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REVIEW
Soil Fertility Potential for Rice Production in West African Lowlands

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Abstract
In this paper, we review the soil fertility characteristics and the nature of material in the West African lowlands in comparison with paddy soils in tropical Asia to examine their potential for rice cultivation. Soil samples collected from major lowland ecosystems, i.e., inland valleys (185 locations) and flood plains (62 locations), in 13 countries (Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Niger, Nigeria, Liberia, Mali, Senegal, Sierra Leone, and Togo) generally show low values of pH, total C and N, available (Bary-2) P, exchangeable Ca and Mg, effective cation exchange capacity (ECEC), and clay content. These properties of the 87 topsoil samples selected from 247 collected samples are well associated with mineralogical composition. The clay and primary minerals predominantly consist of kaolinite and quartz, respectively, which suggests that the lowland soils in the region have low nutrient-holding capacity and a limited potential for inherent nutrient supply. In general, soil pH, available P, exchangeable bases (Ca, Mg, K, and Na), and ECEC decrease while total C, total N and exchange acidity (Al and H) increase with increasing rainfall. This tendency is mostly explained by the enhanced biomass production and soil weathering sequence governed by the climate. In terms of rice production, the lowland soils in West Africa have lower values of general fertility parameters and poorer mineralogical characteristics compared to paddy soils in tropical Asia, which includes Bangladesh, Cambodia, India, Indonesia, Malaysia, Myanmar, Philippines, Sri Lanka, and Thailand. In addition, deficit levels of S and Zn for rice production are widely observed in the lowland soils in West Africa. These findings suggest that soil fertility characteristics show substantially less potential for rice production in West Africa than in tropical Asia.

Discipline: Soils, fertilizers and plant nutrition
Additional key words: agro-ecological zones, flood plains, inland valleys, mineralogical composition, sulfur and zinc deficiency

Introduction

Rice is an important staple food in many West African countries. Rice consumption in West Africa has risen rapidly since the 1970s, as a result of a rapid increase in per capita consumption and population growth[24,54]. The gap between the ever-increasing demand and the shortage of domestic supply was met by a steady increase of imports that eventually led to a record-breaking 3.4 million tons (milled basis) in 1998 at a cost of nearly US$1 billion at the time[24].

One of the major reasons hampering self-sufficiency is the low rice yield in the region. Over the past four decades (1960–2000), rice yield in West Africa has recorded only a slight increase from 1.0–1.2 to 1.5–1.7 tons of milled rice ha^{-1} [24]. In the last two decades (1980–2000), rice yield has appeared to remain practically unchanged[54].

The present paper is a joint contribution from the projects 'Development of Sustainable Rice Farming Systems in Low Activity Clay Soils in West African Lowlands' and 'West African Rice Green Revolution by Sawah Ecotechnology and the Creation of African Satoyama Systems (JSPS Grant-in-Aid No. 19002001)'. These projects are financially supported by the Ministry of Foreign Affairs and the Ministry of Education, Culture, Sports, Science and Technology, The Government of Japan, respectively.
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The stagnant rice yield at the low level can be mostly attributed to the farming system preference. Upland rice farming is very common under traditional shifting cultivation in West Africa, despite its lower yield and higher susceptibility to land degradation than lowland rice farming[16]. This situation indicates a sharp contrast to rice cultivation in monsoon Asia, where lowland rice farming is predominant and grain yield is usually higher than 3.0 t ha^{-1} [16,24].

It is interesting to mention here that the rice production system in West Africa has been shifting from the uplands to the lowlands since the 1980s[24,54]. Moreover, a major increase in rice production in West Africa originated in the last 20 years from the rainfed lowland rice ecology, especially the inland valley bottoms[24,54]. In the early 1980s, the wetlands, i.e., the rainfed or irrigated lowlands, produced approximately 40% of total rice production while they occupied 30% of the rice cultivation area[51], whereas the wetlands currently produce nearly 70% of total rice production in the region, while they occupy about 50% of rice cultivation area[24,54]. These macro data of rice production trends validate that rice production development in the region should focus on the lowlands rather than the uplands to catch up with ever-increasing needs for rice[16]. In West Africa, inland valleys and flood plains are considered to be suitable ecological environments for the development of a sustainable rice-based production system[11,16,55]. By reclaiming an estimated 2 million hectares (in minimum) of wetlands that have potential for rice cultivation[16], the West Africa sub-region can produce more than 5 million tons of rice grains and can fill the present gap between the demand and self-supply (equivalent to imports: nearly 5 million tons).

In spite of the importance of lowland ecosystems in agricultural development, much less information is available on them than on the upland ecosystems, which is a considerable impediment for their utilization and intensification on a sustainable basis. Adams (1993) described multiple roles of wetlands, with a focus on flood plains in dry areas, which sustain populations of human beings and wild species[5]. Carsky (1992) reviewed agronomic constraints in inland valleys and regarded water control and soil fertility as important impediments[11]. The rice production potential of inland valley ecosystems was also agro-ecologically characterized by Andriesse & Fresco (1991) and Windmeijer & Andriesse (1993)[6,55]. A detailed soil survey was conducted in some parts of lowland areas, predominantly in Nigeria[2–4,14,17,31–33]. In addition, Kyuma et al. (1986) evaluated the adaptability of the Fertility Capability Classification (FCC) system to lowland soils in West Africa[26]. However, there has been little effort to evaluate soil characteristics on a regional scale, based on quantitative indicators of soil fertility.

In the present paper we present an overview of soil fertility characteristics of the West African lowlands with a focus on inland valleys and flood plains, because soil problems are important constraints to agricultural production in Sub-Saharan Africa[40,41]. Our primary aim in this paper is to discuss the potential of these two lowland ecosystems for rice production. It is reasonable to compare soil properties between lowland soils in West Africa and paddy soils in tropical Asia, which is a major producer of rice and feeds billions of people. This attempt will allow us to identify soil constraints for lowland rice production in West Africa. As used herein, the term "tropical Asia" refers to 9 countries in South and Southeast Asia, including Bangladesh, Cambodia, India, Indonesia, Malaysia, Myanmar, Philippines, Sri Lanka, and Thailand[25].

Study area and soil samples

The West Africa sub-region is sandwiched between the Sahara Desert and the Gulf of Guinea. Except for the coastal savanna area, also called the Dahomey Gap, which extends from southern Ghana to Benin, rainfall and the vegetation growth period decrease as one moves northward. The sub-region is often divided into four agro-ecological zones, the equatorial forest (EF), Guinea savanna (GS), Sudan savanna (SuS), and Sahel savanna (SaS), according to precipitation and vegetation growth period. Inland valleys are defined as the upper reaches of river systems and are widespread in the sub-region[55]. Inland valleys have limited or imminent processes of alluvial sedimentation and thus do not have any distinct flood plain or levee system with respect to the main rivers and tributaries[55]. Since they are located at upper basins, inland valleys are topographically the lower parts of the watershed, and their bottoms are generally flat or very flat (less than a few percent in slope gradient) and are often suitable for wet rice culturing[16,24]. To date, less than 20% of the total area of valley bottoms is under cultivation[52,53]. Inland valleys and flood plains have 22 to 52 and 12 to 25 million hectares, and occupy approximately 50% to 60% and 20% to 30% of total lowland area in the region, respectively[55]. They constitute a potential 18 million ha for lowland rice production[16]. Inland valleys exist mainly in the GS and EF zones, while flood plains under rice cultivation are distributed predominantly in the SuS and SaS zones. Other lowland ecosystems are coastal swamps/deltas and inland basins, which are not addressed in this paper because they have only a limited importance in West Africa[16,24].

From a geological point of view, the West Africa sub-region can be divided into a southern area where the rocks of the Basement Complex, which comprises the African continental shield that originally formed as a part of Gondwanaland predominate and a northern part where marine and terrestrial sediments and rocks occur, formed in huge tectonic basins[48,55]. The Basement Complex comprises granites and associated metamorphic rocks of the Precambrian age and underlies the whole inventory area. It occurs in most of Guinea, Sierra Leone, Liberia, Côte d'Ivoire, Togo, Benin, Nigeria, Burkina Faso, and Cameroon, as well as in parts of Guinea Bissau, Mali, Niger, and Ghana. The Pre-Cambrian Basement Complex rocks consist of igneous rocks such as granite and basalt as well as metamorphic rocks such as quartzite, schist and slates. Major soils in West Africa are thus at advanced weathering stages and generally show very poor fertility characteristics[29,48,55].

Soil fertility data examined in this paper were obtained from 185 inland valley locations and 62 flood plain locations in 13 countries in West Africa: Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Niger, Nigeria, Liberia, Mali, Senegal, Sierra Leone, and Togo (Fig. 1). The locations are spread over the given four agro-ecological zones, whereas data on the SuS and SaS zones are combined, because the number of samples collected in these two zones are limited and their data sets generally show similar mean values [see Issaka et al. (1997) and Buri et al. (1999; 2000)][9,10,22]. These sampling sites include both potentially reclaimable and actually cultivated soils for rice and other crops [see Issaka (1997) and Buri (1999) for further information][8,20].

General fertility characteristics and soil classification

1. Topsoil fertility status

Table 1 shows means of selected soil fertility parameters of lowland topsoils (0–15 cm) in West Africa according to topography and major agro-ecological zones in comparison with those of lowland rice fields in tropical

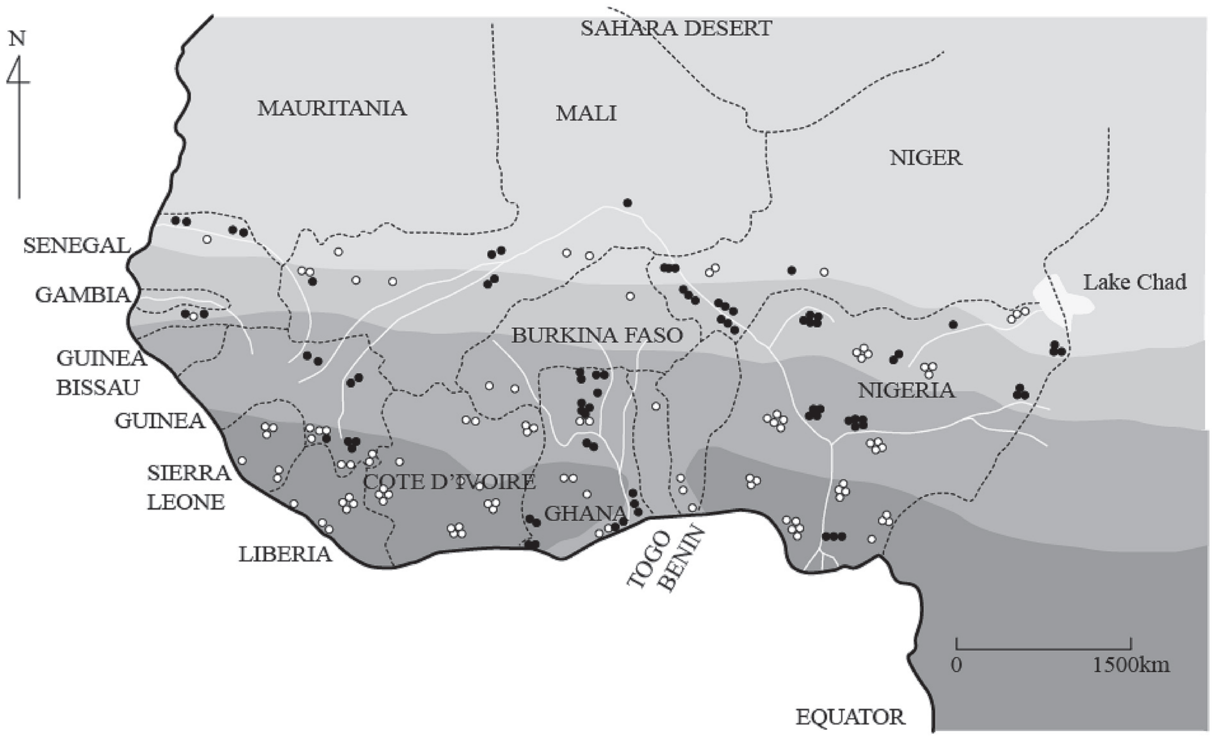

Fig. 1. Main sampling sites of inland valleys and flood plains on an agro-ecological map of West Africa (Abe et al. 2006)

: Sahel savanna zone (Rainfall < 500mm, Growth Period < 90days)
: Sudan savanna zone (Rainfall 500-1000mm, Growth Period 90-165days)
: Guinea savanna zone (Rainfall 1000-2000mm, Growth Period 165-270days)
: Equatorial forest zone (Rainfall > 2000mm, Growth Period > 270days)
● : Sampling sites in flood plains
○ : Sampling sites in inland valleys
: International boundary

Asia. In general, the former have considerably lower available P (Bray-2 P), exchangeable Ca, Mg and Na, effective cation exchange capacity (ECEC: sum of exchangeable bases and exchange acidity), clay content, and clay activity (ECEC value divided by clay content, i.e., ECEC/clay) than the latter. Soil pH and total C and N contents are also somewhat lower in the former than in the latter. The fertility parameters also show that the soils in the West African lowlands are much less fertile than those of Amazon River systems[46]. These results indicate that soil fertility of the West African lowlands is the lowest among the three major tropical regions in the world[9,22,49]. The principal reason for the poor soil characteristics in West Africa is that the major soils in that area are derived from coarse-textured and acidic parent rocks (mainly granite) and have weathered under a tropical climate over millions of years[29,48,55]. In addition, anthropogenic disturbances such as hastened deforestation and subsequent exploitive farming practices have been critically affecting soil fertility[40,41]. For example, low-input subsistence agriculture inevitably causes soil degradation and nutrient exploitation, which are major concerns of environmental deterioration in Sub-Saharan Africa[40,43].

The inland valley soils in the EF zone are characterized by acidic reactions, coarse texture (low clay content) and low content of available P and exchange bases but high amounts of total C, total N and exchange acidity. A relatively high total C content in these soils suggests that the decomposition of organic matter is hindered due to prolonged submergence[36]. This could also explain the relatively high content of total C in the flood plain soils in the EF and GS zones. The inland valley soils in the GS zone show similar soil characteristics to those in the EF zone, except that the GS zone shows very low total C and total N, and exchangeable Ca and Mg as well as clay content are considerably lower in the GS zone than the EF zone.

The inland valley soils in the SuS/SaS zone are slightly acidic and have a relatively higher content of exchangeable bases and clay than those in the EF and GuS zones, whereas their total C, total N and available P are as low as those in the GS zone. On the other hand, the flood plain soils exhibit relatively better soil fertility than do the inland valley soils. It is interesting that the clay content of the flood plain soils is comparable to those of paddy soils in tropical Asia, which shows a clear contrast to those in the inland valley soils. In addition, the flood plain soils have higher values of exchangeable bases and

Table 1. Average general fertility characteristics of topsoils (0–15 cm) of inland valleys and flood plains in West Africa in comparison with those of paddy soils in tropical Asia (Kawaguchi & Kyuma 1977; Issaka et al. 1997; Buri et al. 1999; 2000)

Geographical region /agro–ecological zones	No. samples	pH (H_2O)	Total C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Available P ($mg\ Kg^{-1}$)	Exch. bases ($cmol_c\ kg^{-1}$) Ca	Mg	K	Na	Exch. Acidity ($cmol_c\ kg^{-1}$)	ECEC ($cmol_c\ kg^{-1}$)	Clay (%)	Clay activity ($cmol_c\ kg^{-1}$)
Inland valleys	**185**	**5.3**	**12.8**	**1.11**	**8.7**	**1.9**	**0.9**	**0.3**	**0.2**	**1.0**	**4.2**	**16**	**26**
Equatorial forest	79	5.3	20.4	1.66	11.8	2.3	1.2	0.3	0.3	1.7	5.7	20	29
Guinea savanna	98	5.3	7.3	0.70	6.5	1.3	0.5	0.2	0.1	0.5	2.7	13	21
Sudan/Sahel savanna	8	6.0	5.9	0.67	6.0	4.8	1.9	0.6	0.5	0.3	8.0	20	40
Flood plains	**62**	**5.4**	**11.0**	**0.98**	**7.7**	**5.6**	**2.7**	**0.5**	**0.8**	**0.8**	**10.3**	**43**	**24**
Equatorial forest	7	5.7	14.1	0.86	9.8	4.1	1.5	0.2	0.4	1.5	7.0	39	18
Guinea savanna	19	5.5	16.3	1.33	8.0	3.9	1.9	0.5	0.8	0.7	7.8	35	23
Sudan/Sahel savanna	36	5.5	7.6	0.77	7.3	6.8	3.3	0.6	0.9	0.7	12.3	48	27
Lowland soils in West Africa	**247**	**5.3**	**12.3**	**1.08**	**8.4**	**2.8**	**1.3**	**0.3**	**0.3**	**0.9**	**5.8**	**23**	**25**
Paddy fields in tropical Asia	**410**	**6.0**	**14.1**	**1.30**	**17.6**	**10.4**	**5.5**	**0.4**	**1.5**	**ND**	**17.8**	**38**	**47**

Analytical procedures (IITA, 1979): pH, grass electrode method with 1:1 soil:water extraction; total C and N, dry combustion method; available P, Bray-2 method; exchangeable bases, neutral ammonium acetate extraction method; exchange acidity, titration method with 1 M KCl extraction; ECEC, summation of exchangeable bases and exchange acidity; clay content, pipette method; clay activity, division of ECEC by the clay content.
See Kawaguchi & Kyuma (1977) Issaka et al. (1997) and Buri et al. (1999; 2000) for the value range, standard deviation and/or coefficient of variance.

ECEC than those of the inland valley soils. The similar clay activity index values between the flood plain and inland valley soils would indicate that better soil fertility characteristics in the former than the latter can be largely attributed to the quantity but not the quality of clay minerals. Moreover, the soils in the EF and GS zones have a considerably lower index of clay activity than those of the SuS/SaS zones. This suggests a soil weathering sequence largely governed by rainfall. These mineralogical subjects will be further examined in the following section of this paper.

Soil fertility assessment revealed widespread deficiency of N and P in the West African lowlands, and the sustainable replenishment of N and P is the most challenging issue to improving soil fertility. Effective application of N and P fertilizers is very important in soil fertility management. In addition, the low base contents and harmful acidity would present problems in the soils in the EF. Low base contents are also found in the soils in the GS zone, which has the poorest soil fertility characteristics among the major agro-ecological zones. In fact, many inland valley soils in the EF and GS zones contain very low levels of available K. However, crop responses to K fertilization are rare in Sub-Saharan Africa, except in sandy savanna soils[45], even though exploitation of K by crop harvest is relatively high[43]. This indicates that crop demands for K are still low due to the actual low crop yield levels[40]. In the SuS/SaS zone, soil acidity and base contents are out of constraint but N and P availability becomes worse than the humid zones because of low organic matter content and neutral soil reaction. In addition, a salinity problem appears in some dry areas.

2. Soil profile characteristics

Inland valley soils in the EF zone are low in soil pH, which substantially increases with soil depth, and there is

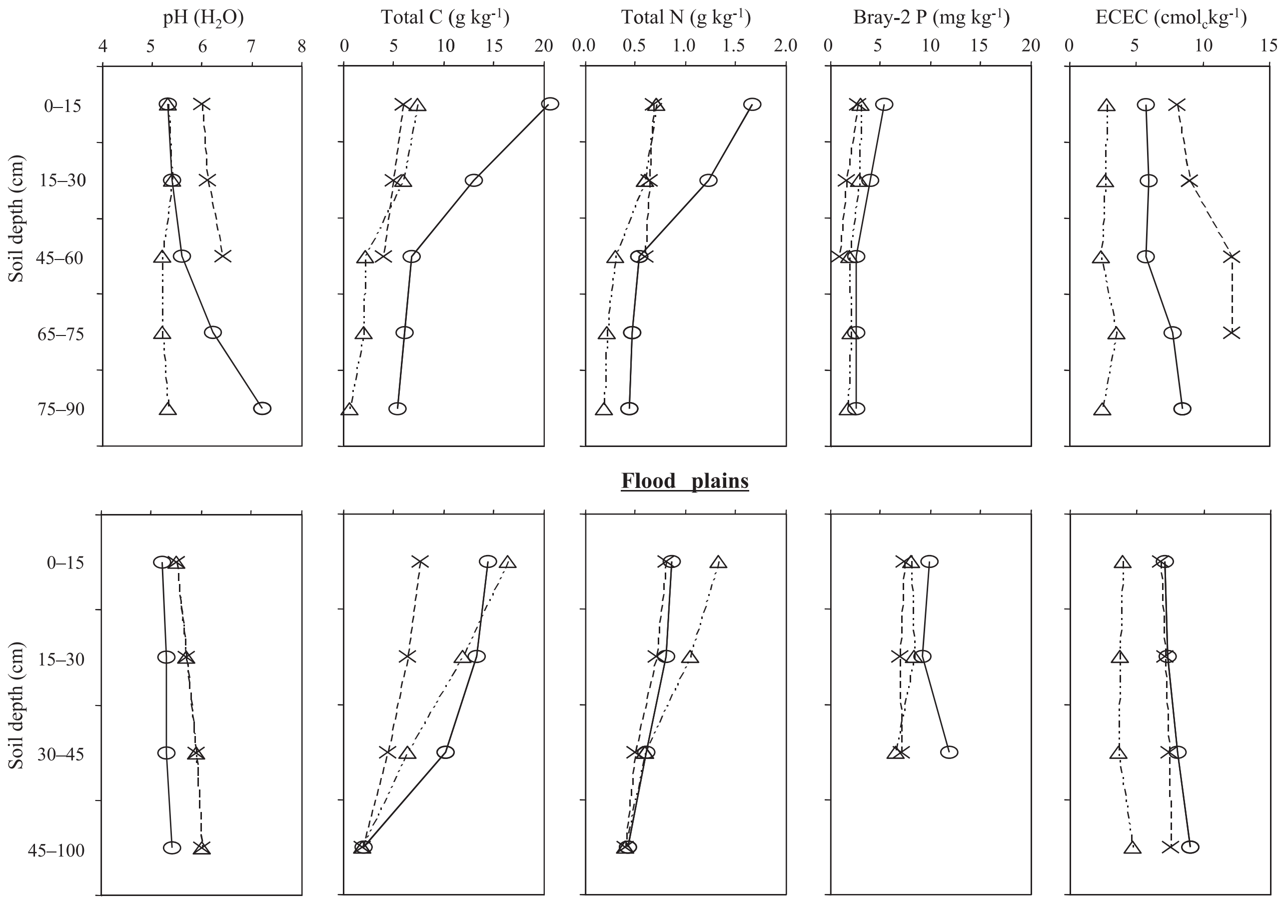

Fig. 2. Profile characteristics for selected fertility parameters in inland valleys and flood plains in West Africa (Issaka et al. 1997; Buri et al. 1999)

See Issaka et al. (1997) and Buri et al. (1999) for the value range, standard deviation and/or coefficient of variance. Plotted values show means of the sample groups according to the topography (inland valleys or flood plains) and agro-ecological zones (EF, equatorial forest; GS, Guinea savanna; SuS/SaS, Sudan and Sahel savanna).

: EF, : GS, : SuS/SaS.

a high level of exchange acidity up to 60 cm deep in soil (data not shown here; see Issaka et al. 1996; 1997)[21,22], reflecting substantial leaching in the humid climate (Fig. 2). The inland valley soils in the GS zone show acidic reactions throughout the profile, but exchange acidity is found at a moderate level. In contrast, slightly acidic reactions and moderate to low values of exchange acidity were found throughout the soil profile in the inland valleys of the SuS/SaS zone. The flood plain soils generally have acidic reactions and a low to moderate level of exchange acidity at all soil depths in all the agro-ecological zones, but the soils in the EF zone show slightly lower pH values and higher levels of exchange acidity than those in the GS and SuS/SaS zones. The inland valley soils in the EF zone have a very high total C content that decreases drastically with soil depth, while those in the GS and SuS/SaS zones have low total C content; in particular, subsoils in the GS zone have very low total C content. The flood plain soils have relatively high total C content, which decreases with soil depth, except for the soils in the SuS/SaS zone. These results suggest vigorous biomass production under humid climate conditions and substantially less biomass production under limited rainfall conditions.

The trend of profile distribution of total N is highly correlated with that of total C (inland valleys: $r = 0.79$; $P < 0.001$, flood plains: $r = 0.83$; $P < 0.001$), except that the flood plain soils in the EF zone show less total N content in relation to that of total C in the upper layers (up to 45 cm in soil depth). The available (Bray-2) P content of inland valley soils is generally very low in all agro-ecological zones. In particular, the drier zones have less available P. The flood plain soils contain a higher amount of available P than do soils in the inland valleys throughout the profile. The ECEC value in the inland valley soils occurs in the following decreasing order: the SuS/SaS > EF > GS zone. In the flood plains, the soils in the GS zone also show lower ECEC values than those in the EF and SuS/SaS zones. This low ECEC value in the soils in the GS zone can be attributed to the sandy texture with low clay content, which originates primarily from coarse-grained granitic rocks. These findings suggest that soil profile characteristics are predominantly affected by the parent material and weathering intensity governed by rainfall in the West African lowlands. In terms of general soil characteristics, the topsoil and subsoil of the flood plains are more fertile than those of the inland valleys.

3. Soil classification

The soils of the inland valleys and flood plains in West Africa are generally classified into three major soil orders, i.e., Entisols, Inceptisols and Vertisols with minor distributions of Histosols, Alfisols and Ultisols in the US Soil Taxonomy[44]. Major great groups are Sulf-, Hydr-, Psamm-, Fluv-, Epi- and Endo-aquents, Udifluvents, Sulf-, Hala-, Epi- and Endo-aquepts, Dystr-, Epi- and Endo-Aquerts, Aqualfs, and Aquults. These are also classified as Fluvisols, Gleysols, Cambisols, Arenosols, Regosols, Loptosls, Vertisols, and Histosols in the World Reference Base for Soil Resources[23]. On the other hand, the Soil Fertility Capability Classification (FCC) system has been developed to interpret soil taxonomy and additional soil attributes in a way that is directly relevant to plant growth[39,42]. In general, inland valley soils have FCC units of L or S (loamy or sandy topsoil), g (water logging), e (high leaching potential), k (low nutrient capital reserves), m (low organic C saturation), i^+ (high P fixation), and a^- (Al toxicity), while flood plain soils have FCC units of L or C (loamy or clayey topsoil), g, k, m, and d. These FCC units are largely affected by the climatic conditions[26]: inland valleys predominate in the humid to sub-humid areas, while flood plains prevail in the semi-arid regions.

Sulfur and micro-nutrient status

Table 2 shows average contents of available S [sulfate–S extracted with $Ca(H_2PO_4)_2$] and micro-nutrients (DTPA-soluble Zn, Fe, Mn, Cu, and Ni) of lowland topsoils (0–15 cm) in West Africa according to topography and agro-ecological zones. The available S and Zn are very low in both inland valleys (4.9 and 1.6 mg kg^{-1}, respectively) and flood plains (3.4 and 1.2 mg kg^{-1}, respectively) in West Africa. Almost all soils of inland valleys and flood plains contain available S content below the critical level required for rice growth (5–20 mg S kg^{-1}) (Fig. 3). Also, 66% of the given soils have available Zn levels below the critical level necessary for rice farming (0.83 mg Zn kg^{-1}). These results suggest that low levels of S and Zn in the soils are major constraints for rice production in the West African lowlands[10], and S deficiency in rice plants is often combined with Zn deficiency[30]. Total C content is correlated significantly with both available S (inland valleys, $r = 0.87$; $P < 0.001$; flood plains, $r = 0.69$; $P < 0.001$) and Zn (inland valleys, $r = 0.87$; $P < 0.001$; flood plains, $r = 0.80$; $P < 0.001$)[10]. This suggests that organic matter is the main source of both S and Zn. As stated above, total C content of the West African lowlands is generally very low and decreases with rainfall. The content of S and Zn was lower in the SuS/SaS zone than in the EF and GS zones, and this trend is rather more distinct in inland valley soils than in flood plain soils. These findings suggest that deficiency problems of S and Zn in rice plants are more prominent in inland valleys of the drier areas with less precipitation and lower soil C content[9]. Soil S availability is often affected by the distance from the seacoast and proximity to industrial activities[30], while Zn availability largely relies on crop residue recycling[35]. Organic matter input and crop residue management are keys to replenishing S and Zn in the soil.

Other available micronutrients are often observed at

Table 2. Average contents of sulfate-S and available micronutrients of topsoils (0-15 cm) of inland valleys and flood plains in West Africa (Buri et al. 2000)

Geographical region /agro-ecological zones	Sulfate-S ($mg\ kg^{-1}$)	Avail. Zn ($mg\ kg^{-1}$)	Avail. Fe ($mg\ kg^{-1}$)	Avail. Mn ($mg\ kg^{-1}$)	Avail. Cu ($mg\ kg^{-1}$)	Avail. Ni ($mg\ kg^{-1}$)
Inland valleys	**4.9**	**1.6**	**220**	**58**	**2.5**	**1.4**
Equatorial forest	6.3	1.6	238	73	2.7	2.1
Guinea savanna	4.1	1.9	203	45	1.6	0.7
Sudan/Sahel savanna	1.4	0.6	128	28	3.9	0.5
Flood plains	**3.4**	**1.2**	**163**	**67**	**3.4**	**1.7**
Equatorial forest	3.1	1.0	121	100	3.3	1.7
Guinea savanna	3.2	1.6	185	82	3.2	2.0
Sudan/Sahel savanna	3.7	0.9	160	34	3.6	1.3

Analytical procedures: Sulfate-S, turbidimetrical determination with $Ca(H_2PO_4)_2$ extraction (IITA 1979); available Cu, Zn, Fe, Mn, and Ni, ICP-AES measurement with DTPA extraction (Dale & Michael 1982).
See Buri et al. (2000) for the value range, standard deviation and/or coefficient of variance.

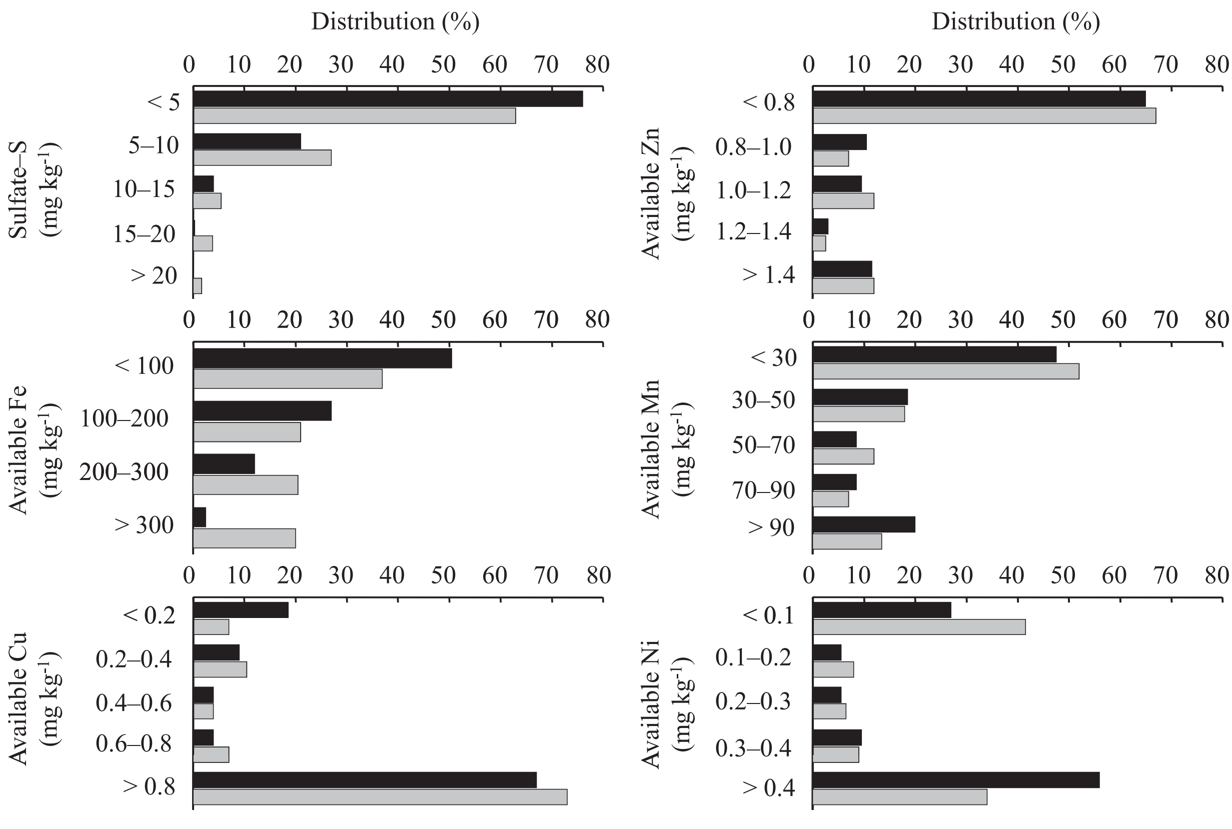

Fig. 3. Frequency distribution of Sulfate–S and available micronutrients (Za, Fe, Mn, Cu, and Ni) in topsoils (0–15 cm) of inland valleys and flood plains in West Africa (Buri et al. 2000)
: Flood plains, : Inland valleys.

moderate levels in the West African lowlands: Fe, 219.8 and 163.1 mg kg^{-1}; Mn, 57.6 and 66.6 mg kg^{-1}; Cu, 2.5 and 3.4 mg kg^{-1}; Ni, 1.4 and 1.7 mg kg^{-1} on average in inland valleys and flood plains, respectively (Table 2). In general, except for available Cu, micronutrient availability shows a decreasing trend towards the dry zones. This can be attributed to the lower organic matter content and higher soil pH in the drier zone[10]. As the micronutrient availability is greatly affected by soil pH, it is very important to correct soil pH to within an appropriate range (5.5–6.5). Although the current availability of Fe, Mn, Cu, and Ni is sufficient to sustain rice farming, further exploitation of nutrients via increasing the removal of rice grains and increasing demand for dry crops after rice cultivation in some areas may cause deficiency problems of these micronutrients in the future. Long-term crop experimentation and concomitant monitoring of micronutrient availability are necessary at benchmark sites in major agro-ecological zones.

On the other hand, the Fe concentration in soil solutions often reaches levels that are toxic to rice plants in many inland valleys[53]. Iron toxicity symptoms in rice plants have been widely documented in the West African lowlands[7,53]. Sulfur and Zn deficiencies in rice as well as limited availability of P, K, Ca, and Mg in soils may stimulate symptoms of iron toxicity[37,38,57,58]. Iron toxicity can be alleviated by the application of potassium sulfate, the introduction of tolerant genotypes, the adoption of a ridge culture, and the improvement of soil drainage[7,56,58].

Mineralogical composition

Semi-quantitative assessment of clay (< 2 μm) mineral composition was performed by X-ray diffraction analysis to plot the percentage of 7, 10 and 14 Å minerals of 87 selected topsoil samples from the West African lowlands on a triangular classification system for clay mineral composition (Fig. 4)[25,28]. The 7, 10 and 14 Å minerals are roughly regarded as kaolinite, micas and smectite and/or vermiculite, respectively. Kaolinite is a non-ex-

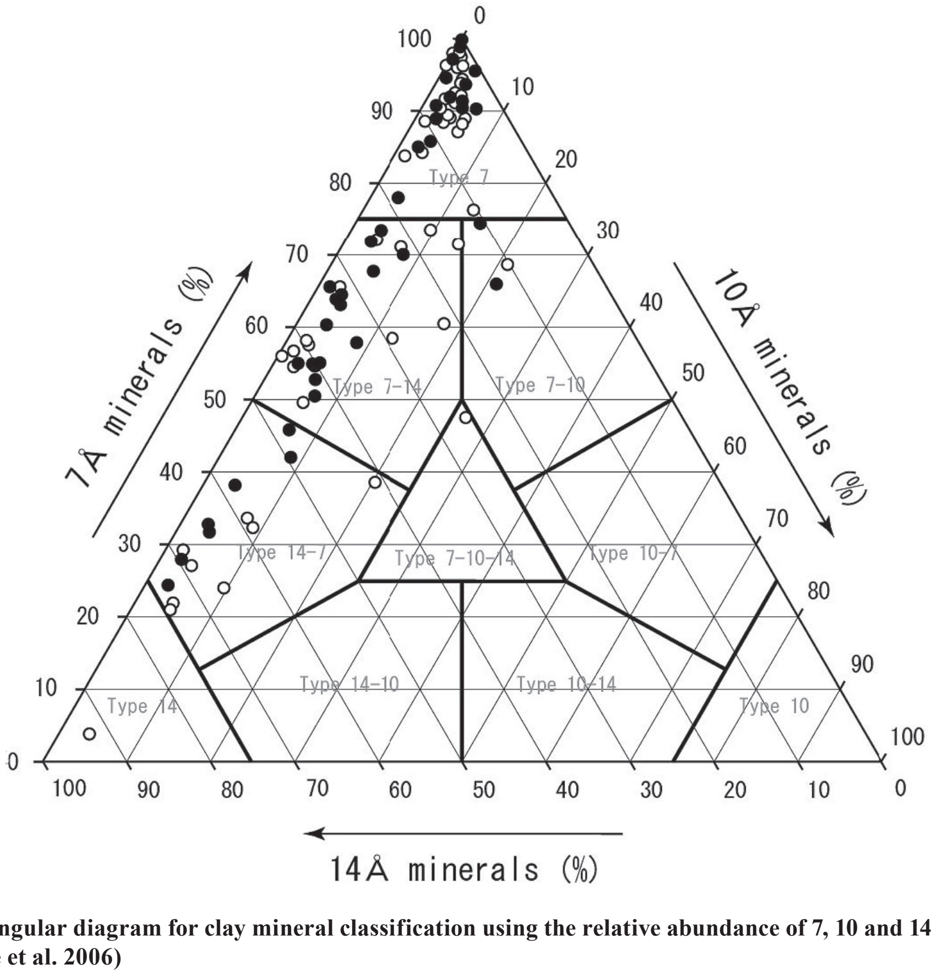

Fig. 4. Triangular diagram for clay mineral classification using the relative abundance of 7, 10 and 14 Å minerals (Abe et al. 2006)
○ : Inland valley, ● : Flood plain.

pandable 1:1 type phyllosilicate mineral having a pH-dependable charge and low CEC. Micaceous clays, with non-expandable 2:1 type phyllosilicate minerals, have a low CEC value but can become a potential K supplier in soils. Both smectite and vermiculite have 2:1 layer structure of phyllosilicate minerals. Smectite is an expandable mineral with a relatively high CEC value. Vermiculite is often found in Vertisols or vertic soils, but their distribution is limited in West Africa[13]. Compared to paddy soils in tropical Asia, lowland soils in West Africa have more 7 Å minerals but less 10 and 14 Å minerals (Table 3). The percentage of distribution of soil clay-mineral types (Table 4) shows that Types 7 and 7–14 are predominant and the percentages of these two soil types accounts for 77%

Table 3. Mean abundance of 7, 10 and 14 Å minerals of topsoils (0-15 cm) of inland valleys and flood plains in West Africa in comparison with that of paddy fields in tropical Asia (Kawaguchi & Kyuma 1977; Abe et al. 2006)

Geographical regions	No.	7-Å minerals (%)		10-Å minerals (%)		14-Å minerals (%)	
/agro-ecological zones	Samples	Mean	S.D.	Mean	S.D.	Mean	S.D.
Inland valleys	**47**	**68.2**	**25.8**	**5.6**	**6.0**	**26.2**	**24.8**
Equatorial forest	26	69.6	24.5	3.9	4.5	26.6	22.6
Guinea savanna	13	69.3	25.3	8.5	7.6	22.2	24.3
Sudan/Sahel savanna	8	62.2	32.9	6.4	5.9	31.5	33.8
Flood plains	**40**	**68.5**	**21.6**	**4.5**	**3.8**	**27.0**	**21.2**
Equatorial forest	5	68.9	20.1	5.0	0.9	26.1	19.3
Guinea savanna	9	86.4	9.8	6.5	6.8	7.1	4.0
Sudan/Sahel savanna	26	62.2	21.9	3.8	2.5	34.0	21.1
Lowland soils in West Africa	**87**	**68.4**	**23.8**	**5.1**	**5.1**	**26.6**	**23.1**
Paddy fields in tropical Asia	**410**	**46.4**	**23.3**	**13.9**	**14.4**	**39.7**	**23.8**

S.D. = standard deviation.

Table 4. Percentage distribution of soil clay mineral types in inland valleys and flood plains of West Africa in comparison with that of paddy fields in tropical Asia (Kawaguchi & Kyuma 1977; Abe et al. 2006)

Geographical regions	Clay mineral types (%)									
/agro-ecological zones	7	7–14	14–7	7–10	7–10–14	14	10	10–7	10–14	14–10
Inland valleys	**46.8**	**29.8**	**17.0**	**2.1**	**2.1**	**2.1**	**0.0**	**0.0**	**0.0**	**0.0**
Equatorial forest	50.0	30.8	19.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Guinea savanna	38.5	46.2	0.0	0.0	7.7	7.7	0.0	0.0	0.0	0.0
Sudan/Sahel savanna	50.0	0.0	37.5	12.5	0.0	0.0	0.0	0.0	0.0	0.0
Flood plains	**37.5**	**40.0**	**17.5**	**5.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Equatorial forest	40.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Guinea savanna	77.8	0.0	0.0	22.2	0.0	0.0	0.0	0.0	0.0	0.0
Sudan/Sahel savanna	23.1	50.0	26.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lowland soils in West Africa	**42.5**	**34.5**	**17.2**	**3.4**	**1.1**	**1.1**	**0.0**	**0.0**	**0.0**	**0.0**
Paddy fields in tropical Asia	**14.8**	**22.0**	**22.9**	**9.1**	**10.9**	**10.5**	**0.0**	**2.8**	**0.8**	**5.2**

See Fig. 3 for the classification of clay mineral types.

of the West African lowland soils. In contrast, paddy soils in tropical Asia have only 36.8% of Types 7 and 7–14, which is about half of that of the West African lowlands. This implies that most soils in the West African lowlands are at a more advanced stage of weathering and consequently have a smaller nutrient-holding capacity than do the paddy soils in tropical Asia. This is well associated with low values of ECEC and clay activity index. There is not much difference in clay mineral composition between inland valleys and flood plains. This suggests that better nutrient-holding capacity as suggested by clay activity is mainly attributed to higher content of clay in the flood plains than in the inland valleys.

The fine-sand fraction (20–212 µm) of the soils used for determining the clay mineral composition as described above has been examined by the combination of X-ray diffraction analysis and petrographic investigation to assess the soils' primary mineral characteristics[2]. The primary minerals of the lowland soils in West Africa predominantly consist of quartz, which is often accompanied by a small quantity of feldspars. The soils contain only very small quantities of weatherable minerals (mostly less than 10% by weight). As noted above, igneous and metamorphic rocks comprising the Basement Complex rocks are acidic in nature (having low base composition) and have been weathering since the Precambrian era[48,55]. Prolonged and intensive weathering followed by leaching and erosion causes a massive destruction of weatherable minerals and leaves persistent relicts behind in lowland soils of West Africa[2,29]. This suggests that the inherent nutrient-supplying potential is substantially limited in these soils. The mineralogical characteristics are well associated with total elemental composition (Table 5). The contents of total phosphorus and bases of lowland soils in West Africa are considerably lower than those of paddy soils in tropical Asia[22]. These findings of mineralogical characteristics confirm that major lowland soils in West Africa are at advanced weathering stages and exhibit very poor fertility characteristics.

Geographical distribution of soil characteristics

Although climatic conditions have a strong influence on soil characteristics, parent materials still have important effects on the base status and clay mineralogical characteristics in soils, resulting in non-zonal spotty distribution of some unique soils. For example, some soils in the Ibo and Yoruba areas in southeastern Nigeria formed on base-rich parent materials and derived from shale or other sedimentary rocks have a substantially high content of P, bases and clay, despite the fact that these soils are located in the EF zone[3,4]. The spotty occurrence of such specific soils is considered to be the effect of basic or neutral parent material that has penetrated into acid basement rocks. The geological distribution of soil clay mineral types (Fig. 5) supports the influence of parent

Table 5. Average elemental oxides composition of topsoils (0-15 cm) of inland valleys and flood plains in West Africa in comparison with that of paddy fields in tropical Asia (Kawaguchi & Kyuma 1977; Issaka et al. 1997; Buri et al. 2000)

Geographical region	Elemental oxides composition (%)								
/agro-ecological zones	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	P_2O_5	MnO_2	Na_2O
Inland valleys	**78.4**	**4.3**	**14.4**	**0.40**	**0.43**	**0.93**	**0.08**	**0.06**	**0.19**
Equatorial forest	78.7	4.3	14.3	0.36	0.38	0.94	0.19	0.06	0.19
Guinea savanna	80.7	4.3	11.9	0.51	0.50	0.89	0.12	0.06	0.25
Sudan/Sahel savanna	67.9	6.2	22.3	0.29	0.62	1.72	0.03	0.04	0.11
Flood plains	**72.3**	**8.3**	**13.4**	**0.51**	**0.54**	**0.77**	**0.07**	**0.04**	**0.71**
Equatorial forest	67.8	9.2	15.1	0.42	0.70	1.03	0.07	0.02	0.69
Guinea savanna	75.0	6.6	11.6	0.44	0.55	1.68	0.06	0.08	0.80
Sudan/Sahel savanna	72.6	8.6	13.4	0.55	0.48	1.10	0.07	0.02	0.67
Paddy fields in tropical Asia	**72.2**	**5.94**	**16.3**	**1.42**	**0.92**	**1.83**	**0.13**	**0.12**	**ND**

Analytical procedures: Colorimetric (P), AAS (K) and ICP-AES (Si, Fe, Al, Ca, Mg, Mn, and Na) determination with total elemental dissolution method (Uchida et al. 1979).
See Kawaguchi & Kyuma (1977) Issaka et al. (1997) and Buri et al. (2000) for the value range, standard deviation and/or coefficient of variance.

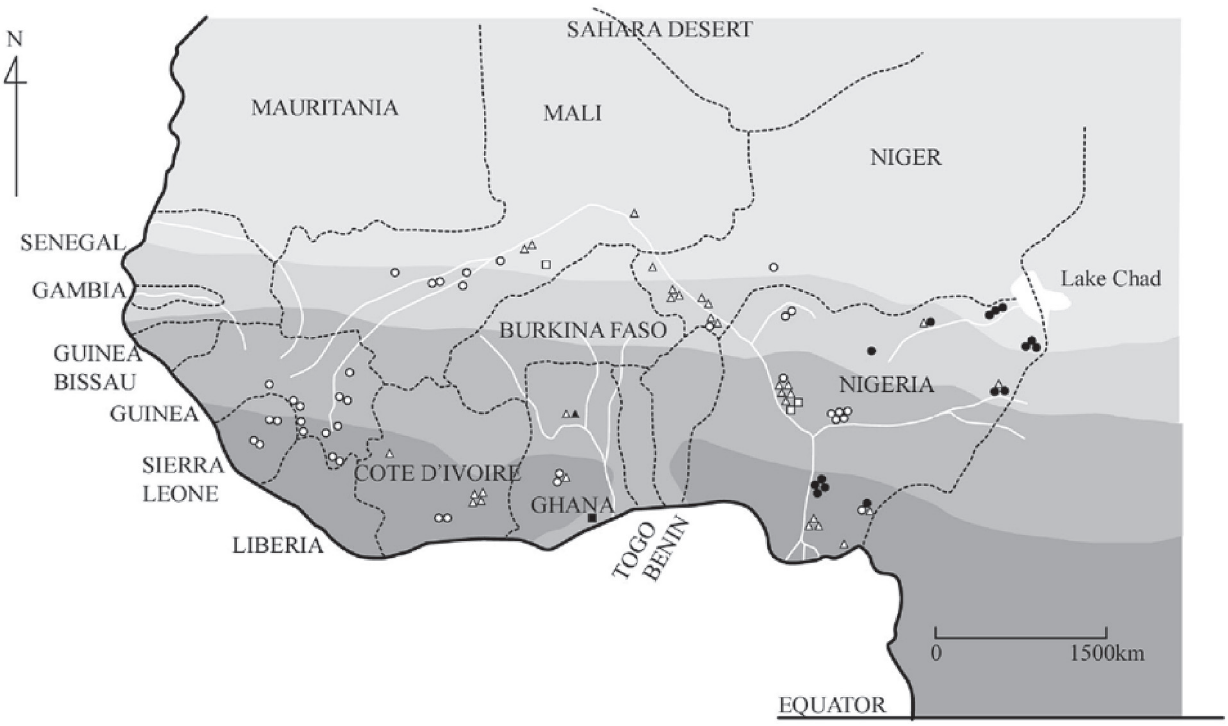

Fig. 5. Geographical distribution of soil clay mineral types in inland valleys and flood plains of West Africa (Abe et al. 2006)

: Sahel savanna zone (Rainfall < 500mm, Plant growth period < 90days)
: Sudan savanna zone (Rainfall 500-1000mm, Plant growth period 90-165days)
: Guinea savanna zone (Rainfall 1000-2000mm, Plant growth period 165-270days)
: Equatorial forest zone (Rainfall > 2000mm, Plant growth period > 270days)

○ : Type 7 ● : Type 14–7
△ : Type 7–14 ▲ : Type 7–10–14
□ : Type 7–10 ■ : Type 14
: International boundary

material as well as climate on soil principal characteristics. Most soils in Guinea and Sierra Leone and some of the soils from western Mali are classified as soil clay mineral Type 7, predominant in 7 Å minerals, indicating the highest rainfall and strongest weathering. These severely weathered soils are deposited in the inland delta of Mali. By contrast, soil clay mineral types containing 14 Å minerals, i.e., Type 7–14, are generally found in the SuS/SaS zone of Mali, Niger and Nigeria. More noteworthy is the occurrence of Type 7–14 soils in high rainfall areas, like the equatorial zones of Cote d'Ivoire, Ghana and Nigeria. Furthermore, soils rich in 14 Å and/or 10 Å minerals, i.e., Type 14–7, 7–10–14 and 14, predominantly occur in the eastern part of West Africa. The geological formation of recent alluvial deposits and the presence of basic rocks may result in the genesis of relatively fertile soils, characterized by the presence of 2:1 type clay minerals (10 and/or 14 Å minerals), while soils of geologically very old origin are less fertile and are predominantly associated with 1:1 type clay minerals (7 Å minerals)[1,9,10,21,22].

Conclusions

We have given an overview of the general fertility characteristics and mineralogical composition of lowland soils in West Africa, focusing on inland valleys and flood plains, which highlights their low fertility status and poor material nature and suggests that lowland soils in West Africa show less fertility potential for rice production than that of paddy soils in tropical Asia. In general, lowland soils in West Africa have sandy texture, poor nutrient status and kaolinitic and/or siliceous mineralogy, although the flood plain soils show relatively higher clay content and better fertility parameters than the inland valley soils. Soil constraints that must be addressed are (i) strong acidity (especially in the EF zone); (ii) low C and N content (particularly in the GS and SuS/SaS zones);

(iii) limited availability of P; (iv) low base status (mainly in the EF and GuS zones); (v) limited availability of S and Zn (more severe in the drier zones); (vi) sandy texture with low clay content (predominantly in inland valley soils); and (vii) low nutrient-holding and potential nutrient-supply capacities.

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