K fertilizer application. Yield response in 2001–2002 and soil chemical data (Table 3) show that the highest yield was achieved when exchangeable K was approximately 0.13 $cmol_c\ kg^{-1}$ and low yields in missing K plots were observed when exchangeable K was 0.09 $cmol_c\ kg^{-1}$. This suggests that the critical level in these conditions is between 0.10 and 0.12 $cmol_c\ kg^{-1}$ in the top 0.3 m of soil.

The initial concentration of 0.13 $cmol_c\ kg^{-1}$ to 0.3 m depth indicates that approximately 200 kg K ha^{-1} was available to the crop in the first season. It is not surprising that there is a response to K fertilizer in the second year because the apparent K deficit after 1 year is 95 kg ha^{-1}, almost one-half of the exchangeable K. The potassium buffering capacity of savanna soils is generally low (Wild 1971), although this characteristic has not been determined for *terre de barre* soils. After 2 years, the K deficit was 141 kg ha^{-1}, almost three-fourths of the initial exchangeable K. If there were no K reserves, the exchangeable K would be 0.05 $cmol_c\ kg^{-1}$ or lower by the third year. There must be some K reserves because exchangeable K was maintained at 0.09 $cmol_c\ kg^{-1}$ without K application (Table 3). Saragoni et al. (1992) observed approximately 30% reduction of exchangeable K during 12 years of continuous cropping without K application on similar soils in Togo.

The response of cassava to TSP in the second year was stronger than expected. This could have been a response to calcium but soil Ca (3.1 $cmol_c\ kg^{-1}$) was high compared to the critical level of 0.25 $cmol_c\ kg^{-1}$ published by Howeler (1981). It is known that grain legumes (Carsky 2003) and maize (Werts 1979) respond to P on sedimentary coastal soils and that the relative response increases with the number of years of continuous cropping. Howeler (2002) showed that P was not the limiting factor for cassava in long term trials at Quilichao, Columbia and Khon Khaen, Thailand. The only report of a critical P level using Bray 1 extract was 7 mg kg^{-1} in the top 0.15 m (Howeler 1981). The soils for this trial were probably above the critical level initially with 6.1 mg kg^{-1} in the top 0.3 m. Although there was no response to applied P in the first year, the overall fresh root yield was strongly related to Bray-1 P (Table 2). The relationship was not as strong in the second year but the crop responded to TSP (Table 1). In 2001–2002, yield was low in the N-0-K treatment with an apparently adequate exchangeable K level of 0.13 $cmol_c\ kg^{-1}$. Plant available P in the upper 0.3 m of soil was 3 mg kg^{-1}, a very low level indeed. It is somewhat surprising that soil P was not related to cassava yield in 2001–2002 while response to P fertilizer was substantial. The relationship was probably confounded by the strong relationship between yield and soil K.

N response was not observed in the first 2 years and the response was significant, but not as great as P and K, in the third year of continuous cropping. N response was not frequently observed in Brazil and Columbia where the most fertilizer trials have been carried out, but on farmers' fields in Thailand, response to N is common (Howeler 2002). A conservative calculation of soil N supply from mineralization of soil organic matter was approximately 100 kg ha^{-1} an^{-1}. Based on uptake in the 0-0-0 treatment, the soil N supply was approximately 177 kg ha^{-1} in the first year, decreasing to 75 kg ha^{-1} in the third.

Leihner (2002) found that cassava responded to 50 kg N ha^{-1} but further N suppressed root yield. According to Howeler (2002) many studies have found that N increases top growth and reduces root growth. This was not observed in the trial as the N-P-K treatment gave higher yields than 0-P-K.

Cassava root yield was stable from 1999–2000 to 2001–2002 in the N-P-K plots but nutrient uptake decreased. This suggests that the cassava crop accumulated more nutrients than needed in the first year and that nutrients were more efficiently used in the third year. Physiological nutrient use efficiency (nutrient uptake per ton dry root yield) in the first year was approximately 30 kg N, 4.5 kg P and 17 kg K ha^{-1}. By the third year, the average of the 0-0-0 and N-P-K treatments was 17 kg N, 1.7 kg P and 13 kg K ha^{-1}. This is similar to the values recorded by Howeler and Cadavid (1983) of 15 kg N, 1.5 kg P and 11 kg K ha^{-1}. Potassium uptake decreased from 112 kg h^{-1} in 1999–2000 to 96 kg ha^{-1} in 2001–2002, while N decreased from 203 to 113 kg ha^{-1} and P from 32 to 11 kg ha^{-1}. This suggests that K was the limiting nutrient as it was the one that was associated with yield maintenance.

Recommendations based on fertilizer response and nutrient balances

The trial was designed to identify limiting nutrients and not to formulate recommendations. However, a recommendation could be made by combining the results of the response study and the nutrient balances. The amounts to apply would be those needed to compensate deficits of nutrients that become limiting. From the yield response, the nutrients to be replaced would be P and K because they became limiting in the second year. From the nutrient balance, approximately 13 kg N, 10 kg P and 60 kg K ha^{-1} would be needed to maintain a neutral balance in the soil-plant system. This approach overestimates slightly the amount of fertilizer needed initially and results in gradual build-up of soil stocks, such as those observed in our study. Cassava fertilizer recommendations already exist in most countries. For example in Benin, the recommended nutrient application for all rainfall regimes and all cassava varieties is 30 kg N, 30 kg P, and 60 kg K ha^{-1} (INRAB 1995). This amount of K was also suggested by our K balance but the recommended P rate appears to be three times higher than necessary. Our results do not justify N application to cassava in the first 3 years. If a complete formula were to be used, then excess N would be applied. One solution would be to grow maize to take advantage of the N.

Recommendations should take residual or carry over effects into account by reducing application in subsequent years if excessive amounts are applied in preceding years. Residual effects of applied K can be expected to be substantial. Poss et al. (1997) showed that leaching losses were low at a *terre de barre* site in southern Togo. Saragoni et al. (1992) found that over a 12 year period with annual K application, increases in exchangeable K were not detected below 0.5 m at a site with a soil similar to the one we studied and below 0.6 m at a highly degraded site. Carry over of P is also well known, although not well documented, in West Africa. Jomini et al. (1991) calculated that each kg P_2O_5 ha^{-1} applied to sandy soils in Niger increased plant available P in the following year by 0.14 mg kg^{-1}.

Recommendations based on 1 or 2 years of study (sometimes the case in Africa where there is insufficient funding for continuous research) would be clearly inadequate. The recommendation based on our first year result would be that no fertilizer is required. The same recommendation would result from the lack of an economic response in the second year although the biological response suggested that P was required and maybe K. It is clear that three or more years are desirable to follow the evolution in yields as nutrients are extracted. Ideally, recommendations should take farmer soil classification or field history into account but this would require trials on several fields for each major soil type and each farmer class or field history class.

Knowledge of limiting nutrients and recommended fertilizer rates should be complemented by appropriate organic matter management for cassava. Efficient use of fertilizer requires adequate soil organic matter levels. One of the reasons that fertilizer is not applied to cassava is that the response to fertilizer on degraded soil is poor. Akakpo and Carsky (unpublished data, 2001) found extremely low cassava yields with high fertilizer rates on the highly degraded Abomey plateau (organic C less than 5 g kg^{-1}). Thus organic matter management is an important part of stimulating fertilizer use.

Conclusions

Our study showed that on non-degraded soils producing 20 t ha^{-1}, the use of fertilizer was not justified in the first year. Responses to P and K were statistically significant in the second and third years but an economic response to fertilizer was suggested by the results only in the third year. The root yield of 20 t ha^{-1} was maintained with exchangeable K >0.12 $cmol_c$ kg^{-1} and Bray-1 P $>$ 3 mg kg^{-1} in the top 0.3 m of soil. The study confirmed negative nutrient balances when fertilizer is not applied and reversal of these negative balances when fertilizer is applied. Nutrient balance suggested that approximately 10 kg ha^{-1} of N and P and 50 to 100 kg ha^{-1} of K would compensate losses from the system. As land use intensifies for crop production, depletion of soil nutrient stocks will result in fertilizer response becoming more likely. Diversification of markets and diversification of cassava products will also increase demand and help stimulate the use of fertilizer.

Yields without fertilizer were almost three times higher than the usual yield (6 to 8 t ha^{-1}) on farmers' fields in the same part of the country, probably because of competition with intercrops and weeds in general as well as poor soil fertility on degraded *terre de barre* soils. The study site can be considered to be at an early to moderate stage of nutrient depletion but it could easily progress to an advanced stage of depletion under market stimulation of production. Our results suggest that an economic response to fertilizer can be expected on relatively fertile *terre de barre* fields after 2 years of continuous cropping. Justification of fertilizer investment depends very much on the value of cassava roots. Demand for cassava roots will be increased by market diversification and product diversification. Also, better integration of fertilizer and cassava output markets can stimulate the use of fertilizer on cassava.

Acknowledgements

The assistance of Mr. K. Anato for plant and soil sampling and Dr. G. Tian and F. Ishida for coordination with the IITA analytical services lab in Nigeria is gratefully acknowledged. Thanks go to Drs. A. Fermont (IITA-Uganda) and M. Wopereis (IFDC-Africa) for review of early drafts.

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