

MINERAL NUTRIENT UPTAKE AND REMOVAL BY COWPEA, SOYBEAN AND MAIZE CULTIVARS IN WEST AFRICA, AND IMPLICATIONS FOR CARBON CYCLE EFFECTS ON SOIL ACIDIFICATION

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SUMMARY

A field study of cowpea, soybean and maize was made at Ibadan, Nigeria, to determine the uptake of mineral nutrients and quantities removed in crop residues and seed. Concentrations of N, the major cations (K, Ca, Mg and Na) and major anions (P, S and Cl), and the micronutrients (Fe, Mn, Zn and Cu) were determined in shoots harvested at flowering and maturity. Concentrations of excess cations in shoots at flowering were 135 $\text{cmol}_c \text{kg}^{-1}$ for soybean, 158 $\text{cmol}_c \text{kg}^{-1}$ for cowpea and 58 $\text{cmol}_c \text{kg}^{-1}$ for maize. In crop residues and seed at maturity, the values decreased to 75 and 56 $\text{cmol}_c \text{kg}^{-1}$ respectively for soybean, 68 and 27 $\text{cmol}_c \text{kg}^{-1}$ respectively for cowpea, and 52 and 10 $\text{cmol}_c \text{kg}^{-1}$ respectively for maize. Nutrient and excess cation concentrations were also measured in 13 soybean and eight cowpea lines grown in replicated field trials at Fashola in the derived savanna zone and Shika in the northern Guinea savanna zone of Nigeria to assess the variation within these species. Maize, mucuna and lablab were included at these sites. The results are discussed in the context of soil nutrient depletion due to removal of nutrient elements in harvested seed and stover. The contribution of seed and stover removal to the proton (H^+) budget and acidification of the soil is also discussed. It is estimated that the quantity of lime required to neutralize the acidity resulting from the removal of 1 t seed is 28 kg for soybean, 14 kg for cowpea and 5 kg for maize. The corresponding values for stover were soybean 35, cowpea 24 and maize 26 kg lime t^{-1} stover. Given the soil pH buffer capacity at the Ibadan site for the surface 16 cm, the yields obtained and assuming that seed and crop residues are removed, carbon cycle acidification would lead to a fall of 1 pH unit after 75 crops for soybean, 114 crops for cowpea and 68 crops for maize. The inclusion of legumes in cropping systems to increase N supply, and the use of P fertilizer to maximize N-fixation by legumes will raise production, but will inevitably accelerate removal of alkalinity and nutrients in harvested products, and the consequent decline in soil fertility. The data presented in this paper can be used in estimating the lime and fertilizer nutrients needed to maintain soil fertility and sustain yields.

INTRODUCTION

Agricultural production over the past 30 years in sub-Saharan Africa has increased, but not kept pace with the population, and food production *per capita* is falling. The intensification of agricultural systems has resulted in declining nutrient availability, soil acidification, soil compaction and a build-up of pest problems (Weber *et al.*, 1996). Consequently, a major focus of agricultural research for this region is the maintenance and improvement of soil fertility (Nandwa, 2003). One strategy has been to include

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legumes either as cover crops (Schulz *et al.*, 2003), or as food crops either inter-planted or in rotation with staple cereal crops (Sanginga *et al.*, 2001). This strategy has been highly successful in the West African savanna, and the input of biologically fixed N has resulted in improved productivity and substantially higher farm incomes (Sanginga *et al.*, 2003). The inclusion of legumes in cropping systems has several benefits. Directly, they provide a high protein food for farm families or grain for sale, and the crop residues can be used to feed livestock. Indirectly, they contribute to increased yields of staple cereal crops through a transfer of biologically fixed nitrogen (Oikeh *et al.*, 1998), and there are reports of benefits through improved availability of sparingly-soluble rock phosphate (Kamh *et al.*, 2002; Vanlauwe *et al.*, 2000). Other reported benefits of legumes in cropping systems include control of weeds such as *Imperata* sp. (Vissoh *et al.*, 1998) and *Striga* sp. (Schulz *et al.*, 2003). Control of cereal root diseases may be another consideration, not yet demonstrated for this system, but shown for break crops in temperate cropping systems (Kirkegaard *et al.*, 1997).

Increasing the productivity of cropping systems in sub-Saharan Africa through the use of N-fixing grain legumes undoubtedly has major benefits for farm communities (Sanginga *et al.* 2003). However, soil fertility is likely to be a major constraint on further increases in crop yields because raising crop yields places greater demand on the supply of nutrients, and in many soils of sub-Saharan Africa nutrients are already in negative balance (Smaling *et al.*, 1993). A related consequence of higher yields and removal of products is an increased rate of soil acidification (Kennedy, 1992). Although grain yields in many African cropping systems are low by world standards, crop residues are often removed as well as grain, with significant consequences for removals of nutrients and acidification of the soil.

Soil acidity is a major factor limiting agricultural production worldwide (Von Uexkull and Mutert, 1995). While many soils in Africa are naturally acidic, others rapidly acidify under intensive, continuous farming (Kang and Juo, 1986; Lal, 1985). Generally, acidity itself does not cause poor growth of plants; rather, it is the associated factors including the unavailability of nutrients such as phosphorus and molybdenum due to fixation, loss of other nutrients such as calcium, magnesium and potassium due to leaching, and most importantly, toxic levels of soluble manganese and aluminium in the soil solution that stunt growth and/or kill roots, resulting in the inability of plants to take up available nutrients and extract water from the soil (Foy, 1984).

Soil acidification is a natural process that is accelerated by agriculture, due to disturbances in the nitrogen (N) and carbon (C) cycles. A common disturbance in the N cycle involves the loss of nitrate by leaching following accumulation in the soil when mineralization exceeds uptake by plants. In legume-based systems this is a major cause of soil acidification (Helyar and Porter, 1989). Harvesting and removal of products leads to soil acidification by altering the C cycle. In this cycle, protons are generated and released by plant roots to balance excess uptake of cations over anions, and organic anions are generated internally to balance excess cation accumulation. If plant material decomposes where it grew, the contained organic anions hydrolyse, consuming equivalent amounts of protons, and there is no net change in soil acidity. However, removal of agricultural produce breaks the cycle, by exporting alkalinity

(Kennedy, 1992). Accordingly, the contribution of the C cycle to soil acidification can be estimated from the yield and ash alkalinity of the material removed.

Although there is information on ash alkalinity for some, mainly temperate crop species (McLay *et al.*, 1997; Pierre and Banwart, 1973; Santonoceto *et al.*, 2002; Slattery *et al.*, 1991), there is less available for crops grown in the tropics and subtropics. Ash alkalinity can be determined directly by ashing plant material and titrating the excess bases, or indirectly by calculating the excess cations after measuring the cations and anions in the tissue (Kennedy, 1992). The values obtained by the two methods are highly correlated (Noble *et al.*, 1996).

This paper reports on a field experiment conducted at Ibadan in Nigeria to determine the nutrient and excess cation accumulation in two cultivars each of soybean (*Glycine max*) and cowpea (*Vigna unguiculata*) compared with maize (*Zea mays*), at flowering and maturity. We also include data on a larger number of soybean and cowpea lines as well as the legumes mucuna (*Mucuna pruriens*) and lablab (*Lablab purpureus*), grown at Fashola in the derived savanna zone of southern Nigeria, and at Shika (near Zaria) in the dry savanna zone of northern Nigeria. Measurements were made on shoots at flowering, crop residues at maturity and seed to estimate the consequences for soil nutrient depletion and acidification resulting from their removal.

MATERIALS AND METHODS

Field sites, experimental design and crop management

There were three field sites representing different agro-ecological zones. Site details are shown in Table 1. The field trial at each site was a randomized block design with four replicates. Plot size at Ibadan was 6 × 4 m with 4 rows spaced 75 cm apart; at Shika and Fashola the plots were 4 × 4 m.

Two cowpea lines, two soybean lines and maize were sown at Ibadan, while at Fashola and Shika eight cowpea and 13 soybean lines were used and one line each of maize, mucuna and lablab were included for reference. The grain legume lines were

Table 1. Selected characteristics of the experimental field sites.

Site	Ibadan	Fashola	Shika
Location in Nigeria	IITA, Ibadan. Field block 7	Farmer's field near Fashola, Oyo State.	IITA field site, Shika near Zaria, Kaduna State.
Co-ordinates	7°30'N, 3°54'E	7°50'N, 3°55'E	11°13'N, 7°12'E
Agro-ecological zone	Forest-savanna transition	Derived savanna	Northern Guinea savanna
Soil	Typic Plinthustalf	Oxic Paleustalf	Haplic Lixisol
Soil pH _(water)	5.5	6.3	6.3
Extractable phosphorus (µg P g ⁻¹ soil)	Olsen-P, 1.5	Resin-P, 3.2 Bicarbonate-P, 3.2	Resin-P, 0.7 Bicarbonate-P, 2.6
Soil pH buffer capacity (cmol.kg ⁻¹ .pH unit ⁻¹)	7.56	Not determined	Not determined
Annual rainfall (mean)	1350 mm	1200 mm	1100 mm
Season	Dry season; trial irrigated	Rainy season; trial rain-fed	Rainy season; trial rain-fed
Sowing/harvest	Jan/May 2003	Jun/Oct 2001	Jul/Oct 2001

promiscuously nodulating types and were chosen on the basis of earlier experiments to measure performance on soils low in plant-available phosphorus (P) and plant response to P fertilizer of soybean (Abdelgadir, 1998) and cowpea (Sanginga *et al.*, 2000). The lines used are listed in Table 2 for the Ibadan site and Table 5 for the Fashola and Shika sites.

The trial at Ibadan was sown on 20 January 2003 at the beginning of the dry season. The flowering stage harvest was on March 11, and the maturity harvest was on April 8 for cowpea and May 6 for soybean and maize. The trial was irrigated for one hour, twice each week. The trials at Shika and Fashola were sown in July 2001 and June 2001 respectively to grow under rainfall during the normal cropping season.

Triple superphosphate was applied and incorporated before sowing at each site to provide 30 kg P ha⁻¹. No N was applied. Insect pests were controlled with recommended pesticides and weeds were removed by hoeing.

Plant sampling and analysis for mineral content

At the Ibadan site, plants were counted two weeks after sowing to estimate establishment densities. Six weeks later, the plots were sampled for above-ground biomass by removing five plants selected at random from the middle two rows. This is termed the flowering harvest; the cowpeas and soybeans were at full flowering and the maize was at the tasselling stage. At maturity, plants from a 9 m² quadrat were harvested. Filled pods were removed from the grain legumes, and cobs were removed from the maize leaving the enfolding sheath attached to the plants. The material left standing was then harvested and is termed 'stover'. The grain was separated from the pods or cob, and the latter termed 'threshing residues'. The stover and the threshing residues were processed and analysed separately, and are referred to collectively as 'crop residues'.

At the Fashola and Shika sites the first harvest was at the R_{3.5} growth stage (Fehr *et al.*, 1971) of cowpea, nine weeks after sowing. Five plants were selected at random from each plot; leaf blades only for the legumes and whole plants for maize were retained for analysis. At maturity, seed only was retained.

Material from the flowering harvests, the stover, threshing residues and seed were dried in an oven at 65 °C for seven days, to constant weight. The harvested material was then weighed. Flowering stage material, stover and threshing residues were shredded and sub-sampled before being ground to a fine powder in a stainless steel puck mill. Sub-samples of seed were ground in the puck mill.

Ground plant material was pressed into pellets and analysed by X-ray fluorescence spectrometry for P, potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), chlorine (Cl), and sulphur (S) (Norrish and Hutton, 1977), iron (Fe), zinc (Zn), manganese (Mn) and copper (Cu) (Hutton and Norrish, 1977). Total nitrogen (N) was determined on a separate sub-sample of plant material by first digesting with sulphuric acid and hydrogen peroxide (Heffernan, 1985) and then measuring the ammonia in the digest by an indophenol blue method using an AlpChem segmented flow analyser.

The concentration of excess cations was calculated as follows:

$$(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^+ + \text{Na}^+) - (\text{HPO}_4^- + \text{S}^{2-} + \text{Cl}^-) \quad (1)$$

expressed as a molar concentration of charge ($\text{cmol}_c \text{kg}^{-1}$ dry weight). We used total P in this calculation assuming that most of the P was present as HPO_4^- . We did not measure sulphate, but used total S instead. This would have introduced an error, the magnitude depending on the proportion of S in reduced (uncharged) forms. Nitrate was ignored because tests showed barely detectable concentrations in the plants at flowering and none would be expected in seed or mature crop residues. The amounts of excess cations taken up from the soil were calculated by multiplying the concentration of excess cations by the vegetative dry-matter or seed yields. The micronutrients Fe, Mn, Zn and Cu were not included in equation (1) because their contribution to cation excess was negligible.

Measurement of soil pH buffer capacity

Soil pH buffer capacity (pHBC) was estimated by the method of Aitken and Moody (1994) as described in Noble *et al.* (2002). Briefly, titration curves were established by adding incremental amounts of HCl to soil suspensions (1:5) in water. Sub-samples of soil (5 g) were weighed into each of six polyethylene tubes and appropriate amounts of deionized water added so that the final volume would be 25 ml. Additions of 0.04 m HCl (standardized), either 0, 0.15, 0.25, 0.5, 1.0, or 2.0 ml were made. One ml of 0.05 m CaCl_2 to minimize variations in ionic strength, and 0.25 ml of chloroform to inhibit microbes were then added to each tube and the suspensions equilibrated for 24 h at 25 °C on an end-over-end shaker. The suspensions were then removed from the shaker and left to equilibrate for a further six days at 25 °C. Tubes were shaken for two minutes each day to resuspend the soil, and on the seventh day the pH was measured using a glass electrode. The mean pH of the samples with no acid added was 6.1 and that with 2 mL 0.04 m HCl added was 5.0. The plot of pH against the acid added was linear over this range and the pH buffer capacity was calculated from the slope of the relationship.

Calculation of potential change in soil pH due to removal of harvested plant material

Potential soil pH change was calculated from the amount of acid added due to removal of excess cations ($\text{mol H}^+ \text{ha}^{-1}$), the measured pHBC ($\text{mol H}^+ \text{kg}^{-1} \text{pH unit}^{-1}$), soil bulk density (BD, kg m^{-3}) and volume of soil (V, m^3) in the relevant depth interval, according to Helyar and Porter (1989). In a given period for a given soil layer:

$$\text{Change in pH} = \text{amount of acid added} \div (\text{pHBC} \times \text{BD} \times \text{V}) \quad (2)$$

Statistical analysis

The results were subjected to analysis of variance using Minitab (release 12), and standard errors (*s.e.*) of the means were calculated.

RESULTS

Ibadan site

Biomass and seed yields. Crop biomass at flowering was greatest in maize, followed by soybean, then cowpea. At maturity, maize had the greatest grain and crop residue yields, but the grain legumes were similar (Table 2). The total biomass at maturity (grain + crop residue) was 1.5-, 2.6- and 2.1-fold greater than at the flowering harvest for soybeans, cowpea and maize respectively. No account was taken of any leaf loss that occurred during senescence in the grain legumes. Because the standard deviations of the means are large, particularly at the flowering harvest, the genotypes of the grain legumes could not be distinguished statistically.

Concentrations of nutrients in shoots and seed

Concentrations of nutrients in the shoots at flowering were generally higher than in the crop residues or seeds (Table 3). The nutrient concentrations are given separately for the stover and threshing residues so that the consequences of different harvesting practices for nutrient removal can be assessed. As a broad generalization, maize had lower concentrations of most nutrients than the legumes. Soybean had consistently lower concentrations of Na and particularly Cl than maize and cowpea. Cowpea tended to have higher concentrations than soybean of most other nutrients in shoots at flowering and in stover, while the opposite occurred in seed.

Shoots at flowering. Soybean shoots had lower levels of major cations, except for Mg, than cowpea shoots, lower N and S and less than one-tenth the concentration of Cl (Table 3). Of the micronutrients, Mn was significantly lower in soybean than cowpea. Comparing the two soybeans, TGM1196 had lower concentrations of N but higher concentrations of P and Zn than TGM1293, while in the cowpeas, IT82-716 had higher Na and P than Dan-ila, but marginally lower Zn. In maize, concentrations of Na and K were similar to soybean, but N, P, S, Ca, Mg, Mn and Cu concentrations were lower than in the legumes. Cl concentrations in maize were substantially higher than in soybean, but less than those in cowpea.

Table 2. Biomass production at flowering, and yield of seed and crop residue at maturity of two genotypes each of soybean and cowpea compared to maize in a field trial at Ibadan, Nigeria. Units are kg ha⁻¹ (*s.e.* in parentheses, *n* = 4).

Species	Soybean		Cowpea		Maize
	Tgm1293	Tgm1196	IT82-716	Dan-ila	Oba 1
At flowering:					
Shoots	1759 (274)	1251 (299)	745 (150)	733 (218)	2799 (458)
At maturity:					
Stover	1077 (56)	1291 (153)	1045 (73)	814 (190)	2971 (345)
Threshing residue	263 (9)	305 (30)	288 (48)	260 (17)	587 (34)
Grain	752 (53)	892 (181)	792 (73)	732 (120)	2446 (198)

Table 3. Concentrations of mineral nutrients in two genotypes each of soybean and cowpea compared to maize grown at Ibadan. Concentrations (means of four replicates) are shown for shoots at flowering and stover, threshing residue and grain at maturity.

Species	Genotype	N	P	K	S	Ca	Mg	Na	Cl	Fe	Mn	Zn	Cu
		g kg ⁻¹								mg kg ⁻¹			
Flowering		Shoots											
Soybean	Tgm1293	35.2	3.10	28.21	3.14	10.33	5.06	0.36	0.73	531	245	43	11
	Tgm1196	27.0	4.03	25.18	3.46	11.79	5.49	0.32	0.72	700	265	84	11
Cowpea	IT82-716	41.2	4.50	42.90	4.95	15.13	4.71	0.66	9.33	812	487	47	12
	Dan-ila	39.4	3.80	40.08	4.84	16.56	4.83	0.47	9.52	919	477	54	14
Maize	Oba 1	14.8	2.73	25.46	1.20	2.26	1.77	0.31	6.58	257	107	38	5
<i>s.e.</i>		1.2	0.20	1.90	0.14	0.63	0.17	0.03	0.41	110	24	2	0.7
Maturity		Stover											
Soybean	Tgm1293	24.3	1.87	16.17	3.26	5.44	4.07	0.83	0.74	364	111	16	8
	Tgm1196	15.8	3.53	14.05	5.10	4.47	5.34	0.48	0.68	431	199	30	7
Cowpea	IT82-716	9.9	1.52	23.21	5.97	6.81	2.86	3.08	6.79	619	186	45	8
	Dan-ila	18.0	1.63	24.14	7.32	6.50	4.27	1.82	7.13	652	232	42	10
Maize	Oba 1	6.4	2.24	12.10	1.25	3.82	3.04	0.60	4.00	958	228	62	5
<i>s.e.</i>		1.8	0.42	1.33	0.29	0.46	0.25	0.19	0.62	95	28	7	0.7
		Threshing residue											
Soybean	Tgm1293	24.4	3.39	19.02	2.03	9.16	7.55	0.48	0.23	436	176	32	9
	Tgm1196	12.9	2.49	23.73	2.70	10.03	8.03	0.47	0.29	337	195	37	7
Cowpea	IT82-716	15.1	1.75	18.08	1.33	5.85	5.51	0.53	2.10	78	139	21	8
	Dan-ila	19.5	1.87	19.44	1.56	6.95	4.62	0.92	3.31	161	155	26	10
Maize	Oba 1	5.3	1.33	6.72	0.83	0.34	1.24	0.08	2.87	50	19	134	4
<i>s.e.</i>		1.0	0.26	0.94	0.11	0.36	0.29	0.02	0.14	21	7	5	0.3
		Grain											
Soybean	Tgm1293	80.7	7.44	22.32	4.25	4.84	3.32	0.17	0.10	92	81	63	18
	Tgm1196	69.4	8.62	23.39	5.21	4.97	3.40	0.17	0.11	123	110	84	18
Cowpea	IT82-716	41.9	4.94	14.28	2.41	0.84	1.81	0.18	0.40	49	27	37	6
	Dan-ila	42.0	4.33	14.70	2.64	1.10	2.08	0.29	0.62	61	33	46	9
Maize	Oba 1	15.6	8.65	9.11	1.49	0.13	2.99	0.08	0.78	53	15	63	3
<i>s.e.</i>		1.1	0.25	0.48	0.09	0.16	0.06	0.02	0.02	6	4	2	0.7

Crop residues at maturity. Stover of soybean had lower concentrations of K, S, Na, Cl and Zn than cowpea (Table 3). Of the two soybeans, Tgm1196 had lower N but higher P, S, and Mg than Tgm1293. Cowpea line IT82-716 had lower N, Mg and S than Dan-ila. Maize stover had lower N than the legumes except IT82-716, lower S and Cu than all the legumes, but similar concentrations of the other elements to the legumes. Nutrient concentrations in the threshing residues differed from those in stover, depending on the element and the species. Stover of all species had similar N concentrations to the threshing residues, but higher S, Na, and Cl. For soybean stover, concentrations of K, Mg and Ca were lower than in threshing residues, while for cowpea stover K was higher. Maize stover had higher concentrations of all elements, except Cu and Zn, than in the threshing residues. These differences between types of

residue, species and nutrients have implications for nutrient flows under different crop residue managements.

Seed. Soybean seed had nearly double the concentration of N found in cowpea seed, and higher concentrations than cowpea of P, K, S, Ca, and Mg and the micronutrients (Table 3). Concentrations of Cl were low in soybean seed, as in the crop residues and vegetative shoots. Soybean Tgm1196 had lower N and higher concentrations of P, S and Zn than Tgm1293, while Dan-ila cowpea had higher Mg, Na and Cl than IT82-716. Maize seed had lower concentrations of N, K, S, Ca, Na, Mn and Cu than the legume seeds.

Sums of anions and cations

Values for concentrations of the anions Cl, P and S shown in Table 3 can be expressed as molar charge concentrations and summed. The sum of anions in maize was $35 \text{ cmol}_{(-)} \text{ kg}^{-1}$ in shoots at flowering, $25 \text{ cmol}_{(-)} \text{ kg}^{-1}$ in crop residues and $39 \text{ cmol}_{(-)} \text{ kg}^{-1}$ in seed. The corresponding values for the legumes (mean of the two genotypes) were cowpea 71, 56 and $32 \text{ cmol}_{(-)} \text{ kg}^{-1}$, and soybean 34, 35 and $56 \text{ cmol}_{(-)} \text{ kg}^{-1}$, indicating that there are no general rules to describe the changes in anion concentration between flowering and maturity or the relative concentrations in seed compared with crop residue. Similar calculations of sums of the major cations, Na, K, Mg and Ca for maize shoots at flowering gave $93 \text{ cmol}_{(+)} \text{ kg}^{-1}$, for maize crop residues $70 \text{ cmol}_{(+)} \text{ kg}^{-1}$ and $49 \text{ cmol}_{(+)} \text{ kg}^{-1}$ for maize seed. The corresponding values for sums of cations in cowpea were 228, 133 and $59 \text{ cmol}_{(+)} \text{ kg}^{-1}$, and for soybean 169, 118 and $112 \text{ cmol}_{(+)} \text{ kg}^{-1}$. Thus, unlike anions the cations appeared to vary in a consistent manner, being highest in shoots at flowering in all species, and lowest in seed. Crop residue values were intermediate between shoots at flowering and seed (maize and cowpea) or the same as seed (soybean).

Concentration of excess cations

Shoots at flowering. Cowpea shoots had higher excess cation concentrations than soybeans, but the values for the two genotypes of each species were similar (Table 4). The value for maize was less than half that for the legumes.

Crop residues at maturity. Stover of soybean and cowpea contained lower concentrations of excess cations than shoots at flowering, but for maize the values were similar for these tissues at the two stages (Table 4). There were no significant differences between or within species for stover. However, the values for excess cations in threshing residues differed significantly between species. For soybean the values were similar to those for flowering shoots, whereas in cowpea they were about 30 % lower. Values for maize threshing residues were about 20 % of those for stover or flowering shoots.

Seed. Soybean seed contained higher concentrations of excess cations than cowpea, the reverse of the order in shoots. There were small but significant differences between

Table 4. Concentrations of excess of cations in dry matter at the start of flowering and at maturity, in crop residue† and seed of two lines each of soybean and cowpea compared with maize grown at Ibadan.

Crop species	Line	Excess cations (cmol _c kg ⁻¹)					
		Flowering shoots	Maturity				
			Stover	Threshing residue	Crop residue	Seed	Whole crop
Soybean	Tgm1293	136	78	135	89	59	78
	Tgm1196	134	72	154	79	53	69
Cowpea	IT82-716	156	69	104	77	25	57
	Dan-ila	159	67	102	76	30	57
Maize	Oba 1	58	52	12	45	10	31
<i>s.e.</i> (<i>n</i> = 4)		4	7	6	4	1	3

†Crop residue values are the weighted average of the stover and threshing residue, and whole crop values are the weighted average of crop residue and seed.

the genotypes of both legume species. Maize seed had a low value for excess cation concentration, less than 20 % of the concentration in stover or flowering shoots.

There were marked changes in concentration of excess cations between the flowering stage and maturity (Table 4). With the exception of threshing residues of soybean, values were lower at maturity than at flowering. Considering the mean value for all above-ground material at maturity, concentrations declined to about 50 % of the flowering value in soybean and maize, and 35 % in cowpea.

Nutrient, dry-matter and excess-cation harvest indices

There were marked differences in the harvest indices (HI) depending on the category (Figure 1). Approximately 40 % of the dry matter and K in tops at harvest was in the seed. A much larger proportion of N and P was in the seed, 60–70 % in the case of N and 60 % of the P in the legumes and 80 % in maize. In contrast, less than 15 % of the Cl was in the seed. The HI of Ca was higher in soybean than cowpea or maize, and the HI of Mg was higher in maize than the legumes and the HI of Zn was lower. The HI of excess cations varied from 15 % in cowpea to 27 % in maize.

Fashola and Shika sites

Excess cations in genotypes of soybean, cowpea, mucuna, lablab and maize

The excess cation values at the Fashola site were higher than at the Shika site; seed 48 and 47 cmol_c kg⁻¹, leaves 186 and 178 cmol_c kg⁻¹ respectively. These differences were significant (*p* < 0.01), but they were relatively small and the values presented are the means for the two sites (Table 5). The mean excess cation concentration in soybean leaves at flowering was 158 cmol_c kg⁻¹ compared to 242 cmol_c kg⁻¹ in cowpea leaves. In seed, the concentrations were lower than in leaves, but the ranking of the two species was reversed, soybeans averaged 57 cmol_c kg⁻¹ and the mean for cowpea seed was 38 cmol_c kg⁻¹. Maize had the lowest concentrations of excess cations in both leaves

Table 5. Excess cation concentrations in leaves at flowering and in seed of thirteen soybean lines, eight cowpea lines, mucuna, lablab and maize grown at Fashola and Shika. Excess cation values are means of the two sites. Units are $\text{cmol}_c \text{kg}^{-1}$ (*s.e.* for each mean is given in parentheses; $n = 8$).

Genotype	Leaves	Seed	Genotype	Leaves	Seed
Soybean lines			Cowpea lines		
Tgm1420	158 (3.3)	56 (0.8)	IT 82D-716	220 (5.1)	34 (1.1)
Tgm1511	164 (5.1)	59 (1.1)	IT 82D-849	277 (9.2)	39 (0.8)
Tgx1456-2E	143 (1.1)	53 (0.7)	IT 86D-715	258 (7.3)	41 (0.5)
Tgm1293	159 (2.2)	61 (0.9)	IT 89KD-374	212 (6.9)	40 (0.5)
Tgm1360	143 (4.4)	60 (0.9)	IT 89KD-349	249 (11.1)	44 (1.9)
Tgm1566	157 (2.8)	61 (2.6)	IT 89KD-391	260 (8.6)	37 (0.5)
Tgm944	154 (3.2)	57 (1.3)	IT 90K-59	233 (6.4)	34 (0.6)
Tgm1540	168 (4.4)	52 (1.1)	Dan-ila	232 (8.9)	38 (0.9)
Tgm1196	155 (5.6)	55 (0.6)			
Tgm1251	184 (5.2)	62 (1.6)			
Tgm1419	153 (5.6)	57 (0.5)	Mucuna	134 (7.2)	25 (1.8)
Tgm1039	159 (3.9)	58 (1.7)	Lablab	170 (5.7)	38 (1.1)
Tgm1576	157 (3.9)	57 (0.4)	Maize	87 (7.0)	12 (0.8)
			Other species		

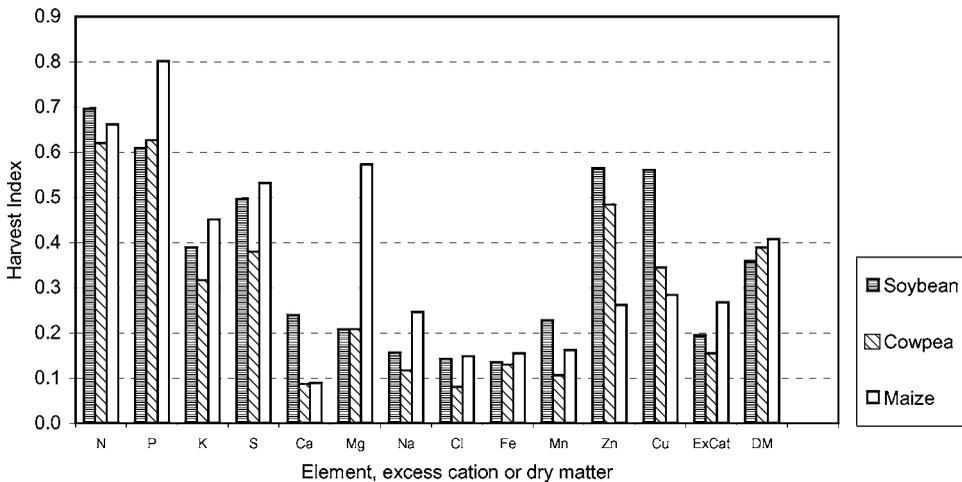


Figure 1. Harvest indices for nutrient elements, excess cations (ExCat) and dry matter (DM) for soybean, cowpea and maize crops grown at Ibadan. The harvest index is the amount in the grain expressed as a proportion of the total amount in the above-ground crop recovered at harvest. The soybean and cowpea values are the means of two lines.

and seed. Mucuna and lablab had concentrations in leaves similar to soybean, but the concentrations in seed were similar to or lower than cowpea.

Within the soybean genotypes, the excess cation concentrations ranged from 143–185 $\text{cmol}_c \text{kg}^{-1}$ in leaves and 53–62 $\text{cmol}_c \text{kg}^{-1}$ in seed. The range in cowpea was 232–277 $\text{cmol}_c \text{kg}^{-1}$ in leaves and 34–44 $\text{cmol}_c \text{kg}^{-1}$ in seeds. Although these genotypes differed significantly, the differences were relatively small, varying up to 10 % from the mean, and could probably be ignored in calculations of C cycle acidification.

DISCUSSION

The data obtained in this work can be used in decision-support models such as those developed by Smaling and Fresco (1993) to calculate nutrient balances in African farming systems. Losses of nutrients from the soil in products harvested and crop residues removed are a major contributing factor to the decline in soil fertility under cropping (Stoorvogel *et al.*, 1993), an issue of considerable concern in African agriculture (Nandwa, 2003). We have provided data for nutrient elements in addition to N, P and K, the three nutrients most often considered in nutrient budgets in Africa (Stoorvogel *et al.*, 1993). The site used at Ibadan was of low to moderate fertility, and the yields obtained were average for well-managed soybean and maize crops in the region and a little above average for cowpea (Table 2). Comparing the nutrient concentrations in the shoots at flowering (Table 3) with published information on critical and adequate nutrient concentrations in the three species (Reuter *et al.*, 1997), it can be concluded that the soybean and cowpea crops were not deficient in any of the nutrients measured, although the nutrient concentrations were at the lower end of the adequate range. For maize, the K and Mg concentrations were in the adequate range, while P and S were close to marginal concentrations. Nitrogen was probably deficient in maize considering that no N fertilizer was applied and the maize grain contained 15.6 g N kg^{-1} , which is close to the critical concentration (Reuter *et al.*, 1997).

Our study also provides data that can be used to estimate soil acidification arising from harvesting and removing grain and crop residues of maize, cowpea and soybean, three crops of importance in sub-Saharan Africa. The loss of fertility and increase in soil acidification due to removing crop residues has long been known (Jones, 1976). If uncorrected, such effects will potentially undermine progress towards increasing yields.

Mineral nutrient concentrations and contents

The two cowpea lines examined in the Ibadan field experiment had similar concentrations of nutrients in their seeds. By contrast soybean Tgm1293 had significantly higher N and lower P concentrations in the seed than Tgm1196. The higher N in Tgm1293 translates into an extra 70 g crude protein kg^{-1} seed (assuming a 6.25 conversion factor for N to crude protein). However, the higher N was not matched by a proportional increase in S, as the N/S ratio in seed of Tgm1293 was 19 compared to 13 for Tgm1169. If this difference is reflected in reduced cysteine and methionine contents, then the extra crude protein in Tgm1293 seed may be of low nutritional quality. It is also worth noting that seed of Tgm1196 had higher concentrations of Fe, Mn and Zn than Tgm1293 seed. Differences in protein and micronutrient concentrations would have implications for human or animal nutrition. Further, the apparent difference in seed crude protein could be important commercially because oil concentration may differ between the lines as oil and protein concentrations are often inversely related in seeds. The two soybean lines have similar HI for P, indicating similar translocation efficiencies (Figure 1). The lower P concentration in seed of Tgm1293 may indicate a higher utilization efficiency for P (more dry matter per unit

of P). In the experiments at Fashola and Shika, P concentration in seed was also lower in Tgm1293 compared to Tgm1196 (data not shown) but N was not measured. This suggests that differences between genotypes need to be further examined with respect to the potential for selection for traits associated with P efficiency, and the nutritional and commercial value of the seed evaluated.

Between flowering and maturity there was a decline in the concentrations of many nutrients in the plants. The extent of the decline varied markedly with nutrient, plant part and plant species (Table 3). Compared with shoots at flowering, the concentration of K, for example, was lower in stover and seed and marginally lower in threshing residues. At flowering, soybean had lower K than cowpea, but in seed the ranking was reversed. Changes in concentration of Ca followed a similar pattern, the marked reversal of ranking of these species for Ca concentration between flowering and seed can be seen in Figure 2. The difference between soybean and cowpea in seed Ca concentration is reflected in the respective harvest indices for Ca (Figure 1). It appears that the translocation of Ca to the seed of cowpea is considerably more limited than to the seed of soybean, although the cause of this difference is not clear.

Concentrations of many nutrients in plants are known to decline with plant age due to rates of dry-matter accumulation exceeding nutrient uptake (Walworth and Sumner, 1987). However, calculations using data in Tables 2 and 3 showed that the quantities of most nutrients in the crop increased over this time (up to 2-fold in the legumes and 1.5- to 3-fold in maize) except in a few cases only: total K in the maize was 12 % lower at maturity than at flowering; total Ca and Mn increased in maize, but decreased by 12 to 25 % in the legumes. These decreases suggest a loss of the nutrient. Such losses could also account in part for the decline in concentration between flowering and maturity for the other nutrients. The mechanisms of nutrient loss from the crop were not investigated. Leaching could account for losses of nutrients present in plants in soluble forms, such as K, but is unlikely to cause losses of Ca or Mn that usually accumulate in plants in insoluble, precipitated forms. It is known that trichomes of some species accumulate specific nutrients; for example, trichomes of sunflower accumulate Mn (Blamey *et al.*, 1986) and loss of such cells would reduce the total amount in the plant. Also, the loss of leaves following the withdrawal of mobile nutrients during senescence may account for the loss of an immobile element such as Ca.

Although removal of Cl in products is unlikely to result in Cl deficiency, it is worth noting that Cl concentration differed markedly between the three species. Soybean had less than 10 % of the Cl concentration in flowering shoots and crop residues of cowpea, and maize also had high concentrations. Sodium concentrations in vegetative shoots and stover were lower in soybean than cowpea. Lauchli (1984) showed that soybean excluded Cl when it was supplied in high concentration, and the ranking of these species for Cl concentration probably reflects their relative salt-tolerances, as soybean is considered moderately salt tolerant while cowpea and maize are moderately sensitive (Francois and Maas, 1999). Genotypic differences in tissue Cl have been reported in soybean (Abel and MacKenzie, 1964), but the two lines grown at Ibadan did not differ in tissue Cl concentration. However, among the 13 lines of soybean grown at

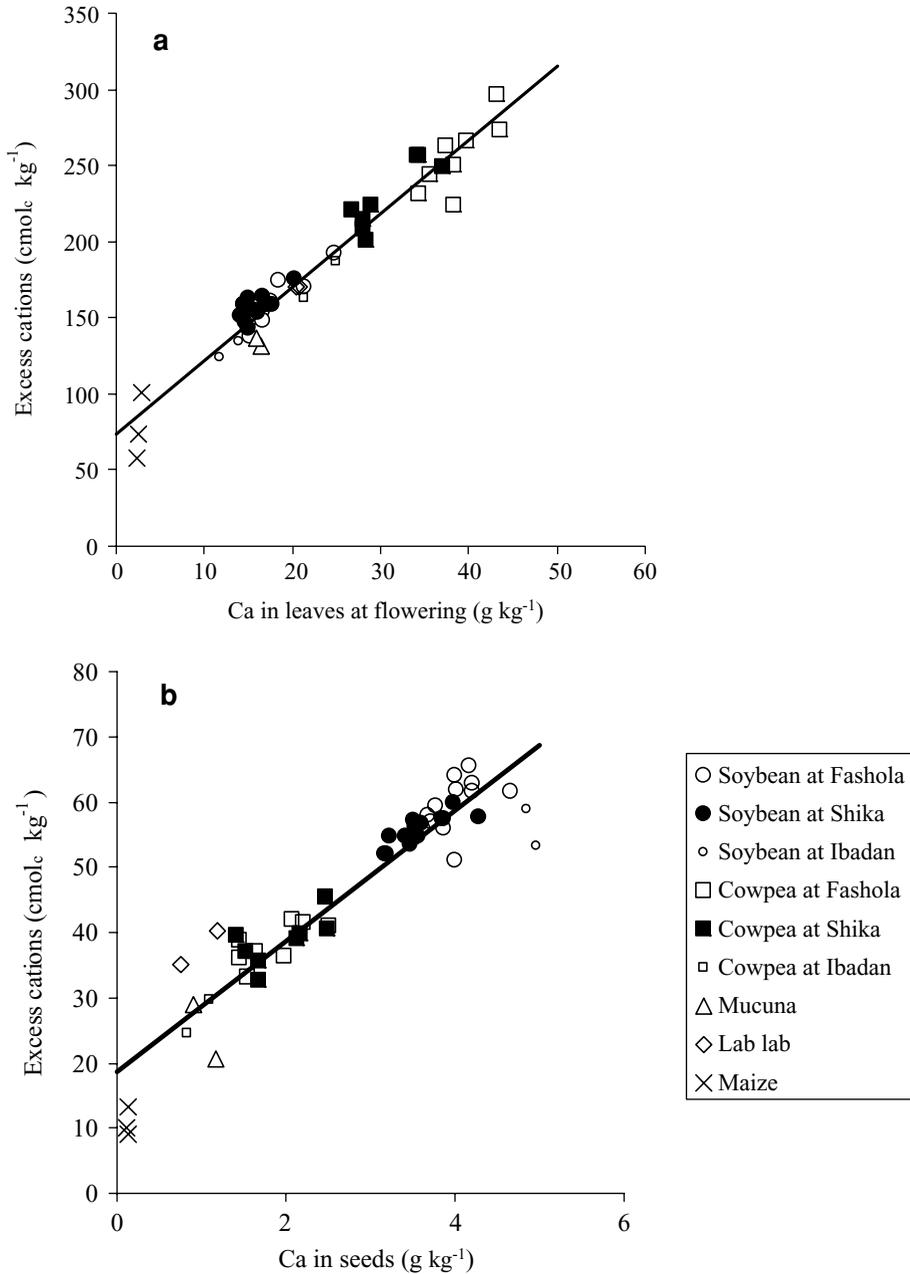


Figure 2. The relationship between excess cations and calcium concentrations in 13 soybean and eight cowpea lines, mucuna, lablab and maize grown at Fashola and Shika, and two soybean, two cowpea and one maize line grown at Ibadan. (a) Leaves at flowering (except for maize from all sites and the legumes from Ibadan where the data are for whole shoots). (b) Seed at maturity. The data points are the means of the four replicates. The regression lines were fitted to the means. In (a) excess cations = $74.1 + 4.8 \text{ Ca}$, $r^2 = 95\%$; $n=52$, and in (b) excess cations = $18.6 + 10.0 \text{ Ca}$, $r^2 = 89\%$; $n=52$, where excess cations are in $\text{cmol}_c \text{ kg}^{-1}$ and elements in g kg^{-1} .

Fashola, Cl concentrations in leaves varied from 0.2 to 2.1 g Cl kg⁻¹. There were also differences among the eight lines of cowpea at that site with concentrations in leaves ranging from 1.6 to 5.8 g Cl kg⁻¹.

Removals of nutrients

The concentrations of various nutrients removed in dry matter harvested at either flowering or maturity (Table 3) are useful for estimating nutrient removals per hectare, provided the relevant dry matter yields are known. Given the yields from the field trial at Ibadan (Table 2), harvesting and removing seed, threshing residues and stover of the crops (mean of two lines for each legume) would have removed (kg ha⁻¹):

Soybean: 90 N, 11 P, 42 K, 10 S, 13 Ca, 11 Mg, 0.33 Mn, 0.09 Zn, 0.03 Cu.

Cowpea: 50 N, 6 P, 39 K, 9 S, 9 Ca, 6 Mg, 0.26 Mn, 0.08 Zn, 0.02 Cu.

Maize: 60 N, 28 P, 62 K, 8 S, 12 Ca, 17 Mg, 0.72 Mn, 0.42 Zn, 0.02 Cu.

The larger amounts removed in maize compared to the legumes reflect mainly the relative crop yields.

Excess cation concentrations

Concentrations of excess cations in the legumes were substantially higher than in maize, and this is a consequence of the higher concentrations of K, Mg and Ca in the legumes, despite their higher concentrations of P and S. The range of excess cation concentrations at the flowering stage in soybean crops in our study (135–165 cmol_c kg⁻¹) overlapped the range in ash alkalinity reported by Pierre and Banwart (1973) for soybean at a similar stage (106–143 cmol_c kg⁻¹). Our values for maize (58–87 cmol_c kg⁻¹) also overlapped those of Pierre and Banwart (1973) for this species (38–81 cmol_c kg⁻¹). Maize seed had 10–12 cmol_c kg⁻¹ excess cations, a value between the 5 cmol_c kg⁻¹ reported for maize seed (Pierre and Banwart, 1973) and the 14–18 cmol_c kg⁻¹ in some other cereal grains (Slattery *et al.*, 1991). The grain legumes had higher excess cation concentrations than maize, and the range of values for soybean seed (53–62 cmol_c kg⁻¹) and cowpea seed (25–44 cmol_c kg⁻¹) was within the range reported by McLay *et al.* (1997) and Slattery *et al.* (1991) for seed of other grain legumes (29–71 cmol_c kg⁻¹). Maize stover contained 52 cmol_c kg⁻¹ excess cations, close to the value of 54 cmol_c kg⁻¹ calculated from data of Pierre and Banwart (1973).

The excess cation values for individual species are often reported as ranges (Pierre and Banwart, 1973). Values for seed of soybean and cowpea genotypes in Table 5 differed up to 8–10 % from the species mean, showing that genotypic differences could partly account for the variation. The differences in mean values between the Ibadan site (Table 4) and the other sites (Table 5) show that site or season effects could have a larger effect than genotype. According to Santonoceto *et al.* (2002) site is more important than season in explaining variation in excess cation concentration within a genotype.

The decrease in concentrations of excess cations in shoots between flowering and maturity (Table 4) is likely to be due, in part, to the different rates of accumulation of anions and cations during crop growth (Table 3). In addition, particularly for the legumes, there was a loss of Ca between these stages which could be due to the shedding of senescent leaves. Leaves of plants are usually higher in concentrations of excess cations than stems (Pierre and Banwart, 1973) and, consequently, excess cation concentrations would fall as leaves are shed.

Relationship between excess cation concentration and concentrations of individual ions

For shoots at flowering, there was a strong relationship between excess cation values and Ca concentrations (Figure 2a). The relationship held for all species at all sites, suggesting that for this set of species at flowering, a measurement of Ca in leaves could be used to predict excess cation concentration. Although concentrations of K were two-fold or more higher than those of Ca (Table 3), K concentrations were not related to excess cation concentrations, and neither were Mg or Na concentrations. Regression relationships with individual major anions were also poor. Earlier work has shown Ca to be a good predictor of excess cation concentrations in tree litter samples (Noble *et al.*, 1996), and in some other grain legumes (McLay *et al.*, 1997).

For seed of the same set of genotypes (Figure 2b), there was a relationship between excess cation values and Ca concentrations, but not as strong as for shoots at flowering, and unlike the latter, there was also a relationship with K concentration (excess cations = $19.0 + 4.02 K$, $r^2 = 80\%$; $n = 52$, where excess cations are in $\text{cmol}_c \text{kg}^{-1}$ and elements in g kg^{-1}) and more of the variation was explained if both Ca and K were included in the regression (excess cations = $6.21 \text{ Ca} + 2.03 \text{ K} - 2.74$, $r^2 = 95\%$). Santonoceto *et al.* (2002) working with oilseed crops also found that excess cations could be related to both Ca and K, but unlike the current study, the relationship held for shoots at flowering as well as seeds.

It appears that Ca is quite consistently related to excess cations in the range of genotypes used and the material sampled, but that the involvement of K depends at least on species, stage of growth and tissue sampled. On the evidence available in Figure 2 and in Santonoceto *et al.* (2002), these relationships hold over locations and seasons. Over a range of conditions, Ca concentration appears to be the most useful surrogate for excess cation concentration, but the relationship needs to be determined empirically in each case.

Removals of excess cations and implications for soil acidification

The data for excess cations in shoots at flowering provide estimates of the quantities of alkalinity mobilized from the root zone to the shoots and the amount that would be removed from the field if the crop was cut for hay or green fodder at that stage. The excess cation values can be converted to lime equivalents, assuming that 50 g CaCO_3 is required to neutralize 1 mol excess cations (i.e. 1 mol H^+). Based on the yields obtained, soybean shoots at flowering contained 103, cowpea 58, and maize 80 kg lime equivalent ha^{-1} (Table 6). Removal of the seed and all residues at maturity would

Table 6. Amounts of excess cations, expressed in lime equivalents†, at flowering and at maturity of the crops grown at Ibadan.

Species	Flowering shoots	Maturity			Total
		Stover	Threshing residue	Seed	
		kg lime ha ⁻¹			
Soybean	103	40	21	23	84
Cowpea	58	33	14	10	57
Maize	80	77	4	12	93

†Calculated from yield (Table 2) and excess cation concentrations (Table 4); values for soybean and cowpea are the means of the two lines; 1 kmol(+) is equivalent to 50 kg CaCO₃.

remove less alkalinity than removal of the crop at flowering in the case of soybean, similar amounts for cowpea, and more for maize, the change between flowering and maturity depending on the relative decline in excess cation concentration in the crop and the relative increase in dry-matter yield between the two stages.

The lime equivalent values for soybean seed (28 kg t⁻¹) and cowpea seed (13 kg t⁻¹) are of the same order as reported for some other grain legumes (15–36 kg t⁻¹ seed) (McLay *et al.*, 1997; Slattery *et al.*, 1991). The seed contributed 27 % of the alkalinity in the whole above-ground crop at maturity for soybean, 17.5 % for cowpea and 13 % for maize (Table 6). The threshing residues of the legumes contributed a similar amount, but the largest contribution (48–83 % depending on species) came from the stover. The amount of acidification due to seed removal is the irreducible minimum that occurs due to cropping through C cycle effects. Given the low harvest index for cation excess (0.15–0.28; Figure 1), soil acidification will be much greater if crop residues are removed as well. Consequently, the management of crop residues is an important issue when considering the effect of cropping on soil acidification caused by C cycle processes. The present data could be used to compare the acidification effect of partial or complete removal of residues by grazing of stubbles to practices aimed at retaining crop residues in the field to decompose *in situ*. It should be pointed out that although retention of residues results in lower net acidification, it effectively transfers alkalinity from the root zone to the surface, leading to a stratification of pH in the profile. In some soils, this process results in an acid, phytotoxic sub-surface horizon that restricts root growth and prevents crops accessing water and nutrients from depth (Helyar and Porter, 1989).

Using the pHBC values determined for the soil in the surface 16 cm at the Ibadan site and assuming that C cycle acidification was confined to that layer, then it can be calculated that a fall in soil pH of one pH unit in the surface 16 cm layer would occur from the removal of the following quantities (t dry matter ha⁻¹):

- (a) crop at flowering (e.g. as hay) – soybean 94, cowpea 81, maize 218
- (b) seed at maturity – soybean 226, cowpea 460, maize 1260
- (c) crop residues at maturity – soybean 151, cowpea 165, maize 281.

Given the yields in Table 2, a fall of one pH unit would occur after 276, 607 and 517 crops for soybean, cowpea and maize respectively, if seed only was removed and crop residues remained in the field. This change in soil pH would occur in one-quarter of the time or less if crop residues were removed as well as the seed, after 75 crops of soybean, 114 crops of cowpea and 68 crops of maize.

The above estimates indicate that soil acidification due to disruption of the C cycle caused by removal of alkalinity in crop material is not of immediate concern. However, the C cycle represents only part of the total acidification due to cropping, and in many agricultural systems acidification due to the N cycle greatly exceeds that due to the C cycle (Kennedy, 1992). The risk of acidification due to the N cycle increases when soil N status is raised by applying fertilizers or using N-fixing legumes to increase productivity, if this leads to an accumulation of nitrate in the soil and the nitrate is leached. Substantial leaching of nitrate has been reported in West African cropping systems; for example, leaching accounted for up to 85 % of N output from an oxisol continuously cropped to maize in Togo (Poss and Saragoni, 1992). In the northern Guinea savanna of Nigeria at the higher fertility site studied by Oikeh *et al.* (1998), 60 kg N ha⁻¹ was lost from under a maize crop that followed maize, while 150 kg N ha⁻¹ was lost when the maize followed soybean. In Oikeh's study the seasonal rainfall was 939 mm (compared to 1350 mm at Ibadan; Table 1) and the losses were attributed mainly to leaching of nitrate. Such losses of N would contribute 4.3 and 10.7 k mol H⁺ respectively. This compares with 0.42 and 0.52 k mol H⁺ contributed by removal of grain and 3.7 and 4.6 k mol H⁺ contributed by removal of stover (calculated from the excess cation values for grain and stover (Table 4) and the yields reported in Oikeh *et al.* (1998). It should be noted also that ammonium-based fertilizers inevitably acidify the soil (Adams and Pearson, 1967; Pierre, 1928).

CONCLUSIONS

The selection of grain legume genotypes adapted to conditions in the savannas of sub-Saharan Africa and their integration into maize- and millet-based cropping systems has been a highly successful strategy for improving soil N status and increasing productivity and farm income in that region (Sanginga *et al.*, 2003). In order to maintain such increased productivity in the long term, issues of accelerated nutrient depletion and soil acidification have to be considered. This study attempts to quantify the likely effects on these processes of removing crop residues and grain of two important grain legumes and maize from the land. Low rates of acidification can be expected where grain is harvested and removed. If crop residues are removed as well, then the rate of acidification would increase considerably. Using the pH buffer capacity measured in the soil from one of the experimental sites, we have attempted to predict the consequences of crop removal on soil pH. This study has dealt only with the consequences of removing grain and crop residues. The role of the N cycle on soil acidification was not considered in our experiments, although its effects usually exceed those of the C cycle and other work has clearly shown the importance of nitrate leaching in cropping systems in sub-Saharan Africa. Further research is needed to quantify

nitrate leaching in these cropping systems and to develop management practices to minimize acidification due to the N cycle (Oikeh *et al.*, 2003). A progressively declining soil pH initially has little effect on plant production, but once critical pH levels are reached, soluble Mn and Al reach phytotoxic levels. The consequent decline in crop growth can be circumvented in many cases by resorting to tolerant cultivars (Pandey and Gardner, 1992). However, this is unlikely to be a permanent solution in the face of continuing acidification, and the loss of fertility through leaching of basic cations as soils acidify (Poss and Saragoni, 1992) is not so readily dealt with. Agricultural productivity in sub-Saharan Africa must be raised by all means possible in order to improve the living standards of the people, but it would be unwise not to add the proviso that some of the increased yields should be used to generate cash flow to pay for lime to replace the alkalinity removed from the land in products, and to purchase fertilizer to replace the nutrients those products contain. Such replacement is a key requirement for sustaining production into the future.

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