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Evaluating the Potential of Underdeveloped Land for Rice Production in Sub-Saharan Africa — A Case Study of Floodplains in the Northern Region of Ghana, West Africa

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Abstract

This study aimed to identify suitable areas for rice cultivation by evaluating the soil characteristics of underdeveloped land in Sub-Saharan Africa. Two transect lines were set on the Zaw floodplain (ZFP) along the White Volta River in the Northern Region of Ghana for a detailed survey on land types and soil sampling. Land types identified along the transect lines were upland (U), lowland grass (Lg), lowland shallow swamp (Lss), and lowland deep swamp (Lds). The soil texture for U, Lg, and Lss was classified as silt loam (SiL), while Lds was classified as silty clay loam (SiCL). Soil pH (H_2O) was above 6 for U and Lg, and below 6 for Lss and Lds. Extractable S and available Zn were significantly greater in Lds than in other land types. Available Cu, Mn, Ni, and total nitrogen (T-N) were significantly lower in U, and total carbon (T-C) was significantly greater in Lds than in other land types. Factor analysis indicated that Lds had better soil fertility and sulfur availability than other land types. However, it seemed unsuitable for rice production due to deep water depth during the rainy season. Although Lss seemed to be relatively less suitable than Lds due to low soil fertility and low sulfur availability, the water depth in Lss was not as deep as in Lds. Access to a water source was easier in Lss than in Lg; thus, the Lss land type was considered comparatively suitable land for rice production in the study area. Nevertheless, the result implies that soil fertility and sulfur could be constraints, thereby requiring the proper application of fertilizer.

Discipline: Watershed and regional resources management
Additional key words: Soil fertility, sulfur deficiency, food security, Tamale

Introduction

Rice consumption in Sub-Saharan Africa (SSA) has doubled since 1970 as rice has become a staple, especially for urban dwellers, and rice demand is expected to be augmented by 130% from the rice consumption of 2010 (IRRI 2010). Most of the supply of rice in SSA largely depends on importation from such mega rice-producing and rice-exporting countries as Thailand and Vietnam. In 2009, six million tons of rice was imported to meet domestic demand, with four million tons destined for consumption in West Africa, which accounts for almost 30% of this region's total rice demand. Therefore, the cost of importing rice imposes a burden on countries where poverty is a chronic problem in local communities. In order to generate a virtuous cycle in rice, its production in SSA should be enhanced, thereby making it imperative to improve crop productivity within the context of local rice production. In this regard, research and development play a crucial role in making substantial changes in an efficient and effective manner.

During the past decade, rice production in SSA increased by 50% due to the increase in harvested area, which

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accounted for 26%, while the increase in average rice yield was less than 1%. These figures suggest that rice production in this region relied more on land expansion than yield improvement. Despite the vast area of SSA, most of its arable land is dominated by highly weathered soils such as Arenosols and Acrisols (20%), Ferralsols (11%), and Lixisols (9%) (FAO 2003), and low soil fertility has been a central problem regardless of country or crop. Most of the traditional agricultural systems are found in upland areas, where crops grow under rain-fed conditions and thus water control is hardly an option to improve yield. According to future predictions by the IPCC (Bates et al. 2008), water scarcity in SSA will become more severe than at present, thereby amplifying water- and fertility-related abiotic stresses in crop production. This will become the basis of a vicious cycle whereby food security will be threatened despite the large demand from current and future populations. In order to overcome this problem, it is essential not only to develop suitable technology for rice production but also to guide producers on how to use developed technology in a suitable and sustainable manner. The actual rice production area in SSA only accounts for 5% of the total arable land (FAO 2011) and there seems to be huge potential for expanding the area of cultivation. However, sustainable rice production is a result of proper land management, which shall be applied to the use of underdeveloped land.

The floodplains in the Northern Region of Ghana were selected as a case study site where rice production is still a new system in the local communities. The Northern Region covers about 30% of Ghana’s total land area and is considered a granary where the rice harvest area and rice production area represent 35% and 38% of the country’s total, respectively (MOFA 2011). In this region, Yamamoto et al. (2012) developed a method of assessing flood probability in order to select suitable areas where water for rice farming can be obtained naturally. Tsujimoto et al. (2013) showed that seasonal flooding played a crucial role in the N-supplying capacity of soil on the floodplains, and this capacity was quantitatively predicted as a logarithmic function of the distance from a main river. In this study, we aimed to identify the suitable areas for rice cultivation by evaluating the characteristics of soil in the floodplains of SSA.

Materials and Methods

1. Site description

The study was conducted on the floodplain of Zaw village (ZFP, N9° 5’ 19.8”, W1° 9’ 6.5”), 60 km southwest of Tamale, the capital of the Northern Region in Ghana (Fig. 1a). This village is located along the western bank of the White Volta River (Fig. 1b) and floodplains are a dominant ecosystem. The ZFP is located in the Guinea savanna zone, where shrubs and annual grasses are the dominant vegetation. Plinthic Ferralsols are a prominent soil type, followed by Dystric Planosols, according to the FAO/UNESCO soil classification (Obeng 1971). The rainfall pattern is mono-modal, extending from June to October, and peaking in August. The total annual rainfall is 1,200 mm, with maximum, minimum, and average air temperatures of 33°C, 24°C, and 29°C, respectively. People in Zaw village are traditionally engaged in upland agriculture to mainly produce maize (*Zea mays*), ground nuts (*Arachis hypogaea*), and such tuber crops as cassava (*Manihot esculenta*) and yam (*Dioscorea rotundata*). Rice cultivation on the ZFP is still new and thus limited in terms of area, number of households, and total production.

2. Land classification on a floodplain

In order to classify the land type of the ZFP, two transect lines were set for ground observation: ZFP upper stream (ZFP-U) and ZFP lower stream (ZFP-L), both of which were set from west to east toward the White Volta River. ZFP-U and ZFP-L are located to the north and south of Zaw village, respectively. Ground observation was conducted in July 2009 along ZFP-U and ZFP-L by recording the land type, with the points of transition from one land type to another being recorded by a portable GPS (GPS60, GARMIN). Because a portable GPS generally has low precision in measuring altitude, the data obtained was verified through direct measurement of topographical changes in the field (e.g. prominent gaps between the edge of a river bank and surface of the river). Land types observed during the survey were classified into four categories: upland (U), lowland grass (Lg), lowland shallow swamp (Lss) where water depth remains around knee height during the rainy season, and lowland deep swamp (Lds) where water depth reaches around the height of shrubs (generally 7-10 m) during the rainy season.

Water for lowland swamps is derived from the White Volta River that overflows during the rainy season. Interviews conducted with local farmers during the survey revealed that they recognized a water depth around knee height as being shallow, where rice can be grown, while they considered water depth more than knee height as being where rice cannot be grown. Rice production was found in some patches in Lss without earth bunding for water control and where dry direct seeding is employed to establish crops. The total length of the transect lines was calculated by ArcMap (ESRI).

3. Soil sampling and analysis

Soil sampling was conducted by using a hand auger (ø = 7 cm, standard type, Daiki Rika Ltd.) during the dry seasons in 2008 and 2009. There were 13, 10, 11, and 15 sampling points in Lss, Lds, Lg, and U, respectively. Soil samples were taken from a 0-15 cm depth along the transect lines and then air-dried for more than two weeks before analysis. A 100-cc stainless core cylinder (Daiki Rika Ltd.) was used to measure soil moisture content after being dried in a mechanical oven for 24 hours at 105°C.

The air-dried soils were first sieved at 2 mm in diameter, and then soil chemical and physical properties were determined by standard methods. Table 1 lists the methods used for each analysis.

4. Statistical analysis

The soil analytical data were processed for statistical analysis. All parameters were subjected to multiple com-

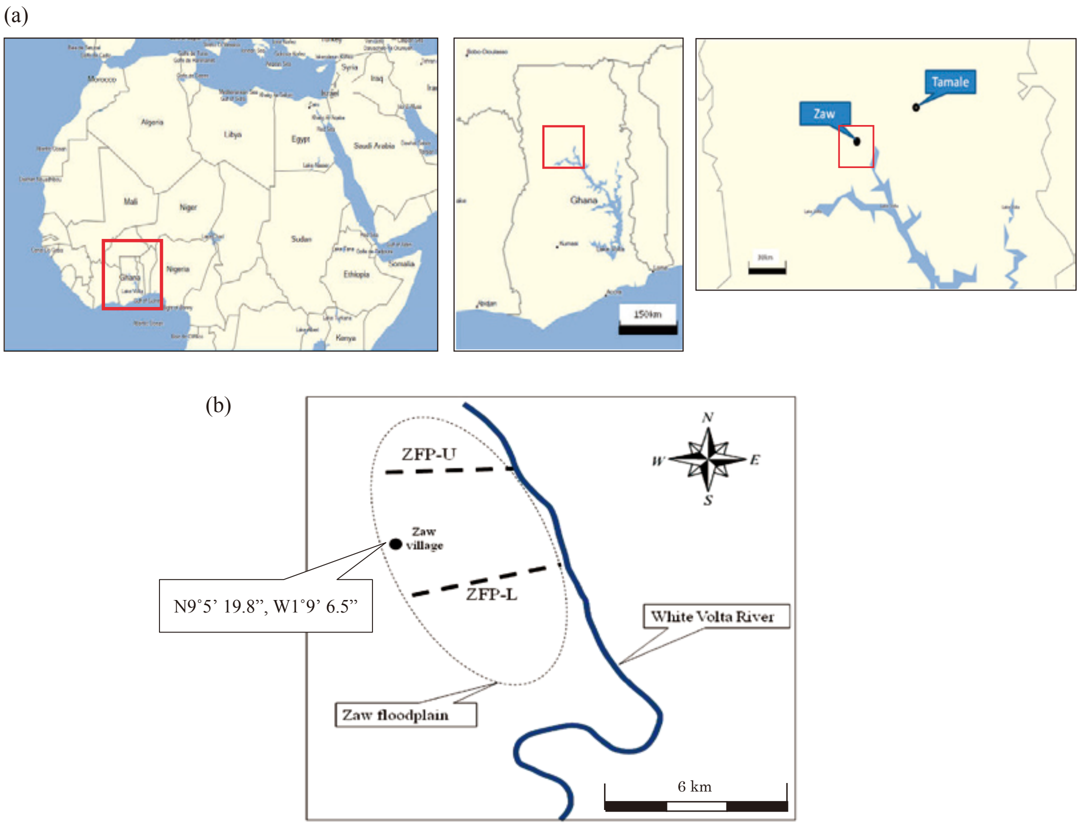


Fig. 1. (a) Geographical location of the study site; (b) positions of the two transect lines on the Zaw floodplain (ZFP)

Table 1. List of analytical methods employed for soil analysis of the study

Parameter	Method	Apparatus	Reference
Particle size distribution	Laser diffraction method	LS13320 (Beckman Coulter)	Segal E. et al. 2009
Soil pH (H_2O)	Soil:H_2O=1:1	Portable pH meter (HORIBA Scientific)	IITA 1979
Total carbon and total nitrogen	Dry combustion method	SUMIGRAPH NC-220F (Sumitomo Chemical Co. Ltd.)	
Available phosphorus	Bray P (No.2)	UV2400 (SHIMAZU)	IITA 1979
Exchangeable bases (Na^+, K^+, Mg^{2+}, Ca^{2+})	1N-NH_4OAC extraction method	ICPE-9000 (SHIMAZU)	IITA 1979
Total acidity	Titration method		IITA 1979
Available Zn, Fe, Mn, Cu, Ni	DTPA extraction	ICPE-9000 (SHIMAZU)	Lindsay and Norvell 1977
Extractable S	KH_2PO_4 extraction	ICPE-9000 (SHIMAZU)	Fox et al. 1964, IITA 1979

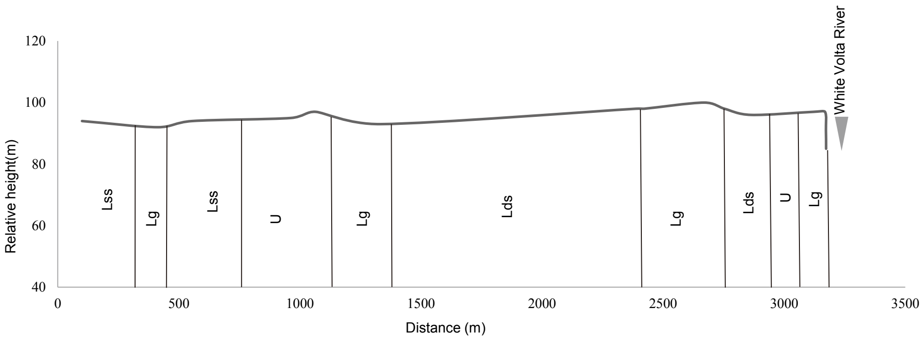
parison. Bartlett's test was employed to test the homogeneity of population variance prior to the ANOVA test. The Kruskal-Wallis test was employed in cases where Bartlett's test showed a significant difference in population variance. When Bartlett's test showed no significant difference, then the ANOVA test was employed to examine differences among land types and the Tukey-Kramer method was employed to conduct a multiple comparison. Factor analysis (FA) was employed to evaluate the soil fertility of different land types as an effective way to interpret the analytical data of various soil parameters in an objective manner (Kyuma 2001). Through FA, three common factors were determined independently with a correlation coefficient between variables and common factors, and the Varimax method was applied to maximize the sum of variances for the factor loadings of each common factor. Common factors were denominated according to the variables with larger loadings. Prior to the analysis, the correlation coefficient for all parameters was examined and parameters of no significance were excluded from FA.

Results and discussion

1. Topography and land types in ZFP

In Fig. 2, a and b show the recorded topographies on the ZFP and land types along the two transect lines (ZFP-U and ZFP-L), respectively. As observed through the two topographies, ZFP-U cuts across the ZFP while ZFP-L had upland and floodplains, and these transect lines covered representative land types on the ZFP from upland to floodplains. The ZFP-U transect line, with a length of 3,200 m, was relatively flat until the eastern edge, where the water surface of the White Volta at the beginning rainy season in May was 6 m below the edge. Most of the areas along this transect line were occupied by lowland shallow swamp (Lss), lowland deep swamp (Lds), and lowland grass (Lg), and one portion of a rice farm was found in Lss at the western end of ZFP-U. In contrast, ZFP-L was 4,000 m in length from the eastern edge to the western edge, and its slope was steeper than that of ZFP-U due to the relative elevation of 28 m. The elevation from the water surface of the White Volta River in May was 4 m below the edge of

(a)



(b)

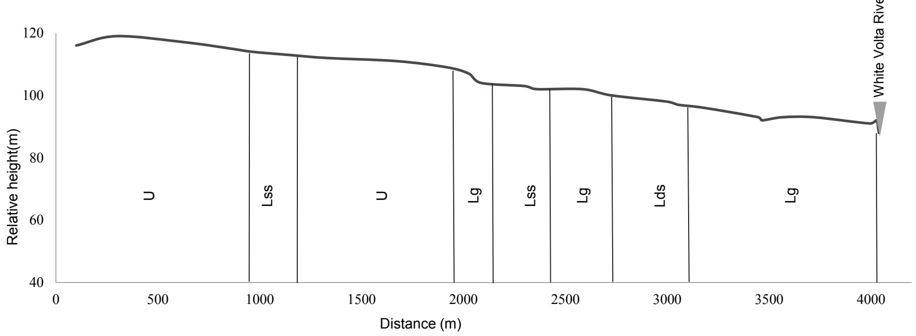


Fig. 2. Example topographies and land types on the ZFP, (a) ZFP-U, and (b) ZFP-L
U: upland crop, Lg: lowland grass, Lss: lowland shallow swamp, Lds: lowland deep swamp

ZFP-U. ZFP-U consists of two different ecosystems (upland and lowland) that were demarcated by a steep drop around 2,100 m from the western end. The land type for upland is suitable for maize, ground nuts, and such tuber crops as cassava and yam. Rice production was also observed along a depression at the western edge of the transect line.

2. General soil properties in the studied floodplain

(1) Soil texture

Table 2 lists the results of particle size distribution of soils in the study area. The soils in U and Lg showed higher sand and lower silt fractions than those of Lss and Lds, and the sand content of Lds was lowest among the land types. However, the difference among the land types was not significant. The clay content for Lds was significantly higher than that for other land types. According to the content of each fraction in soils, Lss, U, and Lg were classified as silt loam (SiL), and Lds was classified as silty clay loam (SiCL), which were consistent with a previous study (Tsujimoto et al. 2013). According to Hatta et al. (2010), kaolinite is the dominant clay mineral in the soils of the ZFP due to the high weathering that results in less holding capacity for water and nutrients.

(2) Soil chemical properties

Table 3 lists the results of chemical analysis for different land types.

Soil pH (H_2O) was significantly higher in U and Lg than in Lss and Lds due to the difference in H^+ and Al^{3+} concentrations in the soils. Lss and Lds showed higher H^+ and Al^{3+} than U and Lg, and this is the reason for low base saturation in those soils (data not shown) which lowered the soil pH (H_2O). Despite the dominant clay type of soils in the study area (Hatta et al. 2010), soils could contain other clay minerals such as smectite — a strong acid type clay — and this could be a reason for the higher Al^{3+} concentration in Lds and Lss. Nevertheless, the level of soil acidity in the study area was around 30% of eCEC, thereby approximating the same results of total acidity obtained by

Table 2. Particle size distribution (%) of soil on the ZFP under different land types

Land type	Sand	Silt	Clay	Soil texture*
Lss	26.7± 12.1	57.9 ± 10.0	15.4 ± 4.5 ab	SiL
Lds	18.8 ± 8.3	62.4 ± 6.6	18.9 ± 2.7 a	SiCL
U	30.7 ± 17.1	56.2 ± 13.6	13.1 ± 3.8 b	SiL
Lg	31.7 ± 24.8	53.8 ± 21.3	14.5 ± 5.2 b	SiL
*p***	0.27	0.55	0.02	

Values in the same column with same alphabetic charcter (s) are not significautly different as per the Tukey-Kramer method.
* USDA classification
***P* was obtained by ANOVA.

Table 3. Chemical properties of soils of different land types, upland (U), lowland grass (Lg), lowland shallow swamp (LSS), and lowland deep swamp (Lds) on the Zaw floodplain

	pH	Total		Bray 2-P	Exchangeable							Exchangeable					
Land type	(H_2O)	C	N	(P_2O_5)	Na^+	K^+	Mg^{2+}	Ca^{2+}	H^+	Al^{3+}	eCEC	S	Cu	Mn	Ni	Fe	Zn
		(%)		(mg kg^{-1})	(cmolc kg^{-1})							(mg kg^{-1})					
U (n=15)	6.11 a	0.56 c	0.06 c	5.74	0.73 b	0.44 cd	1.48 b	3.72 b	0.91 b	0.45 b	7.42 c	10.96 b	0.21 c	33.30 bc	0.92 b	83.25 a	0.13 b
Lg (n=11)	6.16 a	0.82 bc	0.20 ab	4.22	1.66 ab	0.31 c	2.38 b	4.83 b	0.94 b	0.53 b	10.64 bc	11.34 b	0.62 bc	98.57 ac	1.41 b	80.96 a	0.26 b
Lss (n=13)	5.62 b	1.02 b	0.09 bc	4.49	1.44 ab	0.67 bd	2.39 b	4.71 b	1.89 a	2.12 b	13.16 b	10.90 b	2.02 ab	80.61 ab	3.00 ab	97.94 a	1.00 b
Lds (n=10)	5.47 b	2.22 a	0.22 a	6.22	2.30 a	1.34 a	6.35 a	10.48 a	2.62 a	2.83 a	25.92 a	15.03 a	2.82 a	142.38 a	5.30 a	60.50 a	6.03 a
P (Bartlett's test)*	0.11	0.28	0.50	0.74	0.12	0.06	0.27	0.99	0.00	0.56	0.27	0.94	0.00	0.35	0.00	0.00	0.00
P (ANOVA)**	0.01>	0.01>	0.01>	0.87	0.01>	0.01>	0.01>	0.01>		0.05	0.01>	0.01>		0.01>			

Values in the same column with same alphabetic character(s) are not significantly different as per the Tukey-Kramer method.
*: Bartlett's test for the homogeneity of population variance
**: ANOVA test was employed in case Bartlett's test showed no significant difference. The Tukey-Kramer method was employed for a multiple comparison in case the significance level of *P* (ANOVA) is 0.05 or 0.01.

Hirose and Wakatsuki (2002). Extractable S and available Zn were highest in Lds, and other micronutrients such as available Cu, Mn, and Ni were lowest in U. Available Fe was not significantly different among the land types. T-C was highest in Lds, while T-N was lowest in U.

Soil pH, T-C, T-N, eCEC, S, Mn, and Zn are considered crucial parameters for rice growth. According to the results in Table 3, soil pH on the ZFP appeared suitable for crop production, though there was a significant difference among the land types. U showed significantly lower eCEC than other land types and Lds had the highest content among the others, which was consistent with the findings obtained by Buri et al. (1999). Dobermann and Fairhurst (2000) showed that S deficiency for rice plants occurs when the concentration is less than 9 mg kg^{-1}. The soil of the ZFP had S content above the threshold; however, all land types except Lds showed a risk of S deficiency due to approximation to the threshold value. Available Mn for the soil on the ZFP seemed to be at no risk of deficiency due to a value above 1 mg kg^{-1} (Dobermann and Fairhurst 2000). Available Fe appeared to be sufficient compared with its threshold level of more than 4-5 mg kg^{-1} (Dobermann and Fairhurst 2000). Tanaka and Yoshida (1970) proposed a critical Fe level within the range of 70-300 mg kg^{-1} and the soils on the ZFP had Fe within this range; hence, the risk of iron toxicity seems to be negligible.

Effective CEC is one of the indicators for evaluating soil fertility in the floodplains of West Africa (Buri et al. 1999) and an examination of correlation coefficients with other parameters explains a degree of weathering of soil in the study area. According to the analysis results of correlation in Table 4, eCEC showed a significant ($P<0.01$) correlation with clay content and T-C. As Bationo and Buerkert (2001) showed, soil with kaolinite predominantly as the clay mineral had a low capacity of cation exchange, and organic carbon played an important role in improving that capacity. Soil of the ZFP had kaolinite as the dominant clay mineral (Hatta et al. 2010), which implies the importance of T-C for soil fertility management.

(3) Evaluating soil characteristics and identifying problems

The results of factor analysis (FA) was listed in Table 5 along with factor loadings, eigenvalues, and cumulative proportions for each common factor. Each common factor was denominated according to the high factor loadings. The 1st common factor was named soil fertility potential due to higher exchangeable cations, exchangeable bases, and eCEC. The 2nd common factor was named soil sulfur potential due to higher extractable S, and the 3rd common factor was named soil acidity potential due to high exchangeable Al^{3+} and total acidity higher than other variables. Sulfur is one of the essential macronutrients and its deficiency has been reported for rice production in West Africa (e.g., Yamaguchi 1999).

The results of factor analysis in Fig. 3 showed that all common factors for Lds had a positive value, which indicates that the soil in this type of land was considered relatively better for crop growth than the soil in other land types. Although soil acidity potential was higher in Lds than in other land types, the risk could be insignificant because the concentration of exchangeable Al^{3+} was not as high as the critical level. Moreover, Lds was located in a topographical position where the water depth becomes as deep as the height of such perennial plants as shrubs during the rainy season, and thus this land type was not an option for rice production with modern varieties. Lss was relatively less suitable than Lds due to low soil fertility potential and low soil sulfur potential, but some rice cultivations were observed in Lss during the field survey. The water depth in Lss was not as deep as in Lds and thus rice production was one of the possible options for farmers due to the distance from the water source. Yamamoto et al. (2012) reported a highly negative correlation of the distance from the water source with soil fertility on the ZFP. Although Lss could be a candidate for rice growth, the mean factor score of FA in soil fertility and sulfur content were negative values as shown in the results of FA (Fig. 3); thus, nutrient deficiency could be a potential constraint. Tsujimoto et al. (2013) showed a remarkable effect of sulfur application on rice

Table 4. Correlation coefficients for eCEC with exchangeable bases, total carbon, and clay content in the study area

	eCEC	Exch Bases	T-C (%)	Clay %
eCEC	−	0.97	0.53	0.46
Exch Bases	**	−	0.53	0.45
T-C (%)	**	**	−	0.28
Clay %	**	**	ns	−

** significant at 1%

growth and this effect was found to be prominent in places close to a water source where Lss was located (Fig. 2). In contrast, the mean factor score of factor analysis for Lg showed a positive value in soil fertility potential, and soil sulfur potential was slightly higher than that for Lss. Nevertheless, the distance from the water source for Lg was not as close as that of Lss (Fig. 2). The mean factor score of FA for U showed a negative value in both soil fertility potential and soil sulfur potential (Fig. 3), and the distance from the water source was greatest among all land types.

Table 5. Factor loadings, eigenvalues, and cumulative proportions of factor analysis

Factor loading	1st factor	2nd factor	3rd factor
Exch Ca	0.68	0.68	0.20
Exch K	**0.79**	0.14	0.41
Exch Mg	**0.83**	0.45	0.22
Exch Na	**0.87**	-0.22	0.03
Exch Bases	**0.85**	0.47	0.21
Exch H^+	0.64	0.13	0.51
Exch Al^{3+}	0.21	-0.05	**0.93**
Total Acidity	0.44	0.04	**0.88**
eCEC	**0.81**	0.38	0.44
Fe	-0.08	-0.67	0.26
Ni	0.73	-0.11	0.54
Zn	0.61	0.28	0.45
Extractable S	0.15	**0.92**	-0.04
Sand %	0.03	-0.62	-0.12
Eigenvalue	8.19	2.48	1.06
Cumulative proportion	55%	71%	78%
+	Higher soil fertility potential	Higher soil S potential	Higher soil acidity potential
−	Lower soil fertility potential	Lower soil S potential	Lower soil acidity potential

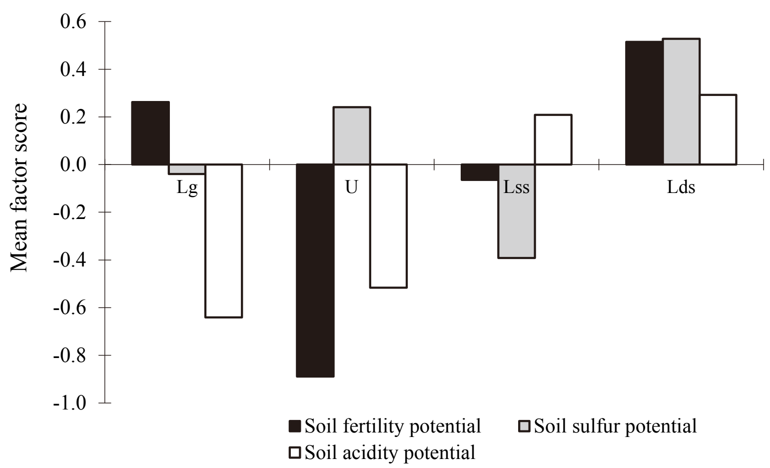


Fig. 3. The results of factor analysis after Varimax rotation

Thus, this implies that U has a potential constraint relative to soil fertility and water supply.

Conclusions

The study showed that land on the Zaw floodplain was currently occupied mainly by grasslands and swamps. Thus, this floodplain seemed to have potential for rice production. However, evaluation through detailed soil analysis indicated that Lds showed better soil properties and higher potential for rice production than other land types such as Lg and Lss. Lds cannot be considered a candidate option for local farmers due to the water depth, which reaches as deep as the height of such perennial plants as shrubs during the rainy season. A site-specific condition plays a crucial role in determining suitable land for rice production. The results obtained also suggested that soil fertility as well as sulfur should be a constraint in certain land types such as Lss, and thus the application of fertilizer must be considered as an optimal means of management. Moreover, the impact of fertilizer application as well as rice production should be carefully assessed in the context of ecosystem services on this floodplain. Further study should be conducted on the same ecosystem in different areas in order to develop existing floodplains in a sustainable and productive manner.

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