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Sulfur and zinc levels as limiting factors to rice production in West Africa lowlands

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Abstract

A total of 172 soil samples from 85 locations within river flood plains and 201 samples from 78 locations within inland valley swamps were collected and analyzed to determine their sulfur (sulfate-S) and micronutrients (Zn, Fe, Mn, Cu, Ni) supplying capacities. The soils were observed to be very deficient in both sulfate-S and available Zn. Mean topsoil (0–15) cm sulfate-S levels were 3.41 mg kg^{-1} for river flood plains and 4.88 mg kg^{-1} for inland valley swamps . Even though mean topsoil available Zn levels were 1.23 and 1.56 mg kg^{-1} for river flood plains and inland valley swamps, respectively, over 66% of West Africa lowlands had available Zn below the critical soil level of 0.83 mg kg^{-1} necessary for rice cultivation. Observed levels of topsoil mean available Fe (163 and 220), Mn (66.6 and 57.6), Cu (3.38 and 2.49), and Ni (1.68 and 1.36) mg kg^{-1} for river flood plains and inland valley swamps, respectively, were moderate across the sub-region. However, isolated areas within both lowlands showed very high levels of available Fe, more especially within the inland valley swamps. A correlation analysis with some selected nutrient parameters showed that topsoil sulfate-S correlated positively and significantly with total C ($r = 0.690$), available P ($r = 0.939$), eCEC ($r = 0.867$) and Clay ($r = 0.859$) for river flood plains but only with total C ($r = 0.874$), available P ($r = 0.873$) and eCEC ($r = 0.612$) for inland valley swamps. Available Zn showed a similar relationship with total C ($r = 0.867$ and 0.800) and available P ($r = 0.690$ and 0.850) but a negative correlation with eCEC ($r = -0.675$ and -0.544) for both river flood plains and inland valley swamps, respectively. Available Ni showed a similar relation to Zn. Available Mn significantly correlated positively with total C and available P but showed a negative correlation with pH for both lowland types. Nutrient availability and

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distribution were more influenced by agro-ecology within the inland valley swamps than the river flood plains.

Keywords: lowlands; micronutrients; rice; sulfur; West Africa; zinc

1. Introduction

The West Africa sub-region has many lowland types, notably river flood plains, inland valley swamps, interior plains, coastal plains and deltas. For some time now, various research activities have been geared towards providing information for the sustainable development of these lowlands. This has become necessary as these areas have been identified as potentially viable areas for increased agricultural production in an environment where agricultural activities are constrained by several factors, notably limited water supply.

While some of these lowlands tend to occur in limited areas, the inland valley swamps and more particularly the river flood plains occur abundantly across all agro-ecological zones within the sub-region. Windmeijer and Andriesse (1993) estimated the total lowland area of the sub-region to be about 75 million hectares, while Wakatsuki et al. (1998) estimated 18 million ha of this area (about 24%) to be potentially viable and suitable for sawah-based rice production. Lowlands, which receive eroded and/or transported material from adjacent uplands, are variable in nature and character as a result of the distinctive features of the land form and climate, quantity, and texture of accumulated sediment and/or flooding frequency.

In view of such diverse soil and climatic conditions, the possibility of variations in both available and total nutrient contents may be high. Nutrient limitations to crop production, particularly rice, have been reported by many workers (Katyal and Ponnamperuma, 1974; Osiname and Kang, 1975; Randhawa and Takkar, 1975; Randhawa and Takkar, 1975; Van Breemen and Moormann, 1978; Peaslee, 1980; Ponnamperuma et al., 1981; Yamauchi, 1989; Yamaguchi, 1997). A number of workers including Okusami (1986), Wakatsuki (1994), Wakatsuki et al. (1989, 1998), Windmeijer and Andriesse (1993), Buri and Wakatsuki (1996), Issaka et al. (1996) Hirose and Wakatsuki (1997) and Buri et al. (1999) have reported the potential and nutrient supplying capacity of the inland valley swamps and river flood plains in the essential macronutrients. However, little information is available on these lowlands' potentiality in providing the essential micronutrients and sulfur, which play equally vital roles in obtaining optimum crop yields.

As a result of the wider variations in parent material and climate within West Africa, large variations may also exist in the levels of these elements. The objectives of this study are therefore (i) to assess the availability of sulfate and some micronutrients, and their distribution with regards to climatic variability across the sub-region, (ii) to provide an information source on the current sulfate-S and micronutrient potentials of these soils (deficiency/toxicity), and (iii) to provide a basis on which sustainable nutrient management methods can be evolved for these lowland soils.

2. Materials and methods

2.1. Study area

West Africa (Fig. 1), with a total area of about 6.2 million km^2, is one of the major geographical regions of Africa and is bounded in the south and west by the Atlantic Ocean, in the east by the Cameroun–Adamawa highlands and to the north by the southern limits of the Sahara Desert (about latitude 15°N). The region varies between about 200 and 500 m in elevation and consists mainly of the worn, monotonous, and fairly level surfaces of the plateau of Pre-Cambrain formations (Harrison Church, 1980). On the basis of the length of growing period, the sub-region has been divided into four main agro-ecological zones, namely; Equatorial forest (EF), Guinea savanna (GuS), Sudan savanna (SuS), and Sahel savanna (SaS).

2.2. Field sampling

Soil samples were collected from major lowland areas (river flood plains and inland valley swamps). In order to cover a wider area, sampling was done

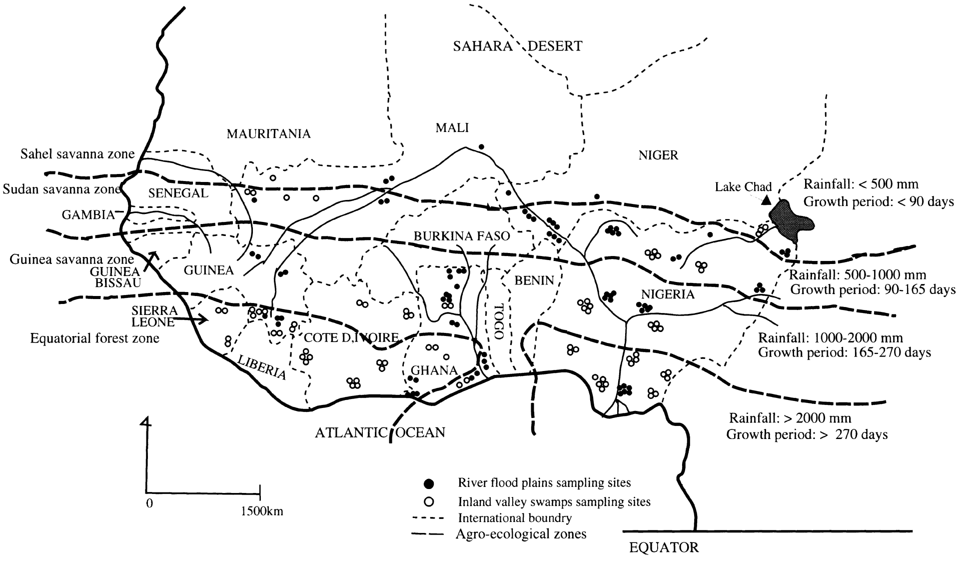


Fig. 1. Some soil sampling sites and major agro-ecological zones in West Africa.

mainly by auger, while a few samples were taken from soil pits. Sampling locations were selected from all the four main agro-ecological zones of the sub-region and covered as many countries as possible. Both topsoil (0–15) cm and subsoil (15–30, 30–45) cm samples were collected. A guide to some sampling locations is provided in Fig. 1.

2.3. Laboratory analysis

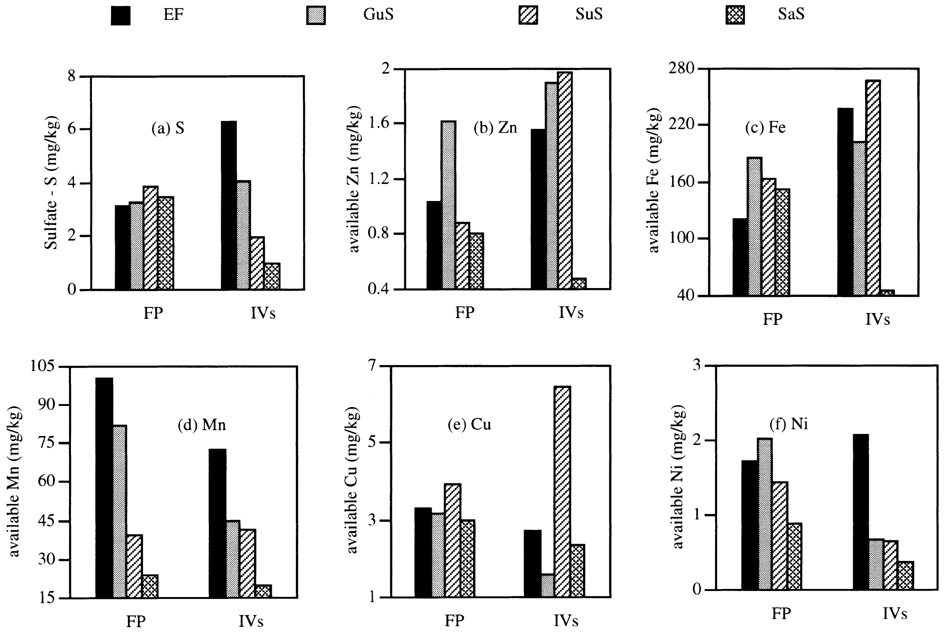
Collected soil samples were air-dried, ground and passed through a 2-mm mesh sieve. Sulfate-S was determined by extraction with calcium phosphate solution containing 500 mgl^{-1} P. The sulfur levels were then determined turbidimetrically as described by IITA (1979). Available Zn, Fe, Mn, Cu, and Ni solutions were first obtained by the DTPA extracting method as developed by Norvell and Lindsay (1972) and Dale and Michael (1982). The concentrations of the various elements were then determined on the Inductively Coupled Plasma-Atomic Emission Spectroscopy (Shimuzu ICP-2000). General fertility parameters and total elemental composition were also earlier analyzed. Those analytical methods were described in our previous papers (Buri and Wakatsuki, 1996; Buri et al., 1999; Issaka et al., 1996).

3. Results

3.1. Available sulfur (sulfate-S)

Observed levels of sulfate-S are shown in Table 3a. Sulfate-S levels were comparatively higher for the topsoil of both river flood plains and inland valley swamps, decreasing gradually with increasing depth. This trend was similar for all the agro-ecological zones across the sub-region, irrespective of lowland type. Mean sulfate-S levels in the topsoil (0–15) cm were 3.41 and 4.88 mg kg^{-1} for river flood plains and inland valley swamps, respectively. The mean sulfate-S levels of the soils in the flood plains remained similar across all agro-ecological zones. The inland valley swamps showed a decreasing trend from the wetter to the drier zones (Fig. 2a). The wetter zones of the EF and Gus of the inland valley swamps showed higher sulfate-S levels than the drier sus and sas zones in the order EF > Gus > SuS > SaS. Variability in topsoil sulfate-S levels (Table 3a) were relatively high (Ref. SD values) within both lowland types but higher for the inland valley swamps than the river flood plains.

The frequency distribution of topsoil sulfate-S is shown in Fig. 3a, with almost 100% of both river flood plains and inland valley swamps showing sulfate-S levels below the soil critical levels of 5–20 mg S kg^{-1} soil required for the normal growth of both flooded rice and upland crops, as proposed by



FP - River flood plains; IVs - Inland valley swamps; EF - Equatorial forest; GuS - Guinea sav.; SuS - Sudan sav.; SaS - Sahel sav.

Fig. 2. Topsoil (0–15) cm mean available nutrient distribution as affected by agro-ecology within West African lowlands.

McClung et al. (1959), Fox et al. (1964), Ensminger and Freney (1966), and Wang (1976).

Topsoil sulfate-S correlated positively and significantly with total C ($r = 0.690$), available P ($r = 0.939$), eCEC ($r = 0.867$) and Clay ($r = 0.859$) for river flood plains and with total C ($r = 0.874$), available P ($r = 0.873$) and eCEC ($r = 0.612$) for the inland valley swamps (Table 6).

3.2. Available zinc (Zn)

Table 3b shows the depth distribution of available Zn for West African lowlands. Mean levels of available Zn in West Africa lowlands topsoils were 1.23 and 1.56 mg kg^{-1} for river flood plains and inland valley swamps, respectively. Available Zn levels decreased sharply with depth within both lowlands types, being more pronounced within the inland valley swamps. This trend was common to all agro-ecological zones except within the EF zone of flood plains. Within both river flood plains and inland valley swamps, the wetter zones of the EF and GuS showed slightly higher levels of available Zn than did the drier SuS and SaS zones (Fig. 2b), reflecting the significantly positive correlation between organic matter and available Zn (Table 6). Variability, however, remained high (high SD values) in topsoil available Zn levels across the sub-region, and like S, variability was higher for the inland valley swamps, especially within the EF and GuS zones.

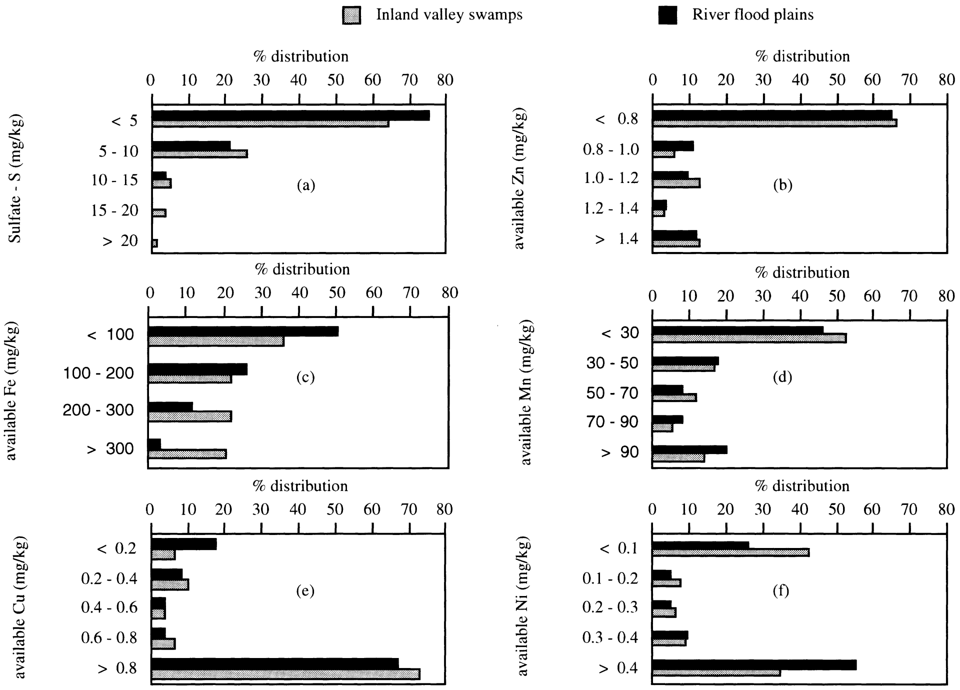


Fig. 3. Frequency distribution of topsoil (0–15) cm available nutrients within West African lowlands.

Fig. 3(b) shows the frequency distribution of topsoil available Zn. The distribution of topsoil available Zn was similar for both river flood plains and inland valley swamps with about 66% of West African lowlands showing available Zn levels below the soil critical level of 0.83 mg Zn kg^{-1} soil necessary for rice cultivation as proposed by Randhawa and Takkar (1975). The distribution of topsoil available Zn was similar to that of sulfate-S within the lowlands.

Available Zn also correlated significantly and positively with total C ($r =$ 0.867 and 0.800) and available P ($r = 0.690$ and 0.850) but negatively with eCEC ($r = -0.675$ and -0.544) for both river flood plains and inland valley swamps (Table 6), respectively.

3.3. Available iron (Fe)

Available Fe distribution down the profile, as presented in Table 4a, were moderate to high, but varied greatly both within and between river flood plains and inland valley swamps. Topsoil mean levels of available Fe for river flood plains and inland valley swamps were 163.1 and 219.8 mg kg^{-1}, respectively. Following a trend similar to that of the other elements, available Fe decreased with increasing depth for West African lowlands. The river flood plains, however, showed lower mean available Fe levels than the inland valley swamps (Fig. 2c).

While there was no clear trend between available Fe and agro-ecology within the river flood plains in the more humid (EF) and sub-humid (GuS and SuS) zones, the inland valley swamps showed higher available Fe levels than the drier SaS zone. Even though variability in topsoil available Fe levels was high (Ref. SD values), the highest variability for both lowland types was observed within the SuS zones. A frequency distribution of topsoil available Fe across the sub-region (Fig. 3c) showed that inland valley swamps had often a higher available Fe than the river flood plains. This is reflected in the fact that more than 20% of sampled areas within the inland valley swamps and less than 10% of river flood plains showed available Fe levels higher than 300 mg kg^{-1}. This is above the range of 70–300 mg kg^{-1} of available Fe, required for normal rice growth as proposed by Tanaka and Yoshida (1970).

Available Fe, however, showed no significant relationship with most of the selected nutrient characteristic (Table 6) except pH ($r = -0.527$) within the river flood plains.

3.4. Available manganese (Mn)

Available Mn vertical distribution is as given in Table 4(b). Available Mn levels were moderate across West Africa lowlands with respective topsoil means of 66.6 mg kg^{-1} for river flood plains and 57.6 mg kg^{-1} for the inland valley swamps. Available Mn showed a similar trend with the other elements, decreasing with increasing depth. Mean available Mn levels, however, increased with increasing precipitation (Fig. 2d). For both river flood plains and inland valley swamps, the higher rainfall zones of the EF and GuS showed higher available Mn levels than the SuS and SaS where rainfall is lower in the order $\mathrm{EF} > \mathrm{GuS} \gg \mathrm{SuS} > \mathrm{SaS}$ for the river flood plains, and $\mathrm{EF} \gg \mathrm{GuS} = \mathrm{SuS} > \mathrm{SaS}$ for the inland valley swamps. Highest levels and variability (Ref. SD values) in topsoil available Mn were observed within the EF for both lowland types. Decreases in available Mn with increasing depth were more pronounced within the inland valley swamps. Nonetheless, the frequency distribution of available topsoil Mn (Fig. 3d) showed a relatively similar trend for both lowland types.

Available Mn positively and significantly correlated with total C ($r = 0.921$ and 0.865) and available P ($r = 0.907$ and 0.867) but showed a negative significant correlation with pH ($r = -0.763$ and -0.792) for both river flood plains and inland valley swamps, respectively (Table 6).

3.5. Available copper (Cu)

Table 5(a) shows observed levels of available Cu for West African lowlands. Mean topsoil available Cu levels were 3.38 mg kg^{-1} for river flood plains and

Table 1
Some general properties of topsoil (0–15) cm of West African lowlands used in this study

Location	pH (H_2O)	TC g kg^{-1}	TN g kg^{-1}	C/N ratio	Average P[a] mg kg^{-1}	K cmol(+) kg^{-1}	Ca cmol(+) kg^{-1}	Mg cmol(+) kg^{-1}	Na cmol(+) kg^{-1}	Ex. Ac cmol(+) kg^{-1}	eCEC cmol(+) g kg^{-1}	Clay g kg^{-1}	Clay activity cmolkg^{-1} clay^{-1}
River flood plains[b]													
West Africa	5.4	11.0	0.98	10.9	3.2	0.49	5.61	2.69	0.77	0.82	10.31	431	24
Equatorial forest	5.2	14.1	0.86	18.2	4.2	0.17	4.11	1.47	0.35	1.47	7.03	394	18
Guinea savanna	5.5	16.3	1.33	12.0	4.1	0.47	3.92	1.93	0.75	0.71	7.80	346	23
Sudan savanna	5.4	8.3	0.88	9.0	2.3	0.57	7.26	3.08	0.55	0.88	12.34	540	23
Sahel savanna	5.7	6.2	0.71	8.6	2.8	0.56	5.86	3.81	1.47	0.46	12.14	373	32
Inland valley swamps[c]													
West Africa	5.3	12.8	1.11	12.0	3.9	0.25	1.89	0.88	0.19	0.99	4.20	160	26
Equatorial forest	5.3	20.4	1.66	12.0	5.3	0.27	2.28	1.24	0.26	1.67	5.72	200	29
Guinea savanna	5.3	7.3	0.70	10.0	2.9	0.20	1.33	0.51	0.11	0.51	2.66	130	21
Sudan savanna	5.9	5.5	0.68	8.0	2.6	0.52	4.67	1.85	0.48	0.14	7.66	200	39
Sahel savanna	6.0	6.2	0.66	9.0	2.7	0.63	4.82	1.87	0.46	0.46	8.24	200	41

[a] Bray No. 1.

[b] Buri and Wakatsuki, 1996; Buri et al., 1999.

[c] Issaka, 1997; Ex. Ac = exchangeable acidity.

2.48 mg kg^{-1} for inland valley swamps. Available Cu levels decreased generally with increasing depth within West Africa lowlands as did the other elements. Topsoil available Cu distribution within river flood plains was in the order EF > SuS > GuS > SaS. Within the inland valley swamps available Cu were highest within the SuS, followed by the EF, SaS and GuS in that order.

Mean available Cu levels within the inland swamps were generally lower than river flood plains except within the SuS zone (Fig. 2e). Available Cu levels were generally moderate to high across West African lowlands. The frequency distribution of available topsoil Cu as shown in Fig. 3e clearly indicates that less than 20% of river flood plain and less than 10% of inland valley swamp areas have values below the soil critical level of 0.2 mg Cu kg^{-1} soil as proposed by Ponnamperuma et al. (1981).

Topsoil available Cu correlated significantly with total clay ($r = 0.945$ and 0.519) for both lowland types (Table 6), but with a higher coefficient for river flood plains than inland valley swamps, reflecting the higher total clay content (Table 1) of those areas.

3.6. *Available nickel (Ni)*

The depth distribution of available Ni is shown in Table 5b. As in the case of available Cu, soils of West African lowlands showed moderate to high levels of available Ni. Mean available Ni levels fluctuated with depth within the river flood plains but showed a general decreasing trend with increasing depth within the inland valley swamps. Among lowland types, mean available Ni levels were higher for the river flood plains than for the inland valley swamps (Fig. 2f) except within the SuS. Within both river flood plains and inland valley swamps, available Ni levels generally decreased from the humid to the sub-humid and to the drier zones, with the SaS recording the lowest levels.

Available Ni also significantly correlated with total C ($r = 0.946$ and 0.984) and available P ($r = 0.705$ and 0.985) but negatively with pH ($r = -0.587$ and -0.661) for both river flood plains and inland valley swamps respectively (Table 6). The element also showed a significant negative relationship with eCEC ($r = -0.790$) for river flood plains. Topsoil frequency distribution of available Ni (Fig. 3f), however, showed a similar trend for both river flood plains and inland valley swamps.

4. Discussion

Most soils within the West Africa sub-region including the lowlands are relatively low in inherent fertility. The soils are acidic, have low clay content (particularly the inland valleys) and are developed over parent materials that are low in nutrient reserves. As shown in Table 1, West Africa lowlands topsoils are quite acidic, have low organic matter levels, low base status and low clay content. This is a partial reflection of the generally low total basic oxides levels (K_2O, CaO, MgO) but higher SiO_2, Al_2O_3 and Fe_2O_3 levels (Table 2). Prolonged weathering and leaching of these soils may be the main reason for such low basic total oxide levels. This coupled with the sandy nature (more particularly the inland valleys), low colloidal activity (low organic matter and erratic rainfall distribution) and low clay activity (indicative of the dominance of silicate clay minerals) as shown in Tables 1 and 2, have provided an environment where cation retention and the overall build-up of soil plant nutrients is very low. Since the consequences of flooding (possible material transport and deposition) and various crop management (cropping systems) factors combine to influence the availability of plant nutrients, West Africa lowland soils are therefore generally low in most plant nutrients with sulfur deficiency and micronutrient limitations being widespread.

The observed levels of sulfate-S and the selected micronutrients (Tables 3–5), show a wide range of variation both within and between agro-ecological zones for river flood plains and inland valley swamps. Under an intensification of land use from shifting to continuous cultivation, the sandy soils (especially the inland valley swamps) will show S and Zn deficiencies. Soil available Fe, Mn, Cu, and Ni levels were, however, moderate to high across West Africa lowlands. The generally low levels of sulfate-S across the region may be ascribed to the distribution of both organic matter (Table 1) and precipitation (Fig. 1). Sulfate-S

Table 2
Total elemental oxide levels (g kg^{-1}) of topsoil (0–15) cm of West African lowlands used in this study

Location	P_2O_5	Fe_2O_3	Al_2O_3	SiO_2	K_2O	CaO	MgO	MnO_2	Na_2O
River flood plains									
West Africa	0.69	82.8	134	723	10.3	5.1	5.4	0.4	7.1
Equatorial forest	0.73	92.4	151	678	16.8	4.2	7.0	0.2	6.9
Guinea savanna	0.56	66.0	116	750	12.8	4.4	5.5	0.8	8.0
Sudan savanna	0.78	98.9	153	689	7.4	5.8	5.5	0.2	6.9
Sahel savanna	0.64	59.4	95	801	7.7	4.9	3.5	0.2	6.2
Inland valley swamps[a]									
West Africa	0.83	42.6	144	784	9.3	4.0	4.3	0.6	1.9
Equatorial forest	1.87	42.7	143	787	9.4	3.6	3.8	0.6	1.9
Guinea savanna	1.22	43.0	119	807	8.9	5.1	5.0	0.6	2.5
Sudan savanna	0.21	44.0	234	700	5.4	2.1	4.3	0.4	0.1
Sahel savanna	0.28	72.5	217	667	24.2	3.4	7.4	0.4	1.7

[a] Calculated from Issaka (1997).

Table 3
Means and range values of sulfate-S and available Zn for the different agro-ecological zones in West Africa lowlands
SD represents standard deviation for topsoil only.

Depth (cm)	West Africa		Equatorial forest		Guinea savanna		Sudan savanna		Sahel savanna	
	mean	range	mean	range	mean	range	mean	range	mean	range
(a) Sulfate-S (mg kg $^{-1}$) river flood plains										
0–15	3.41	0.32–14.91	3.12	0.43–14.91	3.24	0.33–10.22	3.87	0.32–11.29	3.45	0.34–6.27
15–30	2.92	0.37–9.57	3.94	0.37–9.57	2.72	0.37–8.50	2.87	0.67–7.90	2.51	0.49–4.26
30–45	2.07	0.11–7.96	1.94	0.18–5.52	1.81	0.11–7.96	2.34	0.04–7.90	1.79	0.49–3.12
SD	2.77		3.75		2.43		2.81		1.97	
Inland valley swamps										
0–15	4.88	0.19–27.02	6.27	0.59–27.02	4.09	0.19–20.78	1.98	0.92–2.58	0.99	0.78–1.14
15–30	3.78	0.12–11.82	4.45	0.12–11.82	3.52	0.70–11.05	2.31	0.29–3.57	0.71	0.47–0.97
30–45	2.66	0.08–8.69	2.92	0.27–8.69	2.93	0.08–6.43	1.20	0.39–1.87	0.85	0.18–1.96
SD	5.02		5.39		4.68		0.73		0.15	
(b) Available Zn (mg kg $^{-1}$) river flood plains										
0–15	1.23	0.03–6.82	1.03	0.03–6.82	1.62	0.05–6.22	0.88	0.04–3.53	0.80	0.14–2.87
15–30	0.90	0.02–6.62	1.73	0.02–6.82	1.19	0.02–3.77	0.62	0.04–3.12	0.46	0.11–1.58
30–45	0.66	0.02–6.82	1.83	0.13–6.82	0.52	0.02–1.82	0.53	0.04–3.49	0.32	0.06–0.98
SD	1.54		1.64		1.83		0.89		0.90	
Inland valley swamps										
0–15	1.56	0.05–15.54	1.55	0.10–13.10	1.90	0.10–15.54	0.64	0.37–0.99	0.47	0.05–1.01
15–30	0.91	0.02–10.04	1.27	0.02–10.04	0.39	0.02–1.05	0.36	0.15–0.92	0.23	0.09–0.45
30–45	0.55	0.01–10.12	0.80	0.01–10.12	0.29	0.05–1.05	0.11	0.08–0.18	0.12	0.03–0.24
SD	2.92		2.61		3.73		0.29		0.44	

Table 4
Means and range values of available Fe and available Mn for the different agro-ecological zones in West African lowlands
SD represents standard deviation for topsoil only.

Depth (cm)	West Africa		Equatorial forest		Guinea savanna		Sudan savanna		Sahel savanna	
	mean	range	mean	range	mean	range	mean	range	mean	range
(a) Available Fe (mg kg $^{-1}$) river flood plains										
0–15	163.1	0.5–901.2	120.9	6.5–463.1	184.8	1.9–835.5	164.4	0.5–901.2	151.9	3.5–273.3
15–30	98.9	0.5–451.8	169.8	24.0–451.8	84.8	6.8–341.4	92.5	0.5–370.9	77.7	3.3–164.1
30–45	61.8	1.4–346.9	110.9	23.3–209.4	47.8	1.8–189.6	63.2	1.4–346.9	40.1	1.8–96.3
SD	188.4		109.3		213.4		218.6		111.1	
Inland valley swamps										
0–15	219.8	1.2–930.0	238.2	9.8–746.9	203.0	3.0–930.0	267.2	73.7–580.8	44.9	1.2–127.7
15–30	159.1	1.5–857.9	212.4	8.7–857.9	74.0	1.5–232.7	83.6	30.2–134.6	26.1	5.1–47.0
30–45	70.0	0.1–415.7	90.7	0.1–415.7	46.0	1.1–175.4	35.6	14.2–57.4	13.6	3.0–24.1
SD	193.4		193.3		196.2		219.2		71.8	
(b) Available Mn (mg kg $^{-1}$) river flood plains										
0–15	66.6	1.5–479.2	99.9	3.2–418.5	81.7	1.5–479.2	39.7	7.4–97.0	23.9	3.4–69.2
15–30	47.9	1.0–335.7	115.7	2.4–335.7	51.1	1.0–183.0	31.5	1.9–83.4	23.6	1.8–66.3
30–45	37.9	0.1–335.7	96.2	0.1–335.7	40.8	0.4–143.0	23.3	1.9–81.5	17.9	1.8–55.2
SD	85.3		143.0		88.2		27.9		20.6	
Inland valley swamps										
0–15	57.6	1.6–494.8	72.5	1.6–494.8	45.1	5.1–161.5	41.4	28.2–58.1	19.6	3.1–60.4
15–30	49.4	1.3–393.1	63.1	1.3–393.1	34.3	1.6–173.2	30.7	19.3–41.7	17.0	2.7–50.9
30–45	35.5	0.8–420.2	46.9	0.8–420.2	25.3	0.7–92.9	19.7	6.5–31.3	9.4	2.4–20.8
SD	85.6		112.7		39.6		13.3		27.4	

Table 5
Means and range values of available Cu and available Ni for the different agro-ecological zones in West African lowlands
SD represents standard deviation for topsoil only.

Depth (cm)	West Africa		Equatorial forest		Guinea savanna		Sudan savanna		Sahel savanna	
	mean	range	mean	range	mean	range	mean	range	mean	range
(a) Available Cu (mg kg $^{-1}$) river flood plains										
0–15	3.38	0.07–15.77	3.28	0.07–15.77	3.17	0.14–10.60	3.93	0.07–11.05	2.97	0.36–8.68
15–30	3.20	0.07–15.77	4.77	0.31–15.77	1.97	0.07–6.56	3.64	0.04–14.31	3.13	0.37–7.57
30–45	2.81	0.02–18.03	4.30	0.17–15.77	1.40	0.02–4.01	3.33	0.02–18.03	2.40	0.38–6.59
SD	3.36		4.78		3.10		3.41		2.68	
Inland valley swamps										
0–15	2.49	0.08–13.50	2.74	0.08–13.50	1.60	0.33–5.45	6.44	3.29–11.34	2.34	0.35–5.05
15–30	2.39	0.06–13.48	2.57	0.06–13.48	1.59	0.27–4.76	5.32	2.04–9.97	1.77	0.84–2.67
30–45	1.95	0.02–13.47	1.96	0.02–13.47	1.60	0.14–4.07	3.65	1.12–5.76	1.72	1.29–2.16
SD	2.73		3.16		1.20		3.46		1.97	
(b) Available Ni (mg kg $^{-1}$) river flood plains										
0–15	1.68	0.01–15.12	1.71	0.01–15.12	2.02	0.05–7.77	1.45	0.30–4.33	0.90	0.20–3.03
15–30	1.54	0.03–15.12	3.67	0.03–15.12	1.14	0.05–4.29	1.38	0.10–5.23	1.12	0.10–3.51
30–45	1.45	0.02–15.12	3.68	0.02–15.12	0.74	0.02–1.55	1.41	0.08–6.93	1.00	0.14–3.30
SD	2.42		4.26		2.27		1.33		0.89	
Inland valley swamps										
0–15	1.36	0.01–14.36	2.07	0.03–14.36	0.68	0.01–3.91	0.65	0.22–1.37	0.39	0.10–0.83
15–30	1.47	0.02–14.51	2.08	0.05–14.51	0.72	0.02–2.18	0.77	0.22–1.33	0.26	0.05–0.53
30–45	1.02	0.01–14.87	1.42	0.01–14.87	0.57	0.07–1.39	0.58	0.09–1.05	0.24	0.11–0.38
SD	2.89		3.87		0.94		0.51		0.32	

distribution was very similar to that of total C, being low within the drier zones of the SaS and SuS and only increasing slightly within the comparatively higher rainfall and more thicker vegetative zones of the EF and GuS (effect of climatic differences), an indication that both organic matter and precipitation were the main sources of sulfate. This is reflected in the fact that sulfate-S showed a positively high significant correlation with total C, P and eCEC (Table 6) for both river flood plains and inland valley swamps. However, the general soil nutrient status (both available and total) of these soils is very low (Tables 1 and 2). Organic matter in particular has been reported to be more effective in increasing and retaining most cations over clay (Oyediran, 1990; Brady and Weil, 1996). Poor organic matter management resulting in low total C levels therefore has a direct bearing on the widespread sulfate-S deficiency observed for these soils. The ultimate geological sources of sulfur are both seawater and volcanic activity, which supply sulfur to the soil through precipitation. The absence of active volcanic activity in the region may also partially account for such low levels of sulfur.

Such low levels of sulfate-S, as observed in West Africa lowland soils, may account for the high and significant responses in both rice growth and yield, to sulfur application in most parts of the sub-region. Yamaguchi (1997) reported significant responses of rice to sulfur fertilizers for some Ghanaian soils while similar rice responses to sulfur application for some Nigerian soils have also been reported by Osiname and Kang (1975), Enwezor (1976) and Kang et al. (1981). Acquaye and Kang (1987) reported the sulfate-S levels of some Ghanaian soils as 2.2 mg kg^{-1} while Kang et al. (1981) gave the figure for some Nigerian forest and savanna soils as 4.1 mg kg^{-1}. Under this study, observed levels of sulfate-S for lowlands in Ghana were 2.4 and 2.5 mg kg^{-1} for river flood plains and inland valley swamps, whilst Nigerian lowlands were 4.6 and 3.5 mg kg^{-1} for inland valley swamps and river flood plains, respectively.

To obtain good crop yields, the critical concentration of soil sulfate should range from 5–20 mg kg^{-1} soil for flooded rice and upland crops (McClung et al., 1959; Fox et al., 1964; Ensminger and Freney, 1966; Wang, 1976). Sulfur sources for field crops include soil, fertilizers, crop residue, rain, air and irrigation water. Most of these S sources are very limited under present conditions. This coupled with poor farm management practices (the total removal of farm biomass for other purposes in particularly the savanna areas) further results in soil S depletion. In order to reduce soil acidity, the main S fertilizer, ammonium sulfate, has since been replaced by urea in most countries, thus worsening the soil S problem.

Except for a few isolated areas, available Zn was deficient across the West African lowlands. The significantly high positive correlation of available Zn to total C and P (Table 6) and the generally low topsoil organic matter content of West African lowlands (Table 1) is one major factor for the low levels of available Zn. Hence, like S, an effective organic matter management is neces-

Table 6
Correlation coefficients between micronutrients and selected nutrient characteristics in West African lowlands

	River flood plains					Inland valley swamps				
	pH	TC	Av. P	eCEC	Clay	pH	TC	Av. P	eCEC	Clay
S	0.248	0.690*	0.939*	0.867*	0.859*	−0.922	0.874*	0.873*	0.612**	0.215
Zn	−0.088	0.867*	0.690*	−0.675**	−0.512**	−0.509**	0.800*	0.850*	−0.544**	−0.407
Fe	−0.527**	0.113	−0.187	0.222	−0.015	−0.473	0.318	0.325	−0.339	−0.099
Mn	−0.763*	0.921*	0.907*	−0.973*	−0.363	−0.792*	0.865*	0.867*	0.432	−0.014
Cu	−0.455	−0.147	−0.497	0.318	0.945*	−0.506**	−0.256	−0.246	0.546**	0.519**
Ni	−0.587**	0.946*	0.705**	−0.790*	−0.171	−0.661**	0.984*	0.985*	−0.203	0.235

*Significant at $P \leq 0.01$.

sary to maintain and/or increase the current levels of this nutrient. Available Zn, however, showed a significantly negative correlation to eCEC. This surfaces to say that, as efforts are made to increase levels of the basic cations, Zn deficiency may even become more pronounced. About 66% of both river flood plains and inland valley swamps (Fig. 3b) showed available Zn levels below the critical soil level of 0.83 mg Zn kg^{-1} soil for normal rice growth as proposed by Randhawa and Takkar (1975). Katyal and Ponnamperuma (1974) reported that Zn deficiency was widespread and that severe Zn deficiency symptoms were observed in rice grown on soil with available Zn levels below 1.0 mg kg^{-1}, adding that total crop failure was possible under very severe Zn deficiency.

Zn availability has been reported to decrease by almost 100 times with a unit increase in pH (Ponamperumma et al., 1981; Brady and Weil, 1996). This makes Zn the most critical limiting micronutrient to rice growth within the West African lowlands. Since the availability of both soil Zn and applied Zn is also reported to be much higher in upland crops than submerged soils (Yoshida and Tanaka, 1969; Yoshida, 1981), Zn deficiency within the West African lowlands becomes more pronounced under flooded conditions as soil submergence causes a substantial decrease in the Zn concentration in the soil solution by lowering Zn solubility as pH increases. Therefore, for the development of ‘‘sawah-based’’ rice cultivation in West Africa (Wakatsuki et al. 1998), possible Zn deficiency has to be carefully considered in advance.

Available Fe levels were moderate across the region except for some isolated areas which showed high levels (potential for toxicity). This could be ascribed to the general acidic nature of the soils, particularly within the high rainfall areas of the EF where most of the isolated areas occur and to a lesser extent within the sub-humid GuS and SuS zones. This is supported by the fact that, Fe showed no significant correlation with the selected nutrient characteristics except pH ($r = -0.527$) within river flood plains. These isolated areas of high available Fe contents are mostly within the more leached and acidic EF zone and some parts of the more sandy GS and SuS zones. Brady and Weil (1996) reported that soil pH has a deciding influence on micronutrient availability, adding that a pH range of 6.0–7.0 was ideal. Fe toxicity problems (mostly associated with poor soils) may be reduced/minimized when effective management practices for sulfate and available Zn build-up as well as adequate application of K are made operational.

Tanaka and Yoshida (1970) reported that Fe concentrations as high as 300 mg kg^{-1} become common after 4 weeks of submergence. They further went on to say that higher levels of Fe in the soil solution affect the absorption of other nutrients such as P and K. Potassium-deficient plants exhibit Fe toxicity (Yamauchi, 1989). Hence the generally low levels of exchangeable K for West African lowlands (Buri and Wakatsuki 1996; Issaka et al. 1996) within the EF and parts of the GuS, and the higher levels of soil solution Fe observed within these areas, as well as the low levels of sulfate-S and available Zn may explain the Fe toxicity problems encountered in some rice fields across those areas within the sub-region in recent times.

The moderate to high levels of available Mn across the sub-region partly explain the suitability of these lands for rice production under proper management as recommended by Okusami (1986). Both Mn and Ni further showed a high positive correlation to total C and P indicative of the fact that effective organic matter management was a key factor to maintaining/increasing nutrient levels. Mn deficiency or toxicity seldom occurs in rice fields. It is reported to occur only in more degraded and less productive soils (Tanaka and Yoshida, 1970). Under submerged conditions, soil solution Mn increases and becomes beneficial at near-neutral conditions. The West African lowlands have a current pH range of 5.2–6.0. Slight increases in pH with flooding will therefore enhance further increases the concentration of Mn in soil solution. Tanaka and Yoshida (1970) also reported that a high Mn content in rice tissue is associated with high yields, possibly indicating that a high Mn content in the soil is associated with various favorable soil conditions.

West African lowlands were generally moderate to high in available Cu, especially in the topsoil (Fig. 3e). The soils did not show Cu deficient levels even though Cu has been reported to be a hidden limiting factor under most Zn deficient soils. The over 85% of West African lowlands showing topsoil available Cu levels above the critical soil level of 0.2 mg Cu kg^{-1} soil for rice (Takkar and Randhawa 1978), shows that the element is not yet a limiting factor to rice production. Since Ni has a similar behavior to Cu in soils, current levels of available Ni are similar to those of available Cu. Similar conditions and the acidic nature of West African lowland soils is keeping the levels of both available Cu and Ni within nonlimiting levels.

5. Conclusion

Soils of the West African lowlands were observed to be very deficient in sulfate S and available Zn. Available Fe, Mn, Cu, and Ni were at moderate levels, except soil solution Fe which tended to show toxic levels in isolated areas. The relative deficiency in soil sulfate-S and micronutrient supply within the West African lowlands was in the order $S > Zn > Cu = Ni = Mn = Fe$. Fertilizer usage within the region is still very low and in most instances where attempts are made to supplement crop nutrient requirements with artificial fertilizers, much attention is focused on the macronutrients (particularly N) to the detriment of the essential micronutrients. This tendency coupled with unfavorable farm management practices is leading to the rapid soil depletion of some nutrients especially S and Zn.

To correct such deficiencies in order to provide a balanced nutrient environment for crop growth (rice especially), fertilizer additions should include S and

Zn. The use of Zn and S containing fertilizers specially adapted for West African conditions is necessary. Nutrient recycling is mostly non-existent, as total farm biomass (primary sources of S and Zn) is removed from the field after harvest. In order to stabilize and/or increase the very low levels of available Zn and sulfate-S, there is the need for farmers to adopt practices that allow/encourage both organic matter recycling and accumulation. Favourable future solutions will be to encourage the production and use of Zn containing ammonium sulfate instead of urea which is the major fertilizer presently used in West Africa.

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