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Article *in* Plant and Soil · January 2009

DOI: 10.1007/s11104-008-9714-1

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Plant Soil
DOI 10.1007/s11104-008-9714-1

REGULAR ARTICLE

Assessment of nutrient deficiencies in maize in nutrient omission trials and long-term field experiments in the West African Savanna

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Received: 6 March 2008 / Accepted: 30 June 2008

Abstract Low soil fertility is one of the main constraints to crop production in the West African savanna. However, the response of major cereals to fertilizer applications is often far below the potential yields. Low fertilizer efficiency, inadequacy of current fertilizer recommendations, and the ignorance of nutrients other than N, P, and K may limit crop production. Nutrient limitations to maize production were identified in on-farm trials in Togo and in several long-term experiments in Nigeria and Benin. Maize ear leaf samples were analyzed for macro and micro-nutrients, and the Diagnosis and Recommendation Integrated Systems (DRIS) was applied to rank nutrients according to their degree of limitation to maize. In the on-farm trials, both yield and DRIS results indicated that, when N is supplied, P limited maize production in all fields, reducing yields by 31% on average. Sulfur was limiting in 81% of the fields and was responsible for an average yield reduction of 20%. In the long-term experiments where N, P, and K had been annually applied, Ca and Mg indices were strongly negative, indicative of deficiency. Zn indices were negative in all trials. Despite N-fertilizer additions, N indices remained negative in some of the long-term experiments, pointing to low efficiency of applied fertilizers. There was a direct link between DRIS indices and the management imposed in the different experiments, indicating that DRIS is a useful approach to reveal nutrient deficiencies or imbalances in maize in the region.

Keywords DRIS · Ear leaves · Fertilizers · Nutrient indices · Organic inputs

Responsibe Editor: Ismail Cakmak.

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Introduction

In many parts of Africa, land use intensification without adequate nutrient inputs has led to declining crop yields and accelerated nutrient removal and deficiencies to plants (Bationo et al. 1998; de Ridder et al. 2004). Problems with poor soil fertility in West Africa savanna are increasingly addressed by the application of fertilizers containing primarily N, P, and K, though still used at inadequate rates with the overall average applications for all crops of (kg ha^{-1}) 46 (N), 22 (P), and 16 (K) although with very large variations (Vanlauwe et al. 2002). Despite a general response of cereals, such as maize, to the application of NPK fertilizers at current recommendations, the response often remains far below the potential level, especially under on-farm conditions. Increasing yields as a consequence of NPK fertilization, however, accelerates the depletion of nutrients not supplied and does lead to nutrient deficiencies or imbalances. Part of the reason why the yield potentials are rarely reached, despite NPK addition, may be due to other nutrient limitations, although other factors (water stress, diseases, weeds, management,…) may as well play an important role. Responses of maize to S and Zn have been reported before on savanna soils of western and southern Africa (Kang and Osiname 1976; Friessen 1991; Ojeniyi and Kayode 1993; Weil and Mughogho 2000). However, no sufficient information is available to establish the scale of these deficiencies, and a strategy to address these deficiencies is lacking. Beside yield, nutrient deficiencies may affect the nutritional quality of the harvested products. For example, sulfur deficiency in the crop leads to lower protein quality for humans and livestock by lowering the levels of the essential sulfur containing amino acids methionine and cysteine (Zhao et al. 1999). These amino acids are considered to be important in promoting the absorption of Fe and Zn in humans (Snedeker and Greger 1983).

Different approaches to improve soil fertility in the savanna have been used, including green manure, cover crops, crop rotations, and alley-cropping; all of them aiming at improving soil nutrient status as well as soil organic matter (Carsky et al. 1999; Schulz et al. 2001; Carsky et al. 2001; Bationo et al. 2003). However, the major focus has been on N and to some extent on P with little or no information on the long-term effects of these approaches on other nutrients. The objectives of the study were to document nutrient limitations to maize in the West Africa savanna, based on on-farm trials and on long-term soil fertility experiments; and secondly, to test the potential of the Diagnosis and Recommendation Integrated System (DRIS) as a tool to identify nutrient deficiencies in maize.

Materials and methods

Nutrient omission trials

Nutrient omission trials were conducted in the 2004 and 2006 growing seasons in two villages, Affem (9° 9′N, 1°30′E) and Sessaro (8°38′N, 1°10′E), in the central region of Togo. The trials consisted of 18 farmers' fields in 2004 and of 20 farmers' fields in 2006. The selection of fields excluded sloping and hydromorphic fields. Every individual farmer's field in the trial was considered as a replicate (block) and the experimental field size for each farmer was 30 m× 10 m. Soil samples were taken in the fields before the start of the experiment, at 0–10 and 10–20 cm depths. For each field and each depth a composite sample was taken consisting of 12 cores taken along each diagonal of the field. Soils in the two villages cover the typical range of cultivated soils in the savanna with sandy loam or loamy sandy texture and pH ranges between 4.8 and 6.8 (Table 1). A village survey classified all soils in the fields in Affem under the order of Acrisols, whereas soils in the fields in Sessaro were either Acrisols or Cambisols (FAO 1998). Olsen P in all fields and all years was below the critical threshold value of 12 mg kg^{-1} (Vanlauwe et al. 2002). Each farmer's field was subdivided in eight parallel plots of 10 m×3 m, and eight treatments were randomly allocated to these plots (Table 2). The treatments included a treatment which received all nutrients considered in the study (N, P, K, S, Zn, B) with P applied at 40 kg ha^{-1} and referred to as P40 in the text, a treatment in which the P rate in P40 was reduced by half (P20), five treatments in which the nutrients, P, K, S, Zn, and B, were omitted one at a time, and a farmer practice treatment where the farmer managed the plot as he/she wished (Table 2). All plots, except the farmer practice treatment plots, received N at 120 kg N ha^{-1}. Nutrients were applied as urea (N); TSP (P); $(NH_4)_2SO_4$ (S); muriate of

Table 1 Selected soil properties in the top 10 cm of fields used in the nutrient omission trials (minimum, maximum and mean)

Parameter		2004		2006	
		Affem *n*=8	Sessaro *n*=10	Affem *n*=10	Sessaro *n*=10
pH_{water}	Range	5.6–6.3	5.9–6.6	4.8–6.0	5.0–6.8
	Mean	5.9	6.3	5.6	5.8
Org C (%)	Range	0.6–1.1	0.6–1.1	0.4–1.3	0.5–1.5
	Mean	0.86	0.81	0.79	0.79
Total N (%)	Range	0.03–0.09	0.03–0.09	0.05–0.13	0.01–0.12
	Mean	0.06	0.05	0.07	0.06
Olsen P (mg kg^{-1})	Range	1.3–3.2	1.2–7.3	3.1–7.8	2.2–8.9
	Mean	2.32	2.83	4.9	4.5
Exch Ca ($cmol_c$ kg^{-1})	Range	1.7–3.9	2.3–5.5	1.6–5.2	1.7–5.9
	Mean	2.85	3.83	2.5	3.2
Exch Mg ($cmol_c$ kg^{-1})	Range	0.4–1.1	0.8–1.9	0.5–1.4	0.6–1.4
	Mean	0.77	1.13	0.7	0.9
Exch K ($cmol_c$ kg^{-1})	Range	0.1–0.3	0.1–0.3	0.2–0.3	0.2–0.4
	Mean	0.16	0.19	0.2	0.2
Sand (%)	Range	70–82	67–83	73–81	68–83
	Mean	78	76	77	76
Silt (%)	Range	5.6–12	5.6–14	8–16	8–16
	Mean	8.1	10.2	10.9	11.8
Clay (%)	Range	10–18	9.6–18.8	10–14	10–16
	Mean	13.8	13.6	11.5	11.5

potash (K); ZnCl (Zn); and BCl (B). All fertilizers except urea were broadcast and incorporated in the upper 10 cm of the soil prior to maize planting. Urea was split-applied (one half at 2 weeks after planting and the other half at 6 weeks after planting). The open-pollinated maize variety, Ikenne 8149, was sown at 0.75×0.50 m and thinned to two plants per stand (53,333 plants per hectare). Maize was harvested at maturity in a net plot of 9 m^2 (the two middle rows in each plot, excluding 2 m at each end of a row), and grain yields were presented at 12% moisture.

Table 2 Treatments applied in the nutrient omission trials conducted in two villages in central Togo

Treatments	Code	Nutrients added
Farmer practice[a]	FP	As farmer wished
N120P40K80S26Zn5B1	P40 = control	N, P, K, S, Zn, B
N120P20K80S26Zn5B1	P20	N, P, K, S, Zn, B
N120K80S26Zn5B1	P0	N, K, S, Zn, B
N120P40K80Zn5B1	S0	N, P, K, Zn, B
N120P40S26Zn5B1	K0	N, P, S, Zn, B
N120P40K80S26B1	Zn0	N, P, K, S, B
N120P40K80S26Zn5	B0	N, P, K, S, Zn

The numbers in the treatments indicate the rate of application of the nutrient in kg ha^{-1}

[a] Farmer managed the plots as they wished. No record of the management was made.

Long-term experiments

Long-term experiments have been established at various locations to explore strategies for improving soil fertility in maize-based systems in the savanna. In this study, we considered five experiments (Table 3):

1. a 20-year-old experiment, referred to as D2, located in the derived savanna zone of South-West Nigeria, Ibadan (7°30′N, 3°54′E) consisting of maize grown (1) in alley-cropping systems with either *Senna siamea* or *Leucaena leucocephala*, (2) in relay-cropping with *Mucuna pruriens* or (3) with no organic inputs (control). In all systems, maize is grown with or without application of N, P, and K fertilizers (Vanlauwe et al. 2005);
2. two 9-year-old experiments conducted simultaneously from 1998–2006 at two sites: the derived savannah zone of south-west Nigeria, Ibadan (7° 30′N, 3°54′E) referred to as WBE in the text, and the northern Guinea savannah zone, northern Nigeria (10°24′N, 7°42′E) referred to as Shika.

Table 3 Soil type, cropping systems and fertilizer rates in long-term experiments from which ear leaves were sampled

Location	Code	Trial duration and replicates	Soil type (FAO 1988)	Cropping system with maize	Fertilizer input ($kg\ ha^{-1}\ year^{-1}$) N	P	K	S	Reference
Zaria (North Nigeria, northern Guinea savannah zone, 1,050 mm rainfall $year^{-1}$)	Samaru	1997–2006 (3 reps)	Chromic Luvisol	Relay-cropping or rotation with legume (Lablab, Centrosema, Cowpea)	0/120	0/30	0/30	0	Vanlauwe et al. 2001
				Various combination of organic matter (Parkia, cowdung and poultry manure) with fertilizers, but supplying an equal N rate of 90 kg ha^{-1}	0–90	30	30	0	
	Shika	1998–2006 (4 reps)	Haplic Lixisol	Maize in rotation with legume (green manure, forage, dual-purpose legume, grain legumes) or with natural fallow	0/60	40	33	28	Franke et al. 2008
				Continuous maize in N response test	0–120	40	33	28	
Ibadan (South West Nigeria, derived savannah zone, 1300 mm rainfall y^{-1})	WBE	1998–2006 (4 reps)	Plinthic Luvisol	Maize in rotation with legume (green manure, forage, dual-purpose legume, grain legumes) or natural fallow	0/60	17	33	0	Franke et al. 2008
				Continuous maize in N response test	0–120	17	33	0	
	D2	1986–2006 (5 reps)	Ferric Lixisol	Alley-cropping (Senna, Leucaena)	0/120	0/30	0/30	0	Vanlauwe et al. 2005
				Relay-cropping with Mucuna					
				Control (no organic inputs)	0/120	0/30	0/30	0	
Sekou (South West Benin derived savannah zone, 1200 mm rainfall y^{-1})	Sekou	1997–2006 (3 reps)	Rhodic Nitisol	Relay cropping with legume (Mucuna, Cajanus)	0/120	0/30	0/30	0	Vanlauwe et al. 2001
				Various combination of organic matter (Senna) with fertilizers, but supplying an equal N rate of 90 kg ha^{-1}	0–90	30	30	0	

These trials compared 1 or 2-year rotations of maize with a natural fallow or with legumes: a forage legume (*Stylosanthes guianensis*), a green manure legume (*Pueraria phaseoloides*), a dual-purpose legume (forage and edible grain; dual-purpose soybean) or grain legumes (grain cowpea and grain soybean). Adjacent to these trials, N response tests were established at both sites cultivating maize annually with 0, 30, 60, 90 or 120 kg N ha^{-1} applied as urea (Franke et al. 2008). In each rotation system, plots were subdivided into 2 subplots; one received 60 kg N ha^{-1} and the other one without N fertilization. Phosphorus and K were applied in all subplots. Shika experiment started receiving S application as SSP in 2002 after a pot experiment revealed S deficiencies at the site (Schulz et al. 2002);

3. two 10-year-old organic–inorganic interaction trials, one in the derived savanna in south-west Benin, Sekou (6°37′N, 2°14′E) and the other in the Northern Guinea savanna in North Nigeria, Samaru (11°11′N, 7°38′E), which study the effects of various combination of ex situ produced organic inputs (*Senna siamea* prunings, *Parkia biglobosa* prunings, cow dung and poultry manure) with N fertilizers at equal N application on maize, and in situ organic matter production in relay-cropping or rotation of maize with different legume species (*Lablab purpureus*, *Centrosema pascuorum*, *Mucuna cochinchinensis*, *Cajanus cajan*). At both locations, N response tests were established with continuous cultivation of maize with application of urea at 0, 45 and 90 kg N ha^{-1}. Within a system in the in situ organic matter production, N, P and K from fertilizers were either applied or omitted altogether or one at a time.

Treatments in the long-term experiments were laid out as randomized complete block designs with three to five replicates (Table 3).

Maize ear leaf samples and analyses

Maize ear leaf samples were taken between tasseling and silking (±60 days after planting) in all treatments of the nutrient omission trials in 2004 and 2006, and in the long-term experiments in 2006 except for the Sekou trial which was sampled in 2005. The number of ear leaves sampled per plot varied between 18 and 25 depending on the size of the plot. Samples were oven dried at 65°C and ball-milled. For N analysis, ground ear leaf samples were digested in hot sulphuric acid solution in the presence of Se as catalyst (Novozamsky et al., 1983), followed by colorimetric N analysis on a Technicon autoanalyser using the indophenol blue method (Searle, 1984). For the determination of other nutrients, ball-milled samples were digested with nitric acid and the nutrient content in digest determined on inductively coupled plasma optical emission spectrometry (ICP-OES Optima 3300 DV, Perkin Elmer, Norwalk, USA).

Data analysis

DRIS analysis

Based on the nutrient concentrations in ear leaves, the Diagnosis and Recommendation Integrated System (DRIS; Beaufils 1973) was applied to generate nutrient indices applied in the assessment of the nutrient status in the maize. The DRIS uses a system of nutrient ratios and ranks nutrients according to their importance in limiting yields. DRIS indices are calculated based on ratios of each nutrient relative to all other nutrients using the equations below by Walworth and Sumner (1988):

If we consider hypothetical nutrients A through N, then:

$$A\ index = \frac{f(A/B)+f(A/C)+f(A/D)+\ldots+f(A/N).}{n}$$
$$B\ index = \frac{-f(A/B)+f(B/C)+f(B/D)+\ldots+f(B/N).}{n}$$
$$N\ index = \frac{-f(A/N)-f(B/N)-f(D/N)-\ldots-f(M/N).}{n}$$

where *A*/*B* denotes the ratio of the concentrations of nutrients A and B in the maize ear leaves, n is the number of nutrients considered, and *f*(*A*/*B*) is a function of the form:

$$f(A/B) = \left(\frac{A/B}{a/b} - 1\right)\frac{1{,}000}{CV} \quad if\ A/B \geq a/b \quad or$$
$$f(A/B) = \left(1 - \frac{a/b}{A/B}\right)\frac{1{,}000}{CV} \quad if\ A/B < a/b$$

where *a*/*b* is the norm for the ratio of nutrients A and B, and CV is the coefficient of variation associated with that norm.

Norms are established after distinction between high-yielding and low-yielding subpopulations of a large population of observations. Norms are the average ratios from the high-yielding subpopulations. In sub-Sahara

Africa, no norms have been established for maize yet, except for South Africa where norms for only few nutrients have been calculated. We have therefore used norms reported in literature for a subpopulation yielding over 10,000 kg ha^{-1} (Escano et al., 1981). However we used our small database (695 observations) as an attempt to verify the appropriateness of used norms, considering high yielding subpopulation as that yielding at least 4,000 kg ha^{-1}. The resulting high-yielding subpopulation in our case represented 13% of the database. The comparison of norms calculated from our small database and those provided in literature were similar for ratios of major nutrients (N, P, Ca, Mg, S) with a deviation of 1–15% from the norms in Escano et al. (1981). However, norms generated from our database for ratios involving micronutrients (Zn, Cu) were very different from those in literature, most probably because micronutrients were not supplied at any time in our experiments. We therefore judged that the norms in Escano et al. (1981) were appropriate to be used in this study. DRIS indices can range from negative to positive depending on whether a nutrient is deficient, sufficient or excessive relative to other nutrients considered. The more negative an index is, the more imbalanced or deficient that nutrient is relative to others. In our study we calculated indices for N, P, K, Ca, Mg, S and Zn.

Statistical analysis

The effects of fertilizer application rates on maize yield and nutrient concentrations in the nutrient omission trials were determined through analysis of variance with a mixed model (SAS Institute 1992), treating farm as a random classification variable. Data from each village and each year were analyzed separately. Where the analysis of variance was done in the long-term trials, the experimental block was considered as a random variable.

Results

Maize grain yields and nutrient concentrations

Nutrient omission trials

In the nutrient omission trials, maize grain yields ranged between 438 and 4,696 kg ha^{-1} in 2004 and 533 and 5,463 kg ha^{-1} in 2006 (Table 4). Fertilizer application significantly affected maize grain yields in both years ($p<0.0001$). In all villages and all years, the omission of phosphorus (P0) reduced the yields compared to the all nutrient control (P40) with an overall average reduction of 31% (Table 5). Omission of sulphur significantly reduced the yield of the P40 treatment except in Affem in 2004. Although there was reduction in yields by omission of zinc, it was only significant in Affem in 2006. In general the yields obtained with the farmers' practice treatment were less than half of the yields in the P40 treatment and was significantly lower than the yields in all other treatments. Omission of potassium or boron did not affect the yields of the P40 control.

All treatments received an equal rate of N except the farmer practice and N concentrations in ear leaves were, in general, not different between treatments that received N (Table 5). However, farm variations were observed with some farms giving lower concentrations than others. Phosphorus concentrations in ear leaves ranged from 0.10% to 0.35% and were influenced by the P application rates (Tables 4 and 5). Omission of S in the nutrient omission trials resulted in lower S concentrations compared to treatments that received S (Table 5). Potassium concentrations in ear leaves ranged between 1.11% and 2.94% (Table 4). Within a farm, K concentrations were generally lower in plots where K application was omitted compared to other plots (Table 5). Ca and Mg concentrations in ear leaves varied between fields. Within a field, Ca and Mg concentrations were the highest when K was omitted (Table 5); but there was no other clear effect of treatments on these nutrients.

Long-term trials

Given the large number of treatments in the long-term trials, only the averages and ranges of grain yields and nutrient concentrations are presented in this paper for all experiments. However, in order to illustrate the effect of treatments on yields, nutrient concentrations, and their link with DRIS, we showed the details for two experiments (Shika and WBE), which had similar set of treatments but with some differences in management, and were located in two different zones.

The overall range of yields in the long-term trials was similar to that in the nutrient omission trials but differences were observed between trials, and between treatments within a trial. Shika experiment

Table 4 Range of maize grain yields and nutrient concentrations in maize ear leaves in on-farm nutrient omission trials and in selected long-term experiments

Experiments	Code and the rainfall of the season (mm)		Yield (kg ha^{-1})	N (%)	Mg (%)	K (%)	Ca (%)	P (%)	S (%)	Mn (mg kg^{-1})	Zn (mg kg^{-1})
Nutrient omission	Togo 2004	Mean	2,909	2.39	0.16	1.76	0.32	0.22	0.12	49	15.7
	1,042	Min	438	1.32	0.09	1.11	0.20	0.10	0.07	21	9.9
	n=144	Max	4,696	3.93	0.34	2.26	0.49	0.32	0.17	156	25.5
	Togo 2006	Mean	3,243	2.93	0.20	2.33	0.38	0.26	0.18	61	16.8
	1,088	Min	533	2.18	0.13	1.66	0.25	0.13	0.12	32	12.1
	n=160	Max	5,463	3.37	0.31	2.94	0.59	0.35	0.23	117	24.2
Long-term	Sekou	Mean	599	1.56	0.10	1.51	0.19	0.18	0.09	73	13.7
	410	Min	2	1.28	0.07	1.18	0.13	0.14	0.08	35	8.8
	n=26	Max	2,473	2.11	0.15	2.03	0.32	0.23	0.12	168	15.2
	D2	Mean	1,604	2.26	0.08	1.84	0.19	0.22	0.12	169	12.6
	838	Min	151	1.45	0.05	1.35	0.13	0.13	0.09	41	9.3
	n=40	Max	3,011	2.85	0.09	2.10	0.26	0.29	0.15	803	23.0
	WBE	Mean	2,197	1.79	0.13	2.23	0.26	0.22	0.11	63	12.9
	838	Min	1,006	1.28	0.06	1.09	0.12	0.09	0.05	28	4.8
	n=100	Max	3,763	2.40	0.17	2.61	0.37	0.28	0.14	153	19.4
	Shika	Mean	2,657	2.31	0.18	2.61	0.42	0.30	0.18	68	13.1
	855	Min	654	1.66	0.12	1.75	0.26	0.20	0.11	34	9.1
	n=108	Max	5,847	3.27	0.24	3.02	0.56	0.39	0.23	127	19.8
	Samaru	Mean	927	1.92	0.11	1.67	0.23	0.20	0.12	31	13.4
	855	Min	0	1.16	0.05	0.88	0.11	0.10	0.08	16	8.0
	n=99	Max	2,815	2.71	0.24	2.30	0.37	0.35	0.15	77	25.8
Critical values[a]		Range		2.6–3.1	0.10–0.21	1.2–1.7	0.20–0.21	0.22–0.27	0.16–0.24		13–25

[a] Critical nutrient concentration ranges in maize ear leave based on data from tropical and temperate regions (Reuter et al. 1997)

Table 5 Average grain yields, nutrient concentrations in ear leaves and DRIS indices for treatments across all fields used in the on farm trials in the two villages of central Togo

Year	Code and rainfall (mm)	Trt[a]	Yield (kg ha^{-1})	Nutrients (%)						DRIS					
				N	Mg	K	Ca	P	S	N	Mg	K	Ca	P	S
2004	Affem	FP	2121	2.72	0.14	1.96	0.28	0.23	0.14	24.3	−7.3	37.0	−3.0	4.2	6.7
	1,022	P0	2439	2.44	0.17	1.95	0.31	0.17	0.14	14.4	3.6	35.2	1.1	−18.5	4.3
		P20	3137	2.47	0.16	1.95	0.32	0.21	0.14	12.1	2.1	31.9	2.4	−2.5	1.0
		P40	3329	2.37	0.14	1.87	0.31	0.21	0.13	14.0	−3.6	33.9	4.3	2.4	1.0
		S0	2900	2.30	0.15	1.86	0.30	0.22	0.12	12.6	1.2	33.3	3.9	5.1	−7.6
		K0	3148	2.46	0.18	1.73	0.34	0.22	0.13	13.7	7.4	22.2	7.6	2.9	1.7
		Zn0	3195	2.50	0.14	1.99	0.30	0.23	0.13	16.9	−4.5	39.0	0.4	7.4	0.9
		B0	3080	2.43	0.15	1.87	0.32	0.23	0.13	15.8	−2.6	33.0	5.9	6.9	0.5
	LSD		609	0.24	0.02	0.12	0.04	0.02	0.02						
	Sessaro	FP	923	1.78	0.13	1.77	0.25	0.20	0.11	−1.2	−0.2	42.2	−1.6	4.7	−4.0
	1,063	P0	2323	2.39	0.17	1.70	0.30	0.16	0.13	20.0	8.1	27.2	3.7	−23.1	5.4
		P20	3089	2.40	0.17	1.63	0.32	0.21	0.12	16.1	7.1	19.9	5.6	0.8	−2.0
		P40	3311	2.26	0.17	1.70	0.33	0.23	0.12	9.4	6.6	24.2	8.3	9.1	0.1
		S0	2521	2.42	0.17	1.56	0.32	0.23	0.10	23.5	9.2	19.8	10.0	10.0	−17.7
		K0	3058	2.29	0.21	1.37	0.38	0.23	0.12	10.8	18.5	4.7	18.4	7.8	−3.7
		Zn0	3199	2.47	0.17	1.64	0.35	0.24	0.12	16.1	4.8	20.0	11.0	7.8	−1.7
		B0	3071	2.38	0.14	1.75	0.32	0.24	0.12	16.1	−4.7	28.1	7.9	10.7	−2.0
	LSD		475	0.30	0.02	0.14	0.04	0.02	0.02						
2006	Affem	FP	1907	2.99	0.18	2.50	0.35	0.26	0.20	14.9	−1.9	44.1	−2.4	0.9	18.4
	991	P0	2460	2.89	0.19	2.37	0.33	0.19	0.20	13.5	1.7	38.1	−5.9	−22.3	18.8
		P20	3227	2.97	0.18	2.40	0.33	0.24	0.19	13.6	−3.8	37.2	−6.6	−6.0	15.4
		P40	3865	2.86	0.19	2.34	0.35	0.26	0.19	10.8	1.1	37.0	−2.3	2.8	13.4
		S0	2532	2.83	0.17	2.33	0.33	0.27	0.16	14.9	−2.5	39.2	−2.2	5.9	2.8
		K0	3503	2.98	0.21	2.14	0.39	0.26	0.19	12.9	5.7	25.5	4.9	−0.4	11.6
		Zn0	3066	2.90	0.18	2.35	0.34	0.27	0.18	14.2	−1.0	39.5	−2.9	5.3	14.6
		B0	3719	2.93	0.19	2.38	0.35	0.26	0.19	12.3	0.9	37.1	−1.9	1.9	12.9
	LSD		717	0.16	0.02	0.12	0.04	0.02	0.02						
	Sessaro	FP	1351	2.68	0.20	2.31	0.45	0.27	0.17	4.2	3.4	34.8	14.7	4.6	2.9
	1,185	P0	2789	2.92	0.24	2.36	0.49	0.27	0.19	5.4	10.2	27.4	14.5	−5.9	5.9
		P20	3949	3.06	0.21	2.42	0.46	0.29	0.19	10.1	4.8	31.3	12.5	2.9	7.2
		P40	4149	2.93	0.23	2.34	0.49	0.29	0.18	5.6	8.0	26.5	15.4	2.8	3.8
		S0	3387	2.92	0.24	2.20	0.48	0.31	0.16	7.6	9.4	21.8	14.1	9.2	−8.6
		K0	4318	3.09	0.28	2.12	0.55	0.30	0.19	8.2	18.4	16.1	22.4	4.3	5.5
		Zn0	3915	2.95	0.24	2.29	0.49	0.29	0.19	7.5	11.8	27.0	16.6	4.8	6.4
		B0	4139	3.09	0.25	2.07	0.49	0.28	0.18	12.9	14.8	18.7	18.1	2.0	7.0
	LSD		647	0.36	0.04	0.16	0.06	0.06	0.02						

[a] Treatment

provided the highest yields among all long-term experiments with an average of 2,657 kg ha^{-1} (Table 4). Within a cropping system, yields were higher in treatments that received N fertilizers than in treatments without N-fertilization (Table 6). The same trend was observed in WBE experiment although with lower yields compared to Shika experiment. In D2 experiments the lowest yield reported in Table 4 was observed in the treatment that did not receive any fertilizers or organic inputs whereas the highest yields were obtained from the alley-cropping systems with fertilizer additions. Sekou trial received poor rainfall in the season considered in this study (2005) with a total rainfall of 410 mm, suggesting that the crop

Table 6 Maize grain yields (kg ha^{-1}), selected nutrient concentrations (%) and DRIS indices in Shika and WBE experiments

Cropping systems		Shika									WBE								
		Yield	Nutrients				DRIS				Yield	Nutrients				DRIS			
			N	Ca	P	S	N	Ca	P	S		N	Ca	P	S	N	Ca	P	S
Dual Purp soybean 1 y[a]	−N	3,339	2.2	0.48	0.29	0.17	−12.1	17.9	9.6	19.1	1513	1.4	0.23	0.22	0.10	−19.9	−14.1	23.1	3.7
Dual Purp soybean 1 y	+N	4,475	2.5	0.45	0.33	0.19	−2.7	12.9	12.3	25.9	2401	2.2	0.29	0.24	0.12	−4.4	−8.6	11.5	−10.5
Dual Purp Soybean 2 y	−N	3,259	2.0	0.41	0.24	0.15	−16.9	18.0	9.9	23.5	1262	1.6	0.20	0.24	0.11	−17.1	−11.3	21.3	−6.2
Dual Purp Soybean 2 y	+N	3,517	2.4	0.46	0.28	0.18	2.2	15.0	12.7	28.7	3290	1.9	0.26	0.23	0.11	−4.2	−5.5	13.5	−10.6
Fallow 1 y	−N	2,519	1.8	0.41	0.25	0.14	−18.1	18.4	19.2	21.7	2269	1.7	0.27	0.26	0.11	−16.3	−8.5	22.1	−4.7
Fallow 1 y	+N	4,349	2.3	0.53	0.33	0.18	−9.8	22.8	18.3	22.2	3388	2.1	0.28	0.23	0.12	−4.1	−4.8	10.5	−2.9
Fallow 2 y	−N	2,585	2.0	0.36	0.27	0.16	−15.8	16.5	15.8	25.0	2279	1.4	0.25	0.25	0.10	−14.6	−3.7	20.7	−6.7
Fallow 2 y	+N	3,579	2.7	0.40	0.29	0.16	−6.8	18.9	18.8	22.1	2277	2.0	0.31	0.24	0.12	0.7	1.3	6.4	−4.5
Forage 1 y	−N	2,921	2.1	0.52	0.28	0.16	−15.7	8.0	20.8	22.7	2019	1.6	0.26	0.23	0.11	−12.4	−1.9	15.3	−3.2
Forage 1 y	+N	3,768	2.5	0.49	0.29	0.17	−6.8	9.4	11.2	19.9	2909	2.3	0.32	0.22	0.12	3.6	0.3	6.7	−2.6
Forage 2 y	−N	3,994	2.1	0.41	0.31	0.18	−14.6	2.8	19.6	19.7	1265	1.9	0.27	0.24	0.12	−2.9	−4.0	12.2	−7.8
Forage 2 y	+N	4,125	2.6	0.41	0.36	0.22	3.9	1.6	18.6	28.0	3016	2.2	0.30	0.25	0.12	2.9	−4.7	13.4	−6.4
Grain Legume 1 y	−N	1,498	2.0	0.46	0.26	0.15	−11.9	16.0	14.7	28.1	1263	1.5	0.29	0.21	0.10	7.7	3.0	4.5	−4.3
Grain Legume 1 y	+N	3,711	2.3	0.48	0.31	0.21	−1.6	15.1	13.3	32.6	2272	2.0	0.27	0.22	0.12	1.7	−6.4	6.5	−8.5
Grain Legume 2 y	−N	2,477	2.1	0.30	0.28	0.16	−13.1	11.4	18.9	26.1	2021	1.8	0.24	0.23	0.11	−12.3	−6.9	14.9	−6.1
Grain Legume 2 y	+N	4,566	2.3	0.43	0.30	0.17	−6.3	17.5	17.6	29.4	2783	2.2	0.28	0.23	0.13	5.8	−6.6	8.7	−3.9
Green Manure 1 y	−N	2,639	2.0	0.56	0.31	0.18	−25.2	18.9	17.5	13.1	2295	1.6	0.27	0.21	0.10	−12.1	5.0	13.9	−8.4
Green Manure 1 y	+N	4,167	2.5	0.54	0.33	0.20	−8.1	17.7	15.7	22.3	2538	2.0	0.32	0.21	0.11	4.0	5.7	2.9	−7.0
Green Manure 2 y	−N	3,445	2.1	0.50	0.29	0.18	−20.5	15.6	19.4	18.9	1892	1.7	0.30	0.21	0.10	−11.8	10.0	14.4	−7.5
Green Manure 2 y	+N	4,964	2.3	0.51	0.30	0.19	−8.5	15.1	16.9	26.0	2654	2.1	0.37	0.22	0.12	3.5	8.4	3.6	−3.5
N response 0N		2,481	1.8	0.37	0.22	0.14	−15.9	−1.0	23.5	33.2	1868	1.4	0.20	0.22	0.09	−13.5	−5.4	22.6	−3.6
N response 30N		2,727	1.9	0.47	0.25	0.15	−17.2	16.6	17.8	33.4	2155	1.5	0.25	0.22	0.10	−10.0	−1.5	14.1	−4.7
N response 60N		2,853	2.2	0.43	0.27	0.17	−8.1	17.1	19.1	33.7	1895	1.7	0.23	0.21	0.10	−0.8	0.0	10.2	−5.7
N response 90N		4,265	2.5	0.49	0.29	0.18	1.7	14.3	14.6	32.2	2892	2.0	0.29	0.23	0.11	3.6	6.4	5.4	−4.5
N response 120N		4,353	2.6	0.51	0.32	0.19	−0.9	15.5	15.4	32.9	3153	2.1	0.28	0.22	0.11	8.9	−0.1	7.3	−4.6
LSD		848	0.4	0.06	0.03	0.02					599	0.2	0.04	0.02	0.02				

[a] Dual purpose soybean with one year rotation cycle

might have been more constrained by moisture than nutrients, leading to poor yields (Table 4). The maximum yields reported for this experiment were obtained in maize/Mucuna system with NPK applications, whereas the minimum value resulted from the maize monocrop without N applications (Table 4).

Nitrogen concentrations in ear leaves ranged from 1.2–3.3% with the lowest value observed in the Samaru experiment (Table 4). Shika experiment had the highest N concentrations with the majority of treatments having N concentration greater than 2.0% (Tables 4 and 6). Phosphorus concentrations in ear leaves ranged from 0.09 to 0.39% with the highest concentrations obtained in Shika (Table 4). P concentrations were higher in treatments that received P fertilizers compared to their homologue without P addition (data not shown). Ca concentrations in ear leaves ranged from 0.11–0.56% (Table 4). The highest Ca concentrations were observed in Shika, higher than 0.3% except for the control (0N) treatments in the N response test. Ear leaves sampled in the D2 experiment had the lowest Ca concentrations (Table 4), but were higher in fertilized treatments compared to similar treatments without fertilizer additions (data not shown).

Mg concentrations followed a similar trend as the Ca concentrations but were extremely low in the D2 experiment, for all treatments and within a narrow range of 0.05–0.09% (Table 4). Sulfur concentrations in ear leaves ranged from 0.05% to 0.23%, with the highest range observed in Shika where the average S concentrations were about 0.14% and above for all treatments (Table 6). In the other long-term experiments, S concentrations were below 0.15% (Table 4). Mn concentrations in ear leaves varied extensively between experiments. The lowest concentrations were found in the experiment in Samaru and the highest in the D2 experiment (Table 4). Within D2 experiment, Mn concentrations differed much between treatments with an average concentration of 57 mg Mn kg^{-1} in Senna treatments, compared to 441 mg Mn kg^{-1} in the Mucuna treatment with NPK application. In all experiments, Mn concentrations were higher in treatments that received urea fertilizer than in treatments without urea N addition (data not shown). In the N response test, in Shika and WBE experiments, Mn concentrations increased with increasing rate of N addition (46 mg Mn kg^{-1} in 0N vs 67 mg Mn kg^{-1} in 120N in WBE; and 68 mg Mn kg^{-1} in 0N vs 101 mg Mn kg^{-1} in 120N for Shika). Zinc concentrations ranged from 4.8 to 25.8 mg kg^{-1} (Table 4), with 53% of the values being smaller than 13 mg kg^{-1}, whereas 99% of the values were below the maximum limit of the critical range (25 mg kg^{-1}) reported by Reuter et al. (1997).

DRIS indices

In all experiments used in this study and all treatments, Zn indices were negative and were often the most negative of all nutrients (data not shown). This may be due to inappropriate norms for the ratios involving Zn as mentioned earlier for micronutrients, but may be as well an indication of Zn deficiencies since no Zn-containing fertilizers are used in the region. Unless otherwise mentioned, Zn indices will be considered as the most negative in the text and will not be taken into account in the ranking of nutrients.

Nutrient omission trials

In the farmer practice treatment, N indices were negative in 11% of fields in Affem and in 50% of the fields in Sessaro (data not shown). Addition of N at 120 kg ha^{-1} in fertilized treatments turned all N indices to positive (Table 5, Fig. 1).

Phosphorus indices were negative in 33% of the fields in Affem and 37% in Sessaro in the FP treatment. Omission of P in the P0 treatment resulted in negative P indices in all fields (Table 5), whereas the application of the highest P rate in the P40 treatment reduced the number of fields with negative P indices to 23% in Affem and 8% in Sessaro. The reduction of P rate to 20 kg ha^{-1} was accompanied by negative P indices in 76% of the fields in Affem and 50% of the fields in Sessaro. Overall negative P indices were observed in 34% of all fields and treatments (Fig. 1).

In the FP treatment, sulphur indices were negative in 6% of the fields in Affem compared to 50% of the fields in Sessaro. Omission of sulphur resulted in negative S indices in all fields in Sessaro (Table 5) and in 62% of the fields in Affem. Although K indices were smaller in K0 treatment compared to values in treatments that received K (Table 5), they remained positive except for two fields (one in Affem, one in Sessaro).

Ca and Mg indices were negative in 60% of the fields in Affem, whereas in Sessaro negative indices were observed in 37% of the fields for Ca and 50% of the fields for Mg, in the FP treatment. The number of fields with negative Ca indices was reduced upon

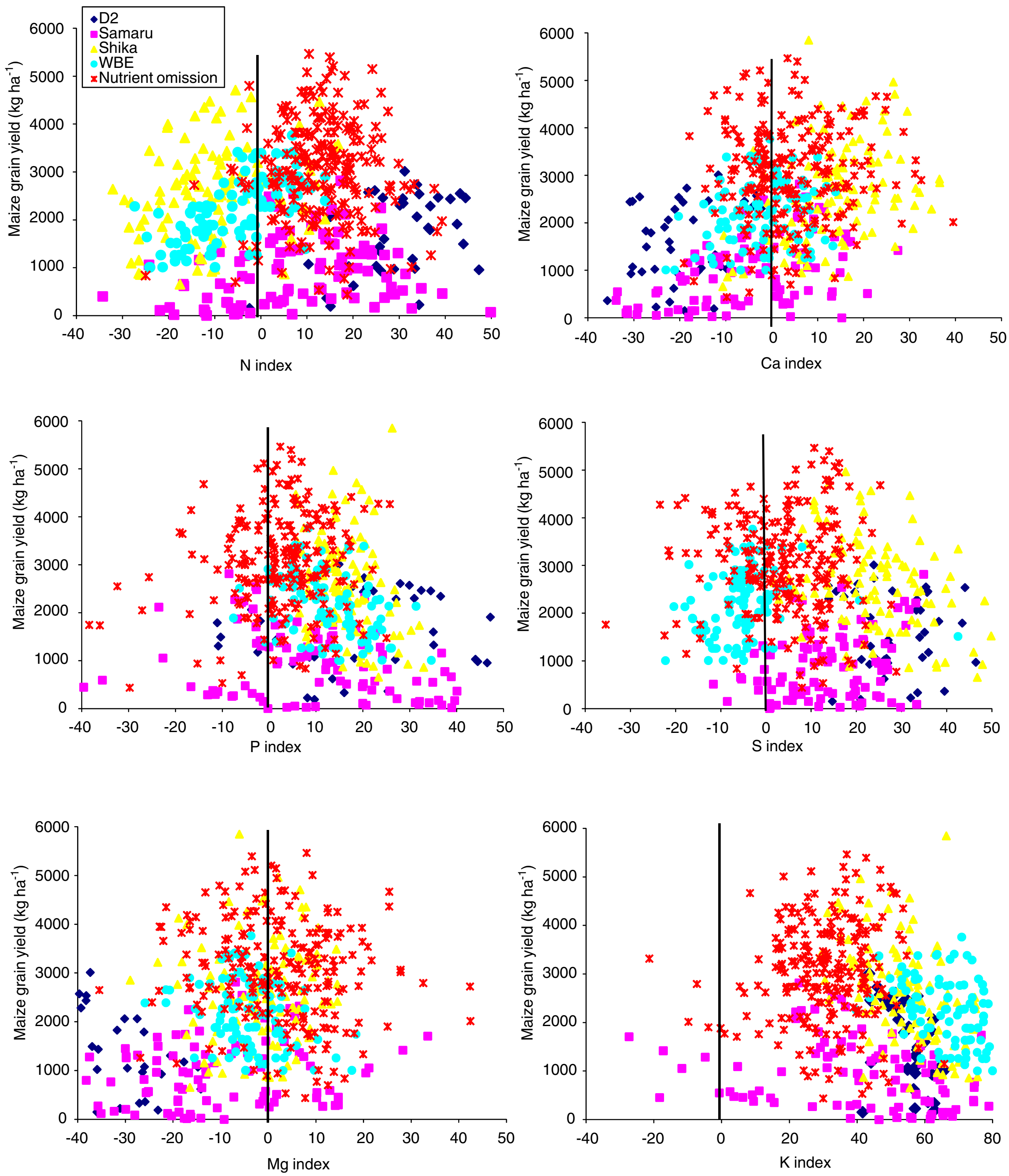

Fig. 1 Maize grain yields as a function of selected DRIS indices calculated based on nutrient concentration in maize ear leaves in nutrient omission and long term trials in the West Africa Savanna. The *vertical line* represents the zero index

application of P in the P40 treatment to 41% in Affem and 8% in Sessaro.

Long-term experiments

N indices Nitrogen indices were mainly negative in Shika with negative indices found in all rotation systems and in the N response test (Fig. 1). Within a system, N indices turned to less negative when urea was applied but only few systems provided positive indices (Table 6). The WBE trial has similar treatments as that in Shika with equal rates of N application, but negative N indices were observed mainly in rotation systems that did not receive fertilizer N. Within a system, the application of N fertilizer shifted N indices to positive except for the dual purpose soybean and the 1 year fallow systems (Table 6). In the N response test, application of N from 0 to 60 kg ha^{-1} resulted in negative N indices whereas positive N indices were obtained from the application of 90 and 120 kg N ha^{-1}. In the D2 experiment, N indices were positive in all treatments, whereas in Samaru experiment, N indices were negative only in treatments that did not receive urea regardless the type and form of organic input (Fig. 1).

P indices In general, P indices were positive in the long-term experiments (Fig. 1). Negative indices were observed in Samaru in treatments that did not receive P fertilizers. In D2, negative indices were obtained in the continuous alley-cropping with Leucaena without fertilizer addition. In the N response test in the Shika and WBE experiments, P indices were positive but values were smaller at high N rates (90 and 120 kg N ha^{-1}) than at low rates (0 and 30 kg N ha^{-1}; Table 6).

S indices Sulfur indices were negative in all the treatments of the WBE experiment (Fig. 1, Table 6). In Sekou, negative S indices were obtained in treatments that received organic matter through Mucuna or Cajanus, and the combination of Senna and urea with 45 kg N ha^{-1} supplied by each of the N sources (data not shown). Those treatments provided the highest yields over years implying that S imbalance might have been accelerated by higher nutrient removal compared with other treatments. In other experiments, S indices were positive (Fig. 1).

K, Ca, and Mg indices K indices were positive in all long-term experiments (Fig. 1).

Ca indices were negative in most of the treatments of the WBE (Table 6), D2, Samaru and Sekou experiments (Fig. 1). In the WBE experiment, only the green manure treatments had consistently positive Ca indices (Table 6). In Shika, Ca indices were positive, in general, except the 0N in response test, and for a few cases in rotation systems where some reps within a treatment provided negative values but not the overall treatment mean (Table 6, Fig. 1). Ca indices were the second most negative in the D2 and Samaru experiments after Mg (Fig. 1), whereas in Sekou, Ca indices were in general the first most negative and were more negative in treatments that received fertilizer only (−27 to −15) than in treatments that received organic input (−3 to −4).

Negative Mg indices were observed in all long-term experiments and in the majority of treatments (Fig. 1). Overall, 63% of the treatments in long-term experiments had negative Mg indices, but there was no clear link between the Mg indices and the treatments. Among all experiments, the D2 had the most negative Mg indices, negative in all treatments, and the most negative among all nutrients (Fig. 1).

Discussion

Maize yields and nutrient concentrations in the nutrient omission trials reflected the treatments imposed with evidence that P and S and to some extent Zn were limiting maize production in the two villages. Nutrient indices generated through the DRIS approach reflected the different management options applied both in the nutrient omission and in the long-term trials. Where P and S were not supplied in the nutrient omission trials, indices of these nutrients were negative. In treatments that did not receive N and P in the long-term experiments, N and P indices were negative, whereas they were positive in similar treatments but with N and P addition. S indices were positive in most of the long-term experiments except in the WBE and in Sekou experiments. Sulfur was applied in the Samaru experiment in 2005, whereas the Shika experiment received S from 2002 onwards, after a pot trial revealed S deficiency on maize grown on soil from Shika (Schulz et al. 2002). Sulphur addition in those experiments would explain the positive S indices. The WBE experiment had similar treatments as the Shika one but no S was added, explaining the negative S indices. However, the 20-year old D2 experiment, located in the same area as WBE did not show any negative S index. While S might have not been limiting, it is also possible that the pronounced Ca and Mg imbalances have hidden the S effect as indicated in progressive diagnosis of deficiencies (Sumner 1981). The direct link between DRIS indices and the management imposed in the different experiments indicates that DRIS is a useful approach to reveal nutrient deficiencies or imbalances in maize in the region. For this, it is necessary to establish norms for a wide range of nutrient ratios, including both macro and micronutrients, which can be referred to while conducting DRIS analysis in the region.

The DRIS approach identified P as the most limiting nutrient in a number of 'P0' treatments which could be predicted from the soil available P results and the yield results. In these treatments, P concentrations were also the lowest and were below the critical range of 0.22–0.27% reported for maize ear leaves (Reuter et al. 1997; Tables 4 and 5). Addition of 40 kg P ha^{-1} in the P40 treatment reversed the trend, P indices becoming positive in most of the fields, whereas more than 50% of the fields had negative P indices when the rate was reduced to 20 kg ha^{-1}. This indicates that the rate of 20 kg P ha^{-1} was not sufficient to overcome P limitation. In the long-term experiments, P was supplied at least at 30 kg ha^{-1}, except for the WBE trial, and hence no negative P indices were observed in general. A rate between 20 and 30 kg P ha^{-1} may be adequate to overcome P deficiencies.

N indices were positive in the nutrient omission trials after application of N fertilizers in all treatments. In these trials, N was applied at 120 kg ha^{-1}, a rate higher than the recommended rate of 90 kg ha^{-1} in the area. In long-term experiments, omission of fertilizer N in the WBE and Shika trials resulted in negative N indices regardless the type of rotation (Table 6). This indicates that the rotation alone did not generate sufficient N for maize. The application rate of 60 kg ha^{-1} in rotation systems in WBE resulted in positive N indices in most systems, suggesting that the rate was sufficient to overcome N limitation. In the N response test, only the application rates of 90 and 120 kg N ha^{-1} resulted in positive N indices. Based on this, it would appear that the contribution of the rotation to N has been of at least 30 kg N ha^{-1} in the WBE trial. Although the application of N fertilizers in Shika increased N indices in all systems, they remained negative in general. Nitrogen concentrations in ear leaves were the highest in this experiment among all the long-term trials. The negative N indices in treatments that received N were probably not a translation of N deficiencies, but rather an indication that N was becoming imbalanced relative to other nutrients. Shika experiment received Ca and S in addition to N, P, and K, unlike other long-term experiments. Studies on progressive diagnosis of nutrient requirements have reported negative N indices as a result of a continuous supply of P, K and S to correct the deficiencies of these nutrients (Sumner 1981). Potassium indices were positive even when K was omitted both in nutrient omission trials and in long-term experiments. Studies of nutrient budgets, based on inputs of K from fertilizers and on its removal through crop harvest, leaching and runoff/erosion, have reported negative balance of K in the region (Stoorvogel et al. 1993). The lack of yield response to omission of K on one hand and the positive K indices may indicate that soils in the region have good capacity to supply sufficient K. Potassium concentrations in ear leaves were in general higher than the critical range of 1.2–1.7% reported by Reuter et al. (1997) for tropical and temperate regions, even when K was omitted in the on-farm trials (Tables 4 and 5). Dust deposition through the harmattan winds, occurring yearly in West Africa, may play a role in replenishing K. Studies have shown that such deposition supplies about 18.7 kg K ha^{-1} annually (Harris 1998).

Most results from this study, particularly from the long-term experiments, indicated that Mg and Ca are nutrients that require attention. Neither Mg nor Ca was considered in the nutrient omission trial design. In long-term experiments, only Shika showed positive Ca indices except in the 0N treatment as control in the N response test. Shika received SSP as source of S to address S deficiency. SSP contained higher Ca than TSP, which may explain the positive Ca indices in this experiment. The fact that the Ca indices were negative in WBE where similar treatments as in Shika were applied but received TSP instead of SSP also support the supply of Ca by SSP. Looking at the range of Ca concentrations in Shika, an attempt was made to define the critical Ca concentration in ear leaves below which Ca indices become negative. The critical concentration was about 0.30%, which is higher than the range of 0.20–0.21% reported by Reuter et al. (1997) for tropical and temperate regions. The only treatment in Shika with lower concentration was the 0N of the N response test and was the only one to have negative Ca indices. This is supported by data from Sekou, where the only treatment with a positive Ca index had a Ca concentration of 0.32% (data not shown). The range of Ca concentrations in D2 was below 0.30% (Table 4), explaining the negative Ca indices obtained in all treatments (Fig. 1). In accordance with previous findings on D2, Ca indices were less negative in Senna treatments indicating less depletion of Ca in that treatment. Vanlauwe et al. (2005) reported higher Ca concentrations in Senna-treated soil and concluded that Senna tree was able to recover subsoil Ca and recycle it to the top layer.

Soils in the West-African Savanna are commonly believed to have adequate Ca and Mg reserves in view of the high Ca and Mg saturation of their exchange complex. However, Agbenin (2003) pointed out that exchangeable Ca and % Ca saturation of the exchange complex are poor predictors of Ca activities in the soil solution, and thus of Ca availability to plants. In a long-term experiment in Zaria (northern Nigeria) he observed that, after continuous cultivation, the Ca activity ratio ($^{a}Ca/\sum^{a}$ cations in solution, where ^{a} is the activity), considered as a good index of Ca availability, had decreased to levels where Ca deficiency is likely, and suggests that, as farmers replace SSP with other P fertilizers that contain little Ca, widespread Ca deficiencies will develop in the region. The fact that D2 had the lowest Ca and Mg concentrations in ear leaves and the most negative indices of these nutrients supports the observations of Agbenin (2003) since D2 was the oldest experiment in the study with 20 years of continuous cultivation. Ear leaf Mg concentrations in all treatments of the D2 experiment were below the critical range of 0.10–0.21% reported for tropical and temperate regions (Reuter et al. 1997; Table 4).

Conclusions

DRIS proved to be capable of identifying nutrient limitations to maize in the region. DRIS indices were found to be very sensitive to the management approaches imposed, indicating deficiencies of a given nutrient where it was not supplied. Nutrient limitations to maize in the savanna go beyond N and P. Prolonged cultivation resulted in deficiencies of Ca and Mg regardless of application of NPK fertilizers or organic matter. Sulfur deficiency occurred at several farm sites at long or short-term cultivation. Zinc concentrations were low compared to concentrations reported elsewhere for maize particularly in the long-term experiments. Strategies for soil fertility improvement should include measures to replenish Ca, Mg, S and Zn alongside the macronutrients N, P and K. Given the usefulness of the DRIS approach, it is necessary to establish norms for a wide range of nutrient ratios, including both macro and micronutrients, which can be referred to while conducting DRIS analysis in the region.

Acknowledgements The authors are very grateful to the Belgian Doctorate General for Development Cooperation (DGDC) for funding the balanced nutrient management project under which this work was conducted. The funding was provided to the International Institute of Tropical Agriculture (IITA). The core of the plant analysis was conducted at the Katholieke Universiteit Leuven (KULeuven) in Belgium.

References

Agbenin JO (2003) Soil saturation extract composition and sulfate solubility in a tropical semiarid soil. Soil Sci Soc Am J 67:1133–1139

Bationo A, Lompo F, Koala S (1998) Research on nutrient flows and balances in West Africa: state-of-the-art. Agric Ecosyst Environ 71:19–35

Bationo A, Mokwunye U, Vlek PLG, Koala S, Shapiro BI (2003) Soil fertility management for sustainable land use in the West Africa Sudano-Sahelian zone. In: Gichuru MP, Bationo A et al (eds) Soil fertility management in Africa: a regional perspective. ASP AAS, Nairobi, pp 253–292

Beaufils ER (1973) Diagnosis and Recommendation Integrated System (DRIS). A general scheme for experimentation and calibration based on principles developed from research in plant nutrition. Soil Sci Bull. No 1, University of Natal, pp 1–132

Carsky RJ, Oyewole B, Tian G (1999) Integrated soil fertility management for the savanna zone of W.Africa: legume rotation and fertilizer N. Nutr Cycl Agroecosyst 55:95–105

Carsky RJ, Becker M, Hauser S (2001) Mucuna cover crop fallow systems: potential and limitations. In: Tian G, Ishida F, Keatinge JDH (eds) Sustaining soil fertility in West Africa. SSSA Special Publication 58, pp 111–135

Escano CR, Jones CA, Uehara G (1981) Nutrient diagnosis in corn grown on Hydric Dystrandepts: II. Comparison of two systems of tissue diagnosis. Soil Sci Soc Am J 45:1140–1144

FAO (1988) FAO/Unesco Soil Map of the World, Revised Legend. World Resources Report 60, FAO, Rome. Reprinted as Technical Paper 20, ISRIC, Wageningen, The Netherlands, 1989, pp 138

FAO (1998) World reference base for soil resources. FAO, ISRIC, ISSS, Rome, Italy, p 91

Franke AC, Laberge G., Oyewole BD, Schulz S (2008) A comparison between legume technologies and fallow, and their effects on maize and soil traits, in two distinct environments of the West African savannah. Nutr Cycl Agroecosyt. doi:10.1007/s10705-008-9174-2

Friesen DK (1991) Fate and efficiency of sulfur fertilizer applied to food crops in West Africa. Fertil Res 29:35–44

Harris FMA (1998) Farm-level assessment of nutrient balance in north Nigeria. Agric Ecosyst Environ 71:201–214

Kang BT, Osiname OA (1976) Sulfur response of maize in Western Nigeria. Agron J 68:333–336

Novozamsky I, Houba VJG, van Eck R, van Vark W (1983) A novel digestion technique for multi-element plant analysis. Commun Soil Sci Plant Anal 14:239–248

Ojeniyi SO, Kayode GO (1993) Response of maize to copper and sulfur in tropical regions. J Agric Sci Camb 120:295–299

Reuter DJ, Edwards DG, Wilhelm NS (1997) Temperate and tropical crops. In: Reuter DJ, Robinson JB (eds) Plant analysis: an interpretation manual. CSIRO, Australia, pp 83–284

de Ridder N, Breman H, van Keulen H (2004) Revisiting a 'cure against land hunger': soil fertility management and farming systems dynamics in the West African Sahel. Agric Syst 80:109–131

SAS (1992) The mixed procedure. SAS Technical report p 229: SAS/STAT software: changes and enhancements. SAS Institute Inc., Cary, NC, USA

Schulz S, Carsky RJ, Tarawali S (2001) Herbaceous legumes: the panacea for West African soil fertility problems? In: Tian G, Ishida F, Keatinge JDH (eds) Sustaining soil fertility in West Africa. SSSA Special Publication 58:179–196

Schulz S, Diels J, Lyasse O (2002) Rehabilitation of severely degraded soil through the application of limiting nutrients: an example from Shika farm. In: Improving and intensifying cereal–legume systems in the moist and dry savanna of West and Central Africa. Annual Report 2002, IITA, Ibadan, Nigeria, pp 4–5.

Searle PL (1984) The Berthelot or indophenol reaction and its use in analytical chemistry of nitrogen. A review. Analyst (Lond) 109:549–568

Snedeker SM, Greger JL (1983) Metabolism of zinc, copper, and iron as affected by dietary protein, cysteine and histidine. J Nutr 113:644–652

Stoorvogel JJ, Smaling EMA, Janssen BH (1993) Calculation of soil nutrient balances in Africa at different scale. I. Supra-national scale. Fertil research 35:227–235

Sumner ME (1981) Diagnosing the sulphur requirements of corn and wheat using foliar analysis. Soil Sci Soc Am J 45:87–90

Vanlauwe B, Aihou K, Aman S, Iwuafor ENO, Tossah BK, Diels J et al (2001) Maize yield as affected by organic inputs and urea in the West African moist savanna. Agron J 92:1191–1199

Vanlauwe B, Diels J, Lyasse O, Aihou K, Iwuafor ENO, Sanginga N et al (2002) Fertility status of soils of the derived savanna and northern guinea savanna and response to major plant nutrients, as influenced by soil type and land use management. Nutr Cycl Agroecosyst 62:139–150

Vanlauwe B, Aihou K, Tossah BK, Diels J, Sanginga N, Merckx R (2005) Senna siamea trees recycle Ca from a Ca-rich subsoil and increase the topsoil pH in agroforestry systems in the West African derived savanna zone. Plant Soil 269:285–296

Walworth J, Sumner ME (1988) Foliar diagnosis: a review. In: Tinker B, Lauchli AV (eds) Advances plant nutrition. Praeger Publishers, NY, pp 193–241

Weil RR, Mughogho SK (2000) Sulfur nutrition of maize in four regions of Malawi. Agron J 92:649–656

Zhao FJ, Hawkesfordt MJ, McGrath SP (1999) Sulphur assimilation and effects on yield and quality of wheat. J Cereal Sci 30:1–17