Soil Science and Plant Nutrition (2007) **53**, 141–149 doi: 10.1111/j.1747-0765.2007.00117.x

ORIGINAL ARTICLE

Soil development and fertility characteristics of inland valleys in the rain forest zone of Nigeria: Physicochemical properties and morphological features

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Abstract

Inland valleys are a widespread topography in West Africa and have significant potential for agricultural development, especially wet rice cultivation. This study investigated the physicochemical and morphological properties of the soils of two inland valleys in Abakaliki and Bende, Southeast Nigeria, where the soils are derived from shale materials, and discusses their agricultural potential as well as the soil-forming process. Particle size analysis suggested that the soils at both sites were fine-silty, fine-loamy or clayey and, thus, would be able to retain a high amount of water. In contrast, the higher content of clay and silt in the Abakaliki soils would enhance much more water retention than the Bende soils. The soils in Abakaliki, except for some subsoil horizons, generally had acidic reactions, low contents of exchangeable bases (Ca, Mg, K and Na) and high amounts of exchangeable acidity (Al and H) for which leaching effects under high precipitation in the area would be implicated. Bray-1 P values in these soils were generally low under such acidic conditions, while organic C and total N were recorded at relatively high levels, in particular at the surface horizons, reflecting large biomass production under a humid climate. The Bende soils showed similar chemical properties to Abakaliki except for relative accumulation of exchangeable bases throughout the profile on the downslope possibly because of the rolling topography. This result suggested that geological fertilization (i.e. afflux of nutrients released during the soil formation in the upland into the lowland) was more beneficial in Bende than Abakaliki. From the findings of the present study, we concluded that soils in both Abakaliki and Bende had good texture for *sawah* development (leveled and bounded rice field with an inlet and an outlet for irrigation and drainage), but their poor chemical properties would be constraints for agricultural production.

Key words: geomorphology, hydromorphic soil, inland valleys, physicochemical properties, Southeast Nigeria, water movement.

INTRODUCTION

It has been estimated that 62% of the total rice production in West Africa comes from the wetlands (West Africa Rice Development Association 2004), which highlights the significant role of lowland ecosystems in rice production. In particular, inland valleys have been recognized as having great potential for the production of swamp rice (Wakatsuki and Masunaga 2005; West Africa Rice Development Association 2002; Windmeijer and Andriesse 1993). However, only 15% or less of the total area of inland valleys in the region has, to date, been under cultivation despite the agricultural potential of inland valleys (International Institute of Tropical Agriculture 1990; West Africa Rice Development Association 1997) because of a lack of understanding of inland valley ecosystems. Andriesse and Fresco (1991) described rice-growing environments in inland valleys based on agro-ecological characterization. Issaka *et al.* (1997), Buri *et al.* (1999) and Abe *et al.* (2006; 2007) recorded the general fertility status and material nature

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Received 26 July 2006.
Accepted for publication 21 November 2006.

of inland valley soils over West Africa. These studies have improved our understanding of how best to utilize inland valley ecosystems. However, intensive assessment on soil properties and, thus, agricultural potential in specific locations has been scarce. Inland valleys under the rain forest climate in Southeast Nigeria are a typical case. The soils in this area have formed in shale materials and are assumed to have distinctive properties, although most soils in West Africa derive from granites and metamorphic rocks (Windmeijer and Andriesse 1993). Therefore, we investigated the physicochemical and morphological properties of the soils in two inland valleys of Abakaliki and Bende, Southeast Nigeria, and speculate on the agricultural potential of these soils and the soil-forming process.

MATERIALS AND METHODS

Two inland valley systems, one near Abakaliki (N 6°15′, E 8°8′) and the other in Bende (N 5°30′, E 7°40′), were selected for this study (Fig. 1). Both sites are located in the southeastern part of Nigeria and have a tropical humid climate with an average annual precipitation of approximately 2,000 mm in a bimodal distribution and a mean annual daily temperature of approximately 27°C. The Abakaliki site lies on a gently undulating peneplain, while the Bende site has a rolling topography. The soils of Abakaliki derive from Cretaceous black shale and siltstone or shale and limestone, while the geological materials of Bende are Tertiary clays, clayey sands and shale, clays and shale with limestone (Federal Survey 1992). Nevertheless, our field survey indicated that the inland valley of Bende had segregation of geological materials (i.e. sandstone in the upland but shale in the wetland). The Abakaliki site had been under swamp rice cultivation for hundreds of years, while the Bende site had only been under cultivation for decades. An overview of the sampling points at each site is given in Fig. 2. The profiles were described according to the recommended procedure of the Food and Agriculture Organization (1977) using horizon designations of the Soil Survey Staff (1981). Furthermore, US Soil Taxonomy (Soil Survey Staff 2006) was applied to classify the soils.

The soil samples obtained were air-dried and crushed to pass through a 2 mm sieve. Bulk density was determined using the clod method (Blake 1965) with paraffin wax melted at 60–70°C. Particle size analysis was done using the hydrometer method (Bouyoucos 1962). Soil pH was measured potentiometrically in distilled water and 1.0 mol L^{-1} KCl (1:1 soil : liquid ratio) using a pH meter after equilibration for 30 min. Exchangeable bases (Ca, Mg, K and Na) were extracted with 1.0 mol L^{-1} neutral NH$_4$OAc. Calcium and Mg were determined by atomic absorption spectrometry (AAS), but K and Na were examined on a flame photometer. Exchangeable acidity (Al and H) was extracted with 1.0 mol L^{-1} KCl and titrated according to Yuan's method (Yuan 1959). Effective cation exchange capacity (ECEC) is the summation of exchangeable bases and exchangeable

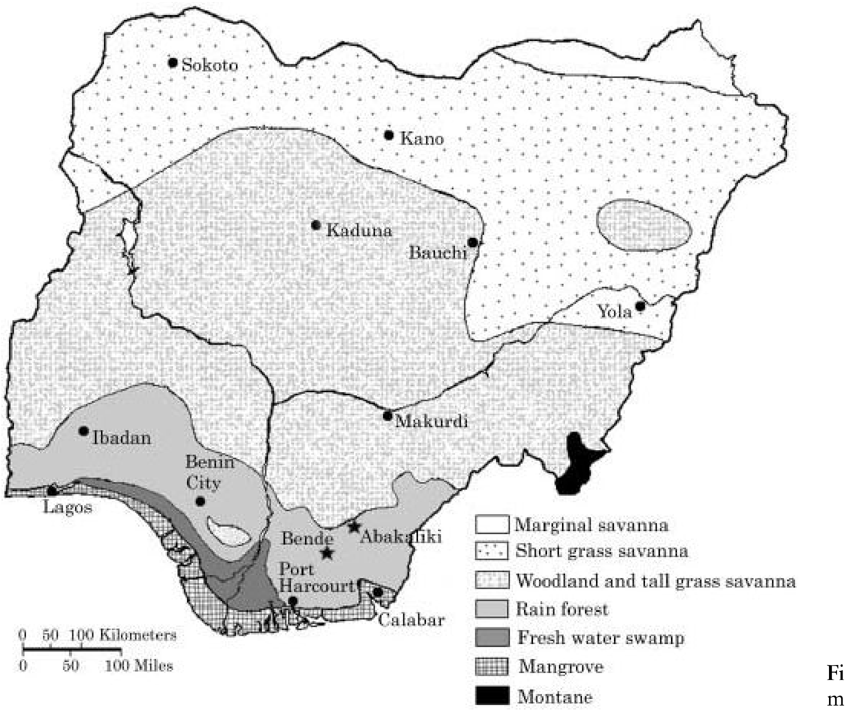

Figure 1 The study sites on a vegetation map of Nigeria.

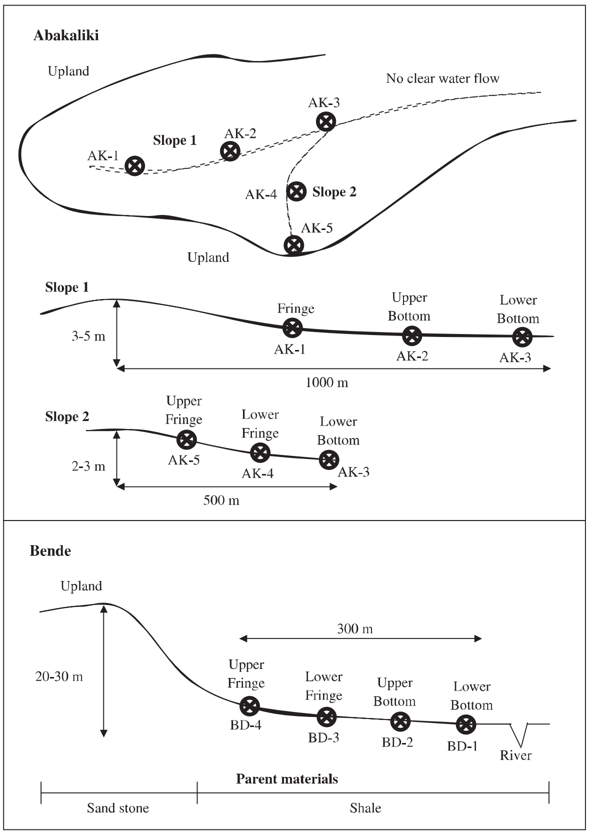

Figure 2 Brief description of the sampling points in the inland valleys.

acidity. Organic C was obtained using the chromic acid digestion method (Allison 1965). Total N was examined using the macro-Kjeldahl method in a Tecator digester system, with N-estimation by a Technicon's auto-analyzer. Available P was obtained using the Bray-1 method followed by a colorimetric examination with molybdate. Free Fe (Fe_d) was extracted using the dithionite–citrate–bicarbonate (DCB) method according to Mehra and Jackson (1960). Amorphous Fe (Fe_o) soluble in acidified NH_4-oxalate was extracted twice from a 1.0 g soil sample by 30 mL of Tamm-A reagent (Tamm 1922) after 1 h shaking in the darkness. The concentration of Fe in the extractants was determined by AAS. The ratio of Fe_o/Fe_d was calculated as an index for the activity of iron oxides (Nagatsuka 1973).

RESULTS AND DISCUSSION

Morphological features

Field observations described the morphological properties of the soils in Abakaliki and Bende (Table 1). All the pedons examined had some mottled horizons either at the epipedon or at the subsoil horizons, which reflected an annual cycle of a wet/dry soil moisture regime (i.e. hydromorphism). Grayish matrix color with low chroma of the pedons also indicated that these soils had developed under the influence of reduced conditions. However, AK-5, BD-3 and BD-4 located on the fringe had relatively a brownish color, regardless of the presence of mottles. The increasing redness of soils on the upslope can be ascribed to decreasing hydration of iron oxides, as described by Torrent *et al.* (1984). The preponderance of Fe/Mn concretions was observed at some subsoil horizons of all the pedons in Abakaliki in collaboration with fragipan at the horizon A2feg and 2Bwfeg in the pedons AK-3 and AK-5, respectively, while the soils in Bende had pedons free of concretions with the exception of the pedon BD-1 (Table 1). This indicated rapid changes in aeration and a concordant fluctuation of redox potentials in the soils of Abakaliki. The formation of horizons with Fe and Mn accumulation was commonly observed in seasonally flooded soils, which reflected the redistribution of Fe and Mn in the flooded profiles (Pickering and Veneman 1984). In contrast, sub-angular blocky was the dominant structure in the pedons of Abakaliki, while angular blocky structure was found in some clayey horizons of Bende. All profiles had the cambic horizon in the subsoil and an aquic moisture regime except for the pedon AK-5, which represented an udic moisture regime.

Physical properties

Table 2 represents selected physicochemical properties of the soils at the study sites. The mechanical analysis showed that the soils in Abakaliki were generally silty. The silt content ranged from 20.4 to 56.2% except in 3BCg and 3Cg horizons of the pedon AK-5, which contained 8.4 and 8.8% of the silt, respectively. In most cases in Abakaliki, the clay content was higher than the sand content. In contrast, the silt content of the pedons in Bende seldom exceeded 20.0%. The sand proportion decreased with increases in soil depth in the pedon BD-1, while in the other pedons of Bende the sand distribution was erratic. The pedons BD-1 and BD-2 at the bottom were clayey, while the pedons BD-3 and BD-4 on the fringe had considerably high sand content. This might reflect the influence of transportation and deposition of materials from the upland into the lowland, whereby coarse materials could deposit first. The particle size distribution at these two sites was considered to be distinctive among inland valleys in West Africa, which usually have a sandy texture (Buri *et al.* 1999). The soils in Abakaliki and Bende formed on shale materials in the Cretaceous or Tertiary era and, thus, had a relatively high content of clay. In contrast, most soils in inland valleys of West Africa have a low clay content derived from granites and associated metamorphic

Table 1 Morphological characteristics of the soils of the inland valleys

		Color						
Horizon	Depth (cm)	Matrix	Mottle	Texture	Structure	Consistence	Boundary	Others
Pedon AK-1, Fluvaquentic Epiaquepts								
Ap	0–20	10YR6/4	10YR6/8	SiCL	2 m sbk	fr shs shp	a s	–
A2	20–40	10YR7/3	–	SiL	3 m sbk	fi shs shp	a s	–
Bwg1	40–81	10YR7/2	–	CL	3 m sbk	fi shs shp	a s	Fe/Mn concretion > 15%
Bwg2	81–111	10YR7/2	–	SiL	4 m sbk	fi vs vp	g s	Fe/Mn concretion <10%
Bwg3	111–170	10YR7/2	5Y2/1	SiL	4 m sbk	fi s p	c s	Mn cocretion < 10%
BCg	170–194	10YR7/2	10YR5/6	L	3 m sbk	fi s p	–	Mn concretion > 20% and quartz gravels
Pedon AK-2, Fluvaquentic Epiaquepts								
Ag	0–28	2.5Y5/1	7.5YR5/6	SiCL	2 f sbk	fr shs shp	c s	–
A2 g	28–47	10YR8/2	7.5YR5/6	CL	3 f sbk	fr shs shp	c s	–
2Bwg	47–74	10YR5/2	2.5YR3/6	SiCL	3 m sbk	fr shs shp	a s	Fe/Mn concretion > 15%
2Bg	74–109	7.5YR5/1	10YR6/6	SiC	3 m sbk	fr s p	d s	Mn concretion < 10%
2BCg	109–150	7.5YR5/1	10YR6/6	SiCL	3 m sbk	fr shs shp	–	Mn concretion > 15%
Pedon AK-3, Aeric Fragiaquepts								
Apg	0–28	7.5Y7/1	10YR5/8	C	2 f sbk	fr shs shp	a s	–
A2feg	28–54	7.5YR4/8	7.5YR2/1	L	ND	ND	c s	Fe concretion > 80%
B1 g	54–100	7.5Y7/1	10YR5/8	C	ND	ND	a s	Fe/Mn concretion < 10%
B2 g	100–158	7.5Y7/1	10YR5/8	C	3 m sbk	fi s p	–	Quartz gravels
Pedon AK-4, Fluvaquentic Epiaquepts								
Apg	0–30	2.5Y5/1	7.5YR5/6	C	2 m sbk	fr shs shp	c s	–
Bwg1	30–50	10YR8/2	7.5YR5/6	SiCL	3 m sbk	fr shs shp	c s	–
Bwg2	50–98	10YR5/2	2.5YR4/6	SiCL	3 m sbk	fr shs shp	a s	Fe/Mn concretion > 15%
BCg	98–148	7.5YR5/1	10YR6/6	SiCL	4 c sbk	fr shs shp	–	Mn concretion < 10%
Pedon AK-5, Typic Fragiudepts								
Ap	0–20	7.5YR4/4	–	SiCL	2 f gr	fr shs shp	d s	–
AB	20–50	7.5YR4/4	–	SiCL	2 f sbk	fr shs shp	a s	–
2Bw	50–76	10YR5/6	–	SL	3 m sbk	fr shs shp	c s	–
2Bwfeg	76–95	7.5YR4/8	10YR5/6	L	ND	ND	a s	Fe concretion > 80%
3BCg	95–135	7.5Y7/1	10YR5/8	LS	3 m sbk	fi s p	g s	–
3Cg	135–170	7.5Y7/1	10YR5/6	SL	3 m sbk	fi s p	–	–
Pedon BD-1, Fluvaquentic Epiaquepts								
Ap	0–21	5YR3/2	–	SCL	2 m sbk	fr s p	c s	–
Bw1	21–50	7.5YR6/1	5YR4/3	C	3 m abk	fi vs vp	c s	–
Bwg2	50–85	7.5YR5/1	2.5YR3/4	C	4 m abk	vfi vs vp	g s	Mn concretion < 10%
Bwg3	85–100	7.5YR5/1	2.5YR4/8	C	4 c abk	vfi vs vp	c s	Mn concretion > 15%
BCg	100–158	7.5YR5/1	10YR5/8	C	4 c abk	fi vs vp	–	Mn concretion > 15%
Pedon BD-2, Fluvaquentic Epiaquepts								
Ap1	0–20	7.5YR3/2	–	C	2 f sbk	fr shs shp	c s	–
Apg2	20–52	10YR5/2	7.5YR5/6	SC	3 f sbk	fr s p	a s	–
Bwg1	52–89	2.5Y6/2	2.5YR4/8	C	4 m abk	fi vs vp	a w	–
Bwg2	89–120	2.5Y6/2	10R3/4	C	4 m abk	fi s p	c s	–
BCg	120–165	2.5Y6/1	2.5YR4/8	SCL	3 f sbk	fr s p	–	–
Pedon BD-3, Fluvaquentic Humaquepts								
Ap	0–20	10YR3/2	7.5YR4/6	SC	3 f sbk	fr shs shp	c s	–
Bw1	20–73	7.5YR6/1	7.5YR4/6	SC	3 m abk	fi s p	c s	–
Bw2	73–100	7.5YR6/1	–	SCL	4 m abk	fi vs vp	g s	–
BC	100–152+	7.5YR6/2	–	SL	3 m abk	fi vs vp	–	–
Pedon BD-4, Fluvaquentic Humaquepts								
Ap	0–18	10YR3/2	5YR4/8	SL	3 f sbk	fr shs shp	c s	–
Bw1	18–30	10YR5/2	5YR4/8	SCL	3 m sbk	fi s p	c s	–
Bw2	30–75	7.5YR6/1	7.5YR5/6	SCL	4 m abk	fi vs vp	a w	–
BC	75–144	7.5YR6/1	–	SL	2 f gr	vfr shs shp	–	–

SiCL, silty clay loam; SiL, silty loam; CL, clay loam; L, loamy; SiC, silty clay; C, clayey; SL, sandy loam; LS, lomy sand; SC, sandy clay; SCL, sandy clay loam; 2, moderate; 3, strong; 4, very strong; m, medium; f, fine; c, coarse; sbk, subangular blocky; abk, angular blocky; gr, granular; fr, friable; fi, firm; vfi, very firm; vfr, very friable; shs, slightly sticky; vs, very sticky; s, sticky; shp, slightly plastic; vp, very plastic; p, plastic; a, abrupt; c, clear; g, gradual; d, diffuse; f, flat; s, smooth; w, wavy; ND, not determined.

Table 2 Selected physicochemical properties of the soils of the inland valleys studied

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})	pH		Exchangeable cations (cmol$_c$ kg^{-1})						ECEC (cmol$_c$ kg^{-1})	Organic C (g kg^{-1})	Total N (g kg^{-1})	Bray-1 P (mg kg^{-1})
						H$_2$O	KCl	Ca	Mg	K	Na	Al	H				
Pedon AK-1																	
Ap	0–20	14.4	50.0	35.6	1.65	4.9	4.6	1.27	0.54	0.24	0.13	1.78	0.80	4.76	19.7	1.3	2.4
A2	20–40	26.0	56.2	17.8	0.93	6.1	5.7	1.08	0.71	0.93	0.05	0.56	0.22	3.55	9.3	0.3	1.8
Bwg1	40–81	34.0	42.0	24.0	0.93	8.0	7.3	1.56	1.88	3.53	0.12	0.10	0.02	7.21	9.3	0.4	1.8
Bwg2	81–111	20.4	50.6	29.0	0.99	9.0	8.1	1.81	2.34	4.72	0.24	0.34	0.13	9.58	8.3	0.3	1.8
Bwg3	111–170	20.4	50.6	29.0	1.16	7.7	7.3	2.81	3.70	3.71	0.11	0.19	0.04	10.56	8.2	0.2	2.7
BCg	170–194	12.0	42.0	46.0	1.71	9.1	8.2	3.78	2.48	3.77	0.11	0.06	0.01	10.21	7.6	0.2	2.7
Pedon AK-2																	
Ag	0–28	14.6	53.4	32.0	1.43	5.1	4.8	0.46	0.30	0.32	0.06	2.89	0.17	4.20	9.3	0.4	1.4
A2 g	28–47	34.0	38.5	27.5	1.19	4.2	4.0	0.89	0.40	0.18	0.14	2.92	0.37	4.90	20.8	1.3	2.1
2Bwg	47–74	12.0	51.5	36.5	1.05	6.0	5.6	1.81	2.14	2.04	0.09	1.90	0.50	8.48	9.5	0.4	0.9
2Bg	74–109	20.0	40.0	40.0	1.68	8.9	8.0	2.74	3.23	4.85	0.24	0.10	0.02	11.18	7.8	0.2	1.0
2BCg	109–150	14.5	51.5	34.0	1.41	8.3	7.5	3.97	3.90	4.91	0.03	0.25	0.05	13.11	7.8	0.3	1.8
Pedon AK-3																	
Apg	0–28	4.8	40.0	55.2	2.04	4.7	4.2	0.43	0.39	0.18	0.35	2.94	0.36	4.65	14.1	0.7	9.0
A2feg	28–54	36.0	44.0	20.0	1.22	4.8	4.6	1.18	1.77	0.17	0.11	2.40	0.59	6.22	13.6	0.8	1.5
B1 g	54–100	30.5	27.5	42.0	1.04	6.3	6.0	5.91	5.09	0.50	0.13	0.56	0.07	12.26	9.1	0.4	1.2
B2 g	100–158	30.0	22.0	48.0	1.70	7.4	6.8	8.92	4.69	0.77	0.13	0.10	0.03	14.64	8.1	0.3	1.0
Pedon AK-4																	
Apg	0–30	34.0	20.4	45.6	1.53	4.5	4.1	0.53	4.95	0.17	0.08	2.98	0.32	9.03	15.7	0.8	3.3
Bwg1	30–50	14.2	52.0	33.8	1.74	4.6	4.1	0.24	0.31	0.18	0.05	2.98	0.59	4.35	10.5	0.4	1.8
Bwg2	50–98	18.2	51.8	30.0	1.50	5.6	5.0	0.38	0.63	0.62	0.06	2.93	0.63	5.25	10.3	0.4	1.3
BCg	98–148	20.0	50.0	30.0	1.51	7.3	6.9	1.49	2.33	3.29	0.07	0.27	0.10	7.55	7.8	0.3	1.0
Pedon AK-5																	
Ap	0–20	18.0	43.8	38.2	1.93	5.0	4.6	0.86	1.14	0.13	0.10	1.01	0.15	3.39	11.8	0.5	3.6
AB	20–50	18.2	44.0	37.8	1.93	4.9	4.6	0.80	0.71	0.15	0.09	1.99	0.83	4.57	11.7	0.5	1.6
2Bw	50–76	53.4	32.4	14.2	1.11	4.7	4.2	0.62	0.57	0.18	0.08	2.80	0.82	5.07	11.9	0.6	1.4
2Bwfeg	76–95	38.0	36.0	26.0	1.13	5.4	5.1	0.27	0.21	0.14	0.02	0.20	0.03	0.87	6.8	2.0	1.8
3BCg	95–135	81.6	8.4	10.0	0.86	5.5	5.3	0.22	0.14	0.13	0.02	0.66	0.07	1.24	6.9	2.3	1.5
3Cg	135–170	76.0	8.8	15.2	0.88	4.6	4.2	0.30	0.34	0.18	0.07	3.25	0.65	4.79	10.9	0.6	3.1

Table 2 *Continued*

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})	pH		Exchangeable cations (cmol$_c$ kg^{-1})						ECEC (cmol$_c$ kg^{-1})	Organic C (g kg^{-1})	Total N (g kg^{-1})	Bray-1 P (mg kg^{-1})
						H_2O	KCl	Ca	Mg	K	Na	Al	H				
Pedon BD-1																	
Ap	0–21	64.2	4.0	31.8	0.94	5.0	4.6	4.90	2.53	0.20	0.12	2.73	1.10	11.58	20.1	1.8	2.7
Bw1	21–50	34.0	19.6	46.4	1.08	4.9	4.6	3.42	2.10	0.16	0.10	2.89	1.31	9.98	15.8	1.2	1.8
Bwg2	50–85	26.0	20.0	54.0	1.87	5.0	4.5	4.97	3.07	0.21	0.24	3.14	1.66	13.29	11.6	0.9	1.5
Bwg3	85–100	25.8	16.2	58.0	2.01	4.9	4.6	3.16	2.60	0.18	0.14	3.25	1.70	11.03	9.8	0.7	1.5
BCg	100–158	30.0	16.8	53.2	1.82	5.1	4.8	3.70	2.93	0.22	0.24	2.03	1.27	10.39	9.2	0.5	0.6
Pedon BD-2																	
Ap1	0–20	40.0	14.3	45.7	0.89	4.9	4.6	6.44	3.19	0.21	0.22	1.97	0.80	12.83	23.9	2.3	3.2
Apg2	20–52	47.5	14.0	38.5	0.91	4.7	4.5	4.77	2.59	0.20	0.14	2.46	0.71	10.87	13.9	0.7	1.2
Bwg1	52–89	38.0	10.0	52.0	1.36	5.0	4.6	3.46	2.47	0.20	0.15	2.02	1.10	9.40	9.9	0.6	10.8
Bwg2	89–120	28.2	11.8	60.0	2.06	5.0	4.6	3.64	2.73	0.19	0.22	2.15	1.17	10.10	9.5	0.5	1.0
BCg	120–165	70.0	8.0	22.0	0.80	4.8	4.4	3.62	3.01	0.20	0.25	2.60	1.72	11.40	9.4	0.5	0.8
Pedon BD-3																	
Ap	0–20	52.1	10.6	37.3	0.94	5.2	4.8	0.61	0.49	0.17	0.09	2.63	1.70	5.69	20.2	1.2	1.0
Bw1	20–73	48.0	10.0	42.0	1.04	5.8	5.2	0.60	0.74	0.17	0.08	2.95	1.75	6.29	13.4	0.9	1.8
Bw2	73–100	63.5	6.2	30.3	0.96	4.7	4.3	0.71	0.91	0.17	0.10	2.72	1.81	6.42	13.1	0.7	0.6
BC	100–152+	76.0	6.2	17.8	0.80	5.0	4.8	0.63	0.60	0.19	0.25	1.98	1.29	4.94	11.5	0.5	1.8
Pedon BD-4																	
Ap	0–18	77.4	4.4	18.2	0.73	5.5	5.1	0.60	0.23	0.15	0.04	2.85	0.98	4.85	19.0	1.4	2.1
Bw1	18–30	70.0	6.0	24.0	0.92	5.3	5.0	0.51	0.32	0.16	0.04	2.24	1.29	4.56	4.2	0.4	1.6
Bw2	30–75	68.0	4.3	27.7	1.01	5.1	4.8	0.54	0.51	0.14	0.06	2.82	0.94	5.01	10.0	0.5	1.2
BC	75–144	82.2	3.8	14.0	0.85	5.1	4.9	0.34	0.26	0.15	0.05	2.16	1.87	4.83	8.2	0.3	10.2

rocks of Pre-Cambrian metamorphic rocks, called Basement Complex (Windmeijer and Andriesse 1993).

The implication of soil particle size distribution on water movement is that the soils would have the ability to retain a high amount of water. Thus, the cultivation of swamp rice in Abakaliki and Bende should not pose any problems. However, Abakaliki appears more promising for wet rice cultivation than Bende because of the higher silt content, which in addition to the clay in the soils of Abakaliki would enhance more water retention than the soils of Bende. In contrast, the relative accumulation of clay at the surface horizons of all the pedons in Abakaliki might be a reflection of good land and water management practices, such as the maintenance of fairly good paddies, even though this area is only at a rudimentary stage of *sawah* development (leveled and bounded rice field with an inlet and an outlet for irrigation and drainage). This would attribute to nature of parent materials in the region.

Bulk density of the soils ranged between 0.80 and 2.06 g cm^{-3}. No definite pattern of bulk density within the profile was observed, whereas the surface horizons of pedons in Abakaliki tended to have a higher bulk density than those in Bende.

Chemical characteristics

In general, the soils in Abakaliki had acidic horizons, but their subsurface horizons were neutral to slightly alkaline, except for the pedon AK-5, which had acidic subsoils (Table 2). In contrast, all the pedons in Bende showed acidic reaction throughout the profile. Correspondingly, the content of exchangeable bases was generally low, but the amount of exchangeable acidity was relatively high in these soils. The acidic nature of parent rocks and leaching effects under high rainfall would be responsible for the acidic reactions of the soils in the region (Eshett *et al.* 1990). The subsoil horizons of the pedons AK-1, AK-2, AK-3 and AK-4 in Abakaliki had a high content of exchangeable bases in accord with the high pH values, indicating leaching of the bases in the surface horizon and their accumulation in the subsoil. In contrast, the pedons BD-1 and BD-2 on the downslope of Bende had a relatively high content of exchangeable bases throughout the profiles regardless of their acidic reactions, while soils on the upslope (i.e. pedons BD-3 and BD-4) contained less exchangeable bases. These results implied that the rolling topography of the inland valley of Bende (see Fig. 2) accelerated the translocation of the bases down the slope and their accumulation at the valley bottom. The values of ECEC of these soils varied substantially from 0.87 to 14.64 cmol$_c$ kg^{-1}, but were generally low. Although these soils had a relatively high content of 2:1-type phyllosilicates, interlayering of hydroxyl-Al in these minerals would reduce their nutrient-holding capacity (S. Abe *et al.*, in press). The contents of organic C at the surface horizons were relatively high because of large biomass production in the humid climate, ranging from 9.3 to 19.7 g C kg^{-1} for Abakaliki and from 19.0 to 23.9 g C kg^{-1} for Bende, and decreased with soil depth. However, an abrupt increase in organic C was observed at a stratified horizon in the subsoil of the pedon AK-5, while its substantial decrease at the Bw1 horizon of the pedon BD-4 resulted from tilling effects. The distribution of total N followed a similar pattern to organic C, but its values ranged between 0.4 and 2.3 g N kg^{-1} at the surface horizon of these soils. In general, the Bray-1 P values of these soils were very low (1.0–9.0 mg P kg^{-1}) and the acidic reactions of the soils resulted in the low levels of Bray-1 P. The acidic reactions and the relatively high content of organic C and exchangeable acidity and low amount of exchangeable bases and available P are common in inland valley soils under a humid tropical climate in West Africa (Buri *et al.* 1999; Issaka *et al.* 1997).

Active Fe ratios (Fe$_o$/Fe$_d$) in the pedons at the study sites were generally low and decreased with soil depth (Fig. 3). This indicated that a higher proportion of Fe was in more crystalline forms at the lower horizons, which corroborated the presence of Fe concretions at the subsoil horizons in the Abakaliki soils and in pedon BD-1 (Table 1). In hydromorphic soils, a zone of Fe accumulation could indicate a zone of fluctuating water table (Okusami *et al.* 1987). All the soils in Abakaliki and the pedons BD-1 and BD-2 had perched water tables, whereas the pedons BD-3 and BD-4 owed their hydromorphism, in general, to high groundwater tables. In contrast, the content of exchangeable acidity and the percentage of Al saturation to ECEC may be useful indices for soil horizon development, which was sometimes obscured by subtle differences in morphological features in the tropical area (Okusami *et al.* 1987). In general, Al saturation has been found to be higher in hydromorphic soils (Ragland and Coleman 1959). A greater Al saturation at the upper horizons of the pedons AK-1 and AK-3 suggested in situ weathering of the horizons that had formed in homogenous parent materials. The pedon AK-2 showed a similar trend in Al saturation to AK-1 and AK-3 despite lithological discontinuity, while AK-5, with multi-parent materials, represented its irregular distribution pattern. The relatively high Al saturation obtained in the pedons AK-4, AK-5, BD-3 and BD-4 and at the upper horizons of AK-2 and AK-3 (Fig. 3) would support the *ferrolysis* concept of Brinkman (1970) and the hypothesis of Buol *et al.* (1980) who proposed that clay mineral lattice destruction resulted in the release of Al ions. *Ferrolysis* was also well demonstrated by the presence of hydroxyl-Al interlayered 2:1 clays in these soils (S. Abe *et al.*, in

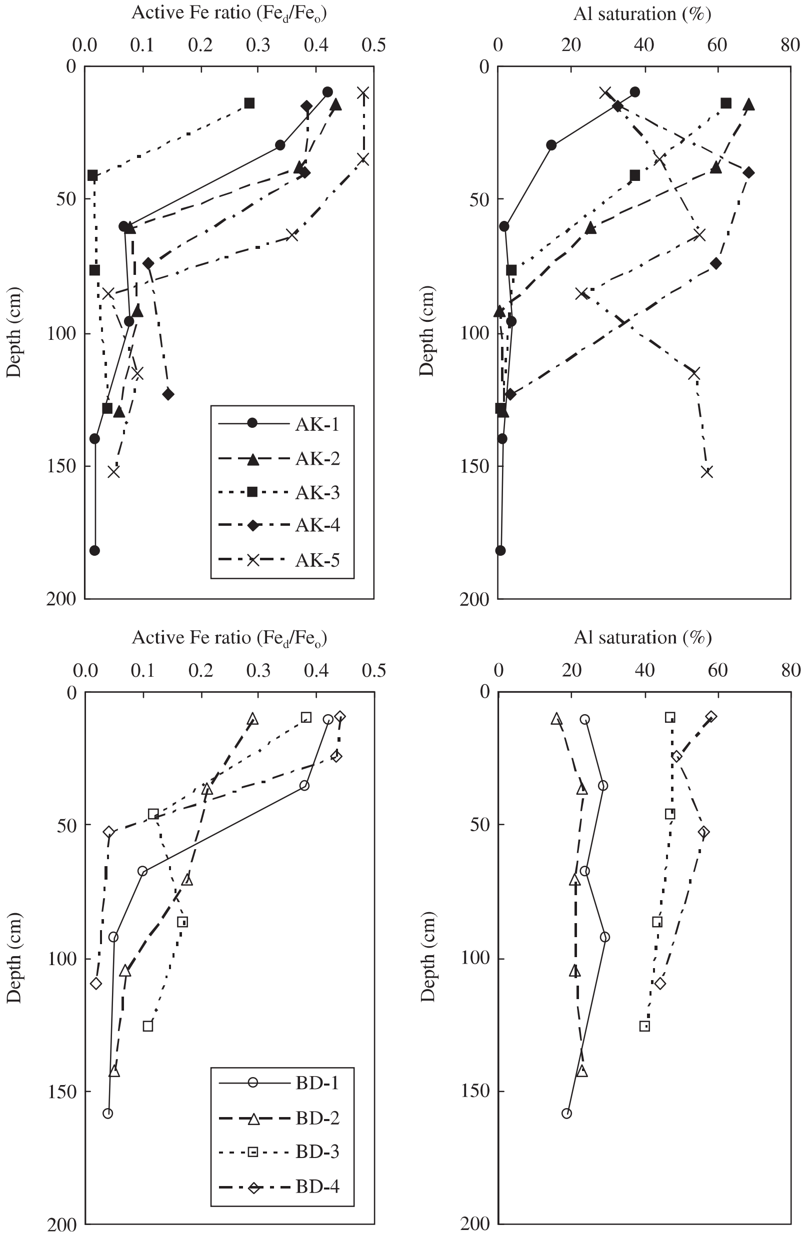

Figure 3 Distribution of the active Fe ratio (Fe_o/Fe_d) and Al saturation (%) in the soils of the inland valleys.

press). A distinct accumulation of Al, especially in hydromorphic soils with perched water table (e.g. the pedon AK-4 in Fig. 3), could indicate the actively weathering zone of the solum because exchangeable Al was not considered to be very mobile in the soil (Gotoh 1976).

Conclusions

Soils in Abakaliki and Bende had relatively high contents of clay and silt, reflecting the nature of the parent materials (i.e. shale materials) and suggested a promising water-holding capacity. In contrast, these soils generally showed poor fertility characteristics resulting from the severe weathering process and leaching effect under the influence of hydromorphic conditions and high precipitation. From the findings of the present study, it was concluded that the inland valleys at both sites would be suitable for swamp rice cultivation if an appropriate management practice (e.g. *sawah* system) was applied with substantial resource investments. Thus, the inland valleys in Abakaliki and Bende may provide an appropriate site to examine *sawah* technology.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to Dr P. Schad for guidance on soil classification. Drs T. Endo and A. Zahoor are acknowledged for their useful comments on an earlier draft of this manuscript. Our thanks are also extended to Mr Manpuku S. Tokumoto for the preparation of Fig. 1.

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