Distribution of free and total aluminium in some cocoa-growing soils of Ghana

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SUMMARY

The Western Region of Ghana is currently carrying the bulk of Ghana's cocoa, and so it is important to investigate the amounts and distribution of total and free Al oxides in some cocoa-growing soils from the region. Six soil series belonging to one major compound association of soils occurring in a toposequence, the Yakasi-Elubo/Oda Compound Association, was used. Soil profile pits of 1 m^2 and to different depths were prepared for each soil series, and soil sampled from different genetic horizons of the profiles and analysed for total and free Al oxide contents and other soil properties. The amount of total and free Al oxide in the profiles increased with depth. The mean values for total and free Al oxides for the surface soils (A-horizons) were 505.7 and 194.3 mmoles Al_2O_3/kg soil, respectively, and those for the B-horizons were 648.9 and 289.5 mmoles Al_2O_3/kg soil, respectively. The pattern of distribution of total and free Al oxides were similar and closely related to the distribution of clay. Except in the lowland soil where *p*H was higher in the A-horizon, *p*H generally decreased with depth where there was maximum accumulation of Al oxides. The upland soils contained higher amounts of Al than the lowland soils of the catena. The higher amounts of Al in the soils may limit cocoa cultivation.

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RÉSUMÉ

OFORI-FRIMPONG, K., ASAMOAH, G. K. & APPIAH, M. R.: *La distribution d'aluminium complet et libre en quelques sols de la culture de cacao du Ghana.* La région de l'ouest du Ghana soutient actuellement le gros de cacao du Ghana donc il est important que la quantité et la distribution d'oxyde d'aluminium (Al) complet et libre en quelques sols de la culture de cacao de la région soient enquêtées. Six séries de sol faisant partie d'une association d'un composé majeur des sols qui se produisent dans la toposéquence, l'Association de composé d'Oda/ de Yakasi-Elibo était employée. Les trous de profil du sol de 1m² et aux différentes profondeurs étaient creusés pour chaque série de sol et le sol échantillonné de différents horizons génétiques des profils et analysé pour le contenu d'Oxyde d'Al complet et libre ainsi que d'autres propriétés de sol. La quantité d'Oxyde d'Al complet et libre dans les profils augmentait en profondeur. Les valeurs moyennes pour les Oxydes d'Al complets et libres des sols du surface (les horizons A) étaient respectivement 505.7 et 194.3 mmôles $A1_2O_3$/kg de sol et celles des horizons B étaient respectivement 648.9 et 289.5 mmôles Al_2O_3/kg de sol. Le modèle de distribution des Oxydes d'Al complets et libres tous deux étaient semblables et étroitement liés à la distribution d'argile. A l'exception de sol de la plaine où le *p*H était plus élevé dans l'horizon A, le *p*H dans l'ensembles, décroissait en profondeur là où il y avait une accumulation maximum des Oxides d'Al. Les sols des hautes terres contenaient des quantités plus élevées d'Oxide d'Al que les sols de la plaine de la chaîne de sols. Les quantités plus élevées d'Oxide d'Al dans les sols pourraient être une limitation à la culture de cacao.

Introduction

Within the last 20 years, cocoa cultivation has been intensified in the Western Region of Ghana where virgin forest abounds. The main soil groups in the cocoa-growing areas of the region are the ochrosol-oxysol intergrades and forest oxysols (Ferralsols) which are marginally suitable and unsuitable, respectively, for cocoa cultivation (Charter, 1953). Some of the cocoa farmers who were interviewed expressed doubts about the sustainability of the soils in the region for cocoa (Arhin, 1985). Ahenkorah & Appiah (1962) identified high acidity, susceptibility to erosion, and aluminium on the exchange complex as some of the limitations to cocoa production on such soils.

The failure of agricultural crops in acid soils may probably be due to high aluminium ion concentration in the soils. Clarkson (1966, 1967) noted that a high aluminium ion concentration in the free space in the root surface may prevent the root from taking up phosphate. High aluminium ions inside the living cell may interfere with sugar phosphorylations. Abruna *et al.* (1970) and Pavan & Bingham (1982) observed in tobacco and coffee, respectively, that the primary effect of aluminium toxicity is direct injury to the root system. The translocation of calcium and phosphorus to the top of plants may also be impeded by high aluminium ions in the roots. Soils containing appreciable amounts of aluminium hydroxide give stable granules (Desphande, Greenland & Quirk, 1968; Saini, Maclean & Doyle, 1965) and also increase the apparent cation exchange capacity of the soils (Barber & Rowell, 1972).

Fertilizer trials on cocoa have shown that most cocoa-growing soils in the tropics lack nutrients, particularly phosphorus, and many reports have shown the advantages of applying P fertilizer to cocoa (Khoo, Chew & Chew, 1980; Ahenkorah *et al.*, 1981; Ojeniyi, 1981; Jadin, 1984; Morais, 1990). Although Ahenkorah (1968) and Halm & Ahenkorah (1978) identified free Fe_2O_3 as an important factor controlling the adsorption of P in some cocoa-growing soils in Ghana, Owusu-Bennoah & Acquaye (1989) found a highly significant correlation between P sorption maximum and free Al_2O_3 in some Ghanaian forest acid soils. With high acidity and aluminium in the soils which at present carry the bulk of Ghana's cocoa, the efficiency of P fertilizers on the soils, therefore, becomes a problem. Few reports are available on the amount of free aluminium oxides in soils used for cocoa cultivation in Ghana (Halm & Ahenkorah, 1978; Owusu-Bennoah & Acquaye, 1989).

This study aimed at investigating the amounts and distribution of total and free aluminium oxides, and their relationships with some soil properties in six forest profiles of the Yakasi-Elubo/Oda Compound Association.

Materials and methods

Site and soil description

The soils were taken from two farm sites of the Nyankoman Cocoa Plantation in the deciduous rainforest of Western Region belonging to one major compound association of soils occurring in a toposequence, the Yakasi-Elubo/Oda Compound Association. The Association consists mainly of the Enchi, Elubo, Yakasi, Disue, and Oda series, with minor intrusions of Sutri series occurring within the upland soils. The Enchi, Elubo, Yakasi, Disue, and Sutri series are well-drained to moderately well-drained upland soils whilst the Oda series is a poorly drained lowland soil (Asamoah, 1981). The soils are classified according to FAO/UNESCO (1978) as follows: Elubo and Yakasi series are Haplic ferrasols, Enchi series as Ferric acrisols, Disue series as Haplic acrisols, and Oda series as Dystric/Entric gleysols.

Field sampling and sample preparation

Soil profiles measuring 1 m^2 and to different depths were prepared in the farm sites. Soil samples were taken from different soil horizons and kept in polyethylene bags. The soil samples were air dried, sieved with a 2-mm sieve, bagged, and labelled.

Chemical analysis

Total aluminium. Duplicate soil samples were digested by sodium carbonate fusion and silica removed by perchloric acid dehydration. Other interfering substances, such as Ca, Mg and Mn, were removed by NH_4OH and NaOH separations (Jackson, 1958). The aluminium concentration in the digest was determined colorimetrically with aluminium reagent to develop the colour.

Free aluminium. The dithionite-citrate-bicarbonate (DCB) extraction method (Mehra & Jackson, 1960) was used. A buffer solution of sodium nitrate and sodium bicarbonate was added to duplicate soil samples and heated on a water bath at a temperature not exceeding 80 °C. Sodium dithionite powder was added to the samples with occasional stirring. Saturated KCl solution was added and the mixture centrifuged and the clear supernatant decanted. The aluminium concentration was determined colorimetrically with aluminiun reagent to develop the colour.

Other soil properties. The soils were characterized by measuring particle size distribution by the pipette method (Avery & Bascomb, 1974), *p*H (1:2.5 in H_2O), organic C by the wet digestion method of Walkley & Black (1934).

Results and discussion

Tables 1 to 6 present the amounts of total free Al oxides, organic matter, and some selected properties of the soils. The total Al oxide

TABLE 1

Analytical Data for Enchi Series

Depth (cm)	Horizon	Percentage particle size fraction Sand	Silt	Clay	pH 1:2.5	Organic matter (%)	Free Al_2O_3 mmoles kg^{-1}	Total Al_2O_3 mmoles kg^{-1}
0 - 4	A_{11}	11.54	24.22	64.24	4.0	2.34	40.7	222.2
4 - 15	A_{12}	6.30	25.04	67.86	3.5	1.42	55.5	248.2
15 - 40	B_{21}	1.00	43.61	55.39	4.9	0.27	48.2	233.3
40 - 91	B_{22}	3.26	28.89	67.85	4.5	0.32	374.1	740.7
91 - 140	B_{23}	2.30	28.01	69.69	4.5	0.67	388.9	800.0
140 - 180	B_{24}	4.21	41.79	54.00	4.6	0.28	133.3	337.0
180 - 240	C	5.96	52.79	41.32	4.5	0.09	118.5	318.5

TABLE 2

Analytical Data for Elubo Series

Depth (cm)	Horizon	Percentage particle size fraction Sand	Silt	Clay	pH 1:2.5	Organic matter (%)	Free Al_2O_3 mmoles kg^{-1}	Total Al_2O_3 mmoles kg^{-1}
0 - 5	A_{11}	14.39	44.50	43.86	4.5	1.58	388.9	803.7
5 - 12	A_{12}	12.28	35.24	52.48	4.8	0.94	400.0	825.9
12 - 49	B_{21}	14.00	27.79	57.21	4.8	0.80	370.3	740.7
49 - 78	B_{22}	13.62	25.87	60.51	4.9	0.76	570.3	1000.3
78 - 120	B_{23}	10.98	26.19	62.83	4.6	0.69	303.7	733.3
120 - 170	B_{24}	5.91	30.90	63.99	4.9	0.48	600.0	1037.0
170 - 200	B_{25}	5.91	34.55	60.09	4.8	0.37	418.5	888.9
200 - 243	C	5.20	31.00	63.80	4.0	0.16	374.0	777.8

TABLE 3

Analytical Data for Yakasi Series

Depth (cm)	Horizon	Percentage particle size fraction Sand	Silt	Clay	pH 1:2.5	Organic matter (%)	Free Al_2O_3 mmoles kg^{-1}	Total Al_2O_3 mmoles kg^{-1}
0 - 4	A_{11}	23.43	15.33	61.24	5.1	2.94	59.3	407.4
4 - 14	A_{12}	16.30	18.40	65.30	4.9	1.39	85.2	455.6
14 - 32	B_{21}	10.87	22.70	66.43	4.9	1.23	85.2	462.9
32 - 68	B_{22}	6.45	25.05	66.50	5.0	1.23	125.9	533.0
68 - 100	B_{23}	5.11	24.99	69.90	5.0	0.82	103.7	488.9

TABLE 4

Analytical Data for Disue Series

Depth (cm)	*Horizon*	*Percentage particle size fraction* Sand	Silt	Clay	*pH 1:2.5*	*Organic matter (%)*	*Free Al_2O_3 mmoles kg^{-1}*	*Total Al_2O_3 mmoles kg^{-1}*
0 - 4	A_{11}	36.39	33.85	29.56	5.8	1.92	70.4	437.0
4 - 10	A_{12}	31.20	37.56	30.99	5.2	0.85	337.0	748.1
10 - 23	A_{13}	31.95	34.19	33.26	4.7	0.47	374.1	774.1
23 - 43	B_{21}	34.93	32.09	32.98	4.9	0.32	137.0	362.9
43 - 89	B_{22}	34.51	30.67	34.82	4.9	0.23	155.6	562.9
89 - 134	B_{23}	35.94	28.97	36.29	5.0	0.27	270.4	437.0
134 - 155	B_{24}	35.87	22.39	41.74	4.9	0.20	388.9	803.7
155 - 200	B_{25}	19.00	24.35	56.65	5.7	0.19	448.1	870.3

TABLE 5

Analytical Data for Oda Series

Depth (cm)	*Horizon*	*Percentage particle size fraction* Sand	Silt	Clay	*pH 1:2.5*	*Organic matter (%)*	*Free Al_2O_3 mmoles kg^{-1}*	*Total Al_2O_3 mmoles kg^{-1}*
0 - 4	A_{11}	48.18	23.40	28.42	5.0	3.31	7.4	55.6
6 - 13	A_{12}	56.57	22.12	21.31	5.9	0.63	3.7	44.4
13 - 35	C_1	47.32	27.24	25.44	6.7	0.27	3.7	48.1
35 - 72	C_2	38.46	22.91	38.63	7.1	0.13	88.9	185.2
72 - 93	C_3	38.29	18.84	42.87	7.2	0.09	218.5	444.4
93 - 123	C_4	36.56	21.96	41.48	7.3	0.09	177.8	407.4

TABLE 6

Analytical Data for Sutri Series

Depth (cm)	*Horizon*	*Percentage particle size fraction* Sand	Silt	Clay	*pH 1:2.5*	*Organic matter (%)*	*Free Al_2O_3 mmoles kg^{-1}*	*Total Al_2O_3 mmoles kg^{-1}*
0 - 5	A_{11}	26.03	34.46	39.51	6.3	6.10	303.4	725.9
5 - 12	A_{12}	39.66	19.36	40.98	3.9	2.37	400.0	825.9
12 - 36	C_1	23.61	22.72	52.67	4.1	3.26	488.9	940.7
36 - 45	C_2	26.80	26.08	47.12	5.9	4.77	418.5	896.3

concentrations in the surface soils (A-horizon) varied from 44.4 to 825.9 mmoles Al_2O_3 kg^{-1} soil with a mean value of 505.7 mmoles Al_2O_3 kg^{-1} soil. The total Al oxide concentrations in the B-horizons also varied from 233.3 to 1037. 0 mmoles Al_2O_3 kg^{-1} soil with a mean value of 648.9 mmoles Al_2O_3 kg^{-1} soil. The C-horizons had total A1 oxide concentrations ranging from 48.1 to 940.7 mmoles Al_2O_3 kg^{-1} soil with a mean value of 502.3 mmoles Al_2O_3 kg^{-1} soil. Similarly, the ranges for the free Al oxide concentrations were 3.7 to 400, 48.2 to 600, and 3.7 to 488.9 mmoles Al_2O_3 kg^{-1} soil for the A-, B- and C-horizons, respectively. The mean values were 194.3, 289.5, and 236.1 mmoles Al_2O_3 kg^{-1} soil for the A-, B-, and C-horizons, respectively. The mean value for free Al oxide in the A-horizon was generally higher than that of 43.5 mmoles Al_2O_3 kg^{-1} soil reported previously by Ahenkorah (1968) for some 13 cocoa-growing soils from another region.

Distribution of Al in the soil profiles

The amount of total and free Al oxide generally increased from the A-horizons down the profile, reaching maximum values in the B-horizons or in C-horizons for soils without the B-horizons. Although water plays an important role in causing the downward movement of clays, oxides of iron and aluminium, and salts of various kinds in soil profiles, the mechanisms for accumulating Al in the B- or C- horizons of soils are not clear. Rowell (1988) suggested that as Fe^{3+} and Al^{3+} migrate downwards, more iron and aluminium are adsorbed until a saturation value is reached for the formation of an immobile, polymerized organo-metallic compound.

Except for the Oda series, the *p*H values of the soils were generally higher in the A-horizons and decreased with the depth of horizon in the B- or C-horizon where there was maximum accumulation of total and free Al oxides (Tables 1-6). Adams & Lund (1966) noted that since the solubility of Al is *p*H dependent, appreciable amounts of Al are generally found in soils at low *p*H values. Rhodes & Lindsay (1978) also observed an increase in total concentration of Al in soil solution at low *p*H values in some upland soils from Sierra Leone. Rowell (1988) noted that the *p*H of an acidic soil usually rises after being water logged. The high *p*H of the C-horizons of the Oda series could, therefore, be the result of the poorly drained soil.

The organic matter contents in the soil profiles decreased with depth. However, the total and free Al oxide concentrations increased with decreased amounts of organic matter (Tables 1-6). The formation of organic-Al complexes on soil surfaces and in solution reduces the amounts of the Al oxides in solution (Bloom, Mcbride & Weaver, 1979).

The amount of clay increased down the soil profile in all the soils. The total and free Al oxides increased with an increase in the clay contents (Tables 1-6). Clay minerals are aluminosilicates; therefore, an increase in clay contents could result in an increase in aluminium oxide contents. Although the pattern of distribution of total and free Al oxides in the soil profiles seemed related to the changes in soil *p*H, organic matter content, and the distribution of clay in the soil profiles, only clay and organic matter contents correlated positively and negatively with free Al oxide contents of the soils (Table 7).

Distribution of Al along the catena

Table 8 presents the average amounts of total and free Al oxides in the A- and B- or C-horizons of the six soil series. The well-drained to moderately well-drained upland soils, that is, Enchi, Elubo, Yakasi, Disue, and Sutri series had higher amounts of Al oxides in both horizons than the poorly drained lowland Oda series. The higher amounts of Al in the well-drained upland soils than in the lowland soils may be due to the effect of alternate wetting and drying processes which resulted in considerable weathering of the upland soils. The average amounts of clay in the upland and lowland soils were 53.2 and 33.03 per cent, respectively. The higher clay contents in the upland soils than in the lowland soils (Table 1) could therefore contribute to the higher amount of Al in the former than in the latter soils.

Conclusion

The Al content of the soils used extensively for

TABLE 7

Correlation Between Free Al_2O_3 and Some Soil Properties

	Simple correlation coefficients					
Properties	*Enchi series*	*Elubo series*	*Yakasi series*	*Disue series*	*Oda series*	*Sutri series*
Clay	+0.43	+0.24	+0.67	+0.60	+0.90*	+0.87
*p*H	+0.29	+0.87	-0.56	-0.32	+0.74	-0.76
Organic matter	-0.41	-0.14	-0.71	-0.36	-0.53	-0.65

* Significant at $P = 0.05$

TABLE 8

Distribution of Average Amounts of Total and Free Aluminium Oxides in A and B Horizons of Soils Along the Catena

	Soil series					
	Enchi	Elubo	Yakasi	Disue	Oda	Sutri
Total Al_2O_3 (m moles/kg)						
A - Horizon	235.5	814.8	431.5	653.1	50.0	775.9
B - Horizon	527.8	879.9	509.6	607.4	271.3*	917.5*
Free Al_2O_3 (m moles/kg)						
A - Horizon	48.1	394.5	72.3	260.5	5.6	351.7
B - Horizon	236.1	452.6	117.8	240.0	122.2*	453.7*

*C-Horizons were used since soil series do not have B-horizons.

cocoa cultivation in the Western Region of Ghana is very high. Although the tolerance level of cocoa to aluminium is unknown, the high concentration of Al in the soils may probably limit cocoa cultivation. Currently, about 30 per cent of Ghana's land under cocoa is in the Western region (CSD, 1989). There is, therefore, the need to develop appropriate technologies to make the soils more productive to cocoa. The provision of organic matter through mulching during cocoa establishment could reduce the deleterious effect of free Al ions through chelation of Al in solution. The judicious application of lime should correct any Al toxicity. If the high aluminium concentration is controlled, the soils could be more productive in cocoa production through the addition of phosphate fertilizers which are generally deficient on such soils.

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