Variations in Selected Soil Physical Properties with Landforms and Slope within an Inland Valley Ecosystem in Ashanti Region of Ghana

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Abstract: One peculiar feature of the inland valleys abundant in West Africa is their site-specific hydrology, underlain mainly by the prevailing landforms and topography. Development and management of these land resources under the increasingly popular *sawah* (a system of bunded, puddled and levelled rice field with facilities for irrigation and drainage) technology is a promising opportunity for enhancing rice (*Oryza sativa* L.) production in the region. Information on the variations in selected soil physical properties as influenced by the prevailing landforms may serve as a useful guide in site selection. This is of practical importance since majority of the inland valleys are potentially unsuitable for *sawah* development and most farmers in the region are of low technical level. Three landforms (river levee, elevated area and depressed area) were identified within a *sawah* field located in an inland valley at Ahafo Ano South District of Ghana. Each of these landforms was topsoil-sampled along on identified gradient (top, mid and bottom slope positions). Parameters determined included particle size distribution, bulk density, total porosity and field moisture content. The soil is predominantly clayey. There were no variations in the particle size distribution among the slope positions in the river levee. Overall, the river levee had lower silt content than the elevated and the depressed landforms. The bulk density, total porosity, and gravimetric moisture content indicated relative improvements only in the depressed area in the order, bottom > mid > top slope. Irrespective of slope position, the three landforms differed in these parameters in the order, depressed > river levee > elevated. The sand fraction impacted negatively on the silt fraction and bulk density of the soil, both of which controlled the soil moisture status. Despite the fairly low silt content of the soil, the silt fraction strongly influenced the gravimetric moisture content (R^2 = 0.80). So too did the soil bulk density on the gravimetric moisture content (R^2 = 0.90). It is concluded that: (1) since the landforms more prominently influenced the measured parameters than the slope positions, the former should take pre-eminence over the latter in soil suitability judgment; (2) with respect to moisture retention, variations in silt fraction and bulk density of this and other clayey inland-valley soils should be used as guide in site selection for *sawah* development.

Keywords: bulk density; landscape position; moisture content; particle size distribution; *sawah* rice field; total porosity

The apparent situation of many cases of unexploited or underutilized inland valley resources in West Africa for rice (*Oryza sativa* L.) production has been identified as the hurdle to achieving green revolution in the region (Wakatsuki *et al*. 1998; Wakatsuki & Masunaga 2005). Consequently, much attention has been focused on the abundant inland valley ecosystems in recent years. The proportion of the total area under rice cultivation that is located in rainfed lowlands in West Africa is put at 38%, and this share is on the rapid increase (West Africa Rice Development

Association, WARDA 2008). A key aspect of this agricultural development is the adoption of the *sawah* technology for rice production (Wakatsuki *et al.* 1998). By definition, sawah refers to a bunded, puddled and levelled rice field with inlet and outlet for irrigation and drainage, respectively.

Based on an inference drawn from Asia, only about 10% of the approximately 200 mil ha of inland valleys in sub-Saharan Africa (i.e., about 20 mil ha) are potentially suitable for development as *sawah* rice fields; the rest suffer from pedologic, topographic or hydrologic constraint or a combination of any two or all of the three factors (Wakatsuki & Buri 2008). Specifically in West Africa, the lowlands are characterized by different landscape positions within the same inland valley and consequently by a variable hydrology (Tsubo *et al.* 2006). One of the most important tasks before researchers who are interested in enhanced and sustained rice production in West Africa is, therefore, contribution to the development and acquisition of skills needed for the selection and management of the abundant inland valley soils. Any skills so developed should thereafter be imparted to the farmers whose technical level is generally low. The importance of contact among this category of farmers in the dissemination process of the *sawah* package (Fashola *et al.* 2006) should be borne in mind while devising site selection criteria for them.

As a hydrophilic crop, one of the most important factors normally considered in site selection is the availability of source of water. Moisture retentive capacity of the soil is as important as the source of water itself, and is controlled mainly by the textural and structural attributes of the soil. The importance of such an index soil property as texture in adjudging inland valleys suitable or not for rice cultivation in the West African setting has earlier been highlighted (Carsky & Masajo 1992). In Nigeria for instance, Olaleye *et al.* (2008) reported that the major constraint to lowlands for rice cultivation in the western region is unfavourable soil texture and that this provokes sub-optimal water and nutrient status. Similarly, bulk density is considered the most important index of soil structure in *sawah*-managed fields. This is because it is the soil property that serves as an indicator of the efficacy of the puddling aspect of the technology. Rice is such sensitive to bulk density that the crop's field performance has been established to have a direct relationship with the soil bulk density (Kukal *et al.* 2008). On the other hand, Toure *et al.* (2009) documented the importance of toposequence in the hydrology and drainage of the inland valley ecosystems of West Africa.

However, most of the available research information about soil conditions in the West African inland valleys focused mainly on fertility and/or pedo-mineralogy (Issaka *et al.* 1996, 1997; Buri *et al.* 1999, 2000; Annan-Afful *et al.* 2004, 2005; Abe *et al.* 2006, 2007, 2009; Udo *et al.* 2009). The physical aspect has been sparingly studied, with little or no emphasis on the effects of topography (Annan-Afful *et al.* 2004; Abe *et al.* 2009). This is in spite of the fact that soil physical fertility is basic for the expression of fertility in the overall soil productivity. Besides, favourable soil and hydrological conditions may differ within an inland valley between the sandy hydromorphic border and the near-permanently flooded alluvial clay areas close to the centre of the valley bottom (Toure *et al.* 2009). Although all-encompassing information would be a more useful guide to site selection for *sawah* development, physical condition of the soil is usually the first to be considered. There is therefore the need to pay adequate research attention to soil physical properties as influenced by such visual features as landform and slope in the inland valleys.

Our drive in this study was that such easily determined but highly influential soil physical properties as texture, bulk density and moisture status would vary in a given inland valley bottom according to the configuration of the landscape. Such variations are expected to provide valuable information that would aid researchers and farmers alike in taking critical management decisions. This paper is therefore a report of the preliminary investigation which was conducted to evaluate and compare these soil properties at various landforms and slope positions within an inland valley in southern Ghana. The objective was to generate data on soil physical properties that would serve as a convenient and quick guide to the suitability or otherwise of an inland valley site for *sawah* development.

MATERIALS AND METHODS

The study site was a *sawah*-rice field at Biemso No. 1 in the Ahafo Ano South District of the Ashanti Region of Ghana. As depicted in Figure 1, the site

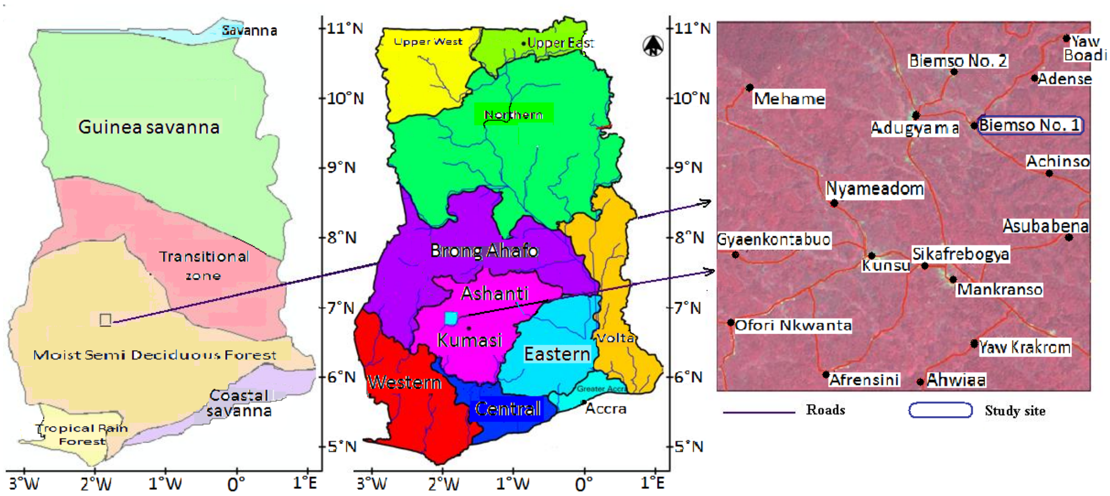

Figure 1. Map showing the specific location of the study site in the eco-regional map of Ghana

falls within the semi-deciduous agro-ecological zone of Ghana and is located by latitude 6°52'N and longitude 1°51'W. The area is on an altitude of approximately 280 m a.s.l. Mean seasonal annual rainfall in this area is about 1300 mm, with a bimodal distribution pattern. The rice field was managed by a group of farmers (referred to as the Zongo Group in the local parlance). It typifies the multifactorial nature of West African inland valleys. Some of the features of the field include: low-lying position and presence of surrounding and sloping uplands, large size of about three hectares, rough terrain with 1–2% slope, complex water distribution processes, and proximity to a river – the Biem River. This river is lying on a lower elevation than the field. A dike was constructed across the river to raise the water head for the purpose of pump-irrigating or canal-feeding the field whenever the need arises. As a result of the constructed dike, the river occasionally overflows its banks.

Although the entire field qualifies to be classified as an inland valley based on the above topographic and hydrologic features, three distinct landforms are identifiable. These listed in the order of their relative proximity to the river include: (1) a levee of the Biem River, which is occasionally splashed and washed by the river; (2) a depressed area lying at the lowest position in the field and; (3) an elevated area with a relatively high sand content and good drainage status compared to the rest of the field. Each of the landforms slopes in the direction of the river, and there is a clear slope. In each of the landforms, three slope positions (top slope, mid slope and bottom slope) spaced between 50 and 75 m apart were identified (Figure 2). With the three slope positions delineated in each of the three landforms, there were altogether nine of such positions referred to as landscape positions in the rest of this paper.

Soil samples were collected from all the nine landscape positions (Figure 2). In each landscape position, the sampling was done in quadruplicates across the slope in a linear manner and at a distance of about 5 m between the replicates. The top (0–15 cm) soil was sampled with cylindrical metal cores (dimension, 5 cm × 5 cm). From the same sampling position and depth, 200 g of soil was also collected for mechanical analysis and

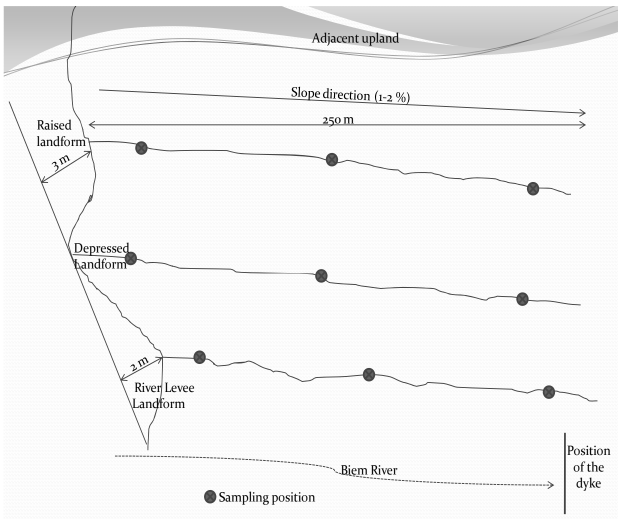

Figure 2. Schematic description of the study site and the sampling points

determination of the prevailing soil moisture status at the time of sampling. This was immediately transferred into a polythene bag and wrapped to avoid moisture loss before analysis. In all, there were 36 each of the core and the non-core samples. As at the sampling time, the rice field (covering the whole sampled area) was already established. The sampling was completed in a day to ensure uniformity in the hydrophysical environment of the soil.

Particle size distribution of the samples was determined by the hydrometer method (Gee & Bauder 1986). The core samples were allowed to drain freely for 24 h before being oven dried for determination of bulk density by the Blake and Hartge's (1986) method. Total porosity was calculated as:

1 – (the determined bulk density/an assumed particle density of 2.65 mg/m^3) × 100 (%).

Using the freely drained core samples, soil moisture content was determined gravimetrically [(mass of wet soil – mass of oven-dried soil)/mass of oven-dried soil] and designated the gravimetric moisture content. Oven-drying was achieved at 105°C for 24 h. Moisture content of the soil under field condition (i.e., the prevailing moisture content at sampling) was first determined gravimetrically and later expressed on volumetric basis, using the determined bulk density. This was designated the volumetric moisture content.

Using a computer software (SPSS for Windows Version 15.0), *F*-test involving analysis of variance due to the landscape positions was performed on the data. For statistical comparison, the means were separated by the least significant difference (LSD) procedure. Relationships among the variables were determined by simple correlation.

RESULTS AND DISCUSSION

Textural properties

Table 1 shows the particle size distribution of the soil under the various landscape positions. Compared to the other landforms, the elevated landform had low sand and high clay contents at the mid slope position. In contrast, the depressed landforms had high sand and low silt contents at the top slope position. In the levee landform, there were negligible variations in the particle size distribution among the three slope positions. This could be due to the closeness of the levee to the

Table 1. Mechanical composition of the different topographic conditions at the study site (in %); textural class – clay

Landscape position		Sand	Silt	Clay
Elevated	top slope	32.7	8.0	59.3
	mid slope	15.3	8.1	76.6
	bottom slope	39.4	6.1	54.5
	mean	29.1	7.4	63.5
Levee	top slope	18.5	18.1	63.4
	mid slope	18.6	20.1	61.3
	bottom slope	13.5	22.0	64.5
	mean	16.9	20.1	63.1
Depressed	top slope	29.6	16.0	54.4
	mid slope	10.8	32.0	57.2
	bottom slope	10.5	30.1	59.4
	mean	17.0	26.0	57.0
LSD		ns	11.2*	ns
CV (%)		44.5	27.7	12.1

LSD – least significant difference, CV – coefficient of variation, *significant at $P \leq 0.05$, ns – not significant

Biem River and the associated occasional surface water flow over the entire levee. During such an event, there is bound to be even distribution of the fine particles in the flooding water, the subsequent sedimentation of which accounted for the observation. Following a similar study in Indonesia and Thailand, Boling *et al*. (2008) reported that only clay fraction of the soil increased from the top of the valley to its bottom in Indonesia (textural class, loam). However, they reported that there were no differences in all the soil separates along another toposequence in Thailand (textural classes, loamy sand and sandy loam).

Irrespective of slope position, sand and clay fractions indicated statistically same values among the three landforms. Variations occurred only for the silt fraction which showed lower value in the elevated landform compared to the other two landforms. Generally, the silt content of the study site is low. This is an indication that the soil is highly weathered and is therefore poor in weatherable minerals. The trend of % silt in the three landforms reflects the density-dependent pattern of surface flow, transportation and deposition of soil materials from upland to lowland. It appears therefore that in this and similar inland valley soils of West Africa, the fractional mass of silt in the topsoil increases with a decrease in elevation. The clayey nature of the entire field as depicted by the textural classes is a reflection of the underlying Tertiary or Cretaceous Shale parent materials on the soil texture (Abe *et al*. 2009). It could also be due partly to deposition by runoff from the adjacent upland and partly to low erosion status of the soil at the present level of cultivation (Ogban & Babalola 2003, 2009).

Structural and water retention properties

Table 2 shows the other soil physical properties under the various landscape positions. Out of the three landforms, differences among the slope positions occurred only in the depressed area where all the three parameters (bulk density, total porosity and gravimetric moisture content) significantly

Table 2. Soil bulk density, porosity and moisture contents at the various landscape positions

Landscape position		Bulk density (mg/m)	Total porosity (%)	Moisture content (%)	
				gravimetric	volumetric
Elevated	top slope	1.48	44.2	25.7	37.8
	mid slope	1.39	47.5	35.4	48.2
	bottom slope	1.52	42.7	28.8	43.2
	LSD	ns	ns	ns	5.4*
	mean	1.46	44.8	30.0	43.1
Levee	top slope	1.23	53.5	45.3	55.6
	mid slope	1.30	51.1	46.7	60.5
	bottom slope	1.31	50.5	41.1	53.9
	LSD	ns	ns	ns	ns
	mean	1.28	51.7	44.4	56.7
Depressed	top slope	1.30	50.9	46.9	61.0
	mid slope	1.07	59.8	76.4	81.3
	bottom slope	0.89	66.6	87.6	77.5
	LSD	0.16*	6.1*	12.6*	0.33***
	mean	1.08	59.1	70.3	73.3
LSD		0.20**	0.08*	15.2***	7.2***
CV (%)		12.1	11.3	24.5	9.8

LSD – least significant difference, CV – coefficient of variation, ns – not significant, *, **, *** significant at $P \leq 0.05$, 0.01 and, 0.001, respectively

Table 3. Mean soil bulk density, porosity and moisture contents at the various slope positions

Slope position	Bulk density (mg/m^3)	Total porosity (%)	Moisture content (%)	
			gravimetric	volumetric
Top	1.34	0.50	39.3	51.5
Mid	1.25	0.53	52.8	63.3
Bottom	1.24	0.53	52.5	58.2
LSD	ns	ns	ns	6.2**
CV (%)	10.4	9.7	23.0	8.4

LSD – least significant difference, CV – coefficient of variation, ns – not significant, **significant at $P \leq 0.01$

($P \leq 0.05$) deteriorated up the slope (Table 2). This trend may be associated with the layering sequence of runoff-laden fine earth materials from the adjacent sloping upland. The low bulk density in the bottom slope position indicates low level of soil compactness and associated improvement in root penetration (Ogban & Babalola 2003), and hence favourable root activity (Ogban & Babalola 2009). With respect to the bulk density, Boling *et al.* (2008) reported similar observation in Pati and Rembang Districts of Indonesia. Similar to the results on the gravimetric moisture content, other authors working in rice fields with bunds for water control in different inland valley bottoms reported that the depth of ponding decreased from the bottom position through the mid position to the valley fringe (Tsubo *et al.* 2006; Boling *et al.* 2008; Toure *et al.* 2009). In the present study, however, the mid position indicated higher values of volumetric moisture content than the bottom slope position in both the elevated and the depressed landforms. This may be associated with the relative amounts of the soil separates at that slope position, i.e., low sand and high clay contents (for the elevated area) and the low sand and high silt contents (for the depressed area) (Table 1).

Overall, the landforms (regardless of the slope positions) had more pronounced influence on the structural and water retention properties than did the slope positions within each landform. The elevated landform maintained the least favourable values of these soil properties (highest bulk density, lowest total porosity and lowest gravimetric moisture content). On the other hand, the depressed landform maintained the most favourable values (lowest bulk density, highest total porosity and highest gravimetric moisture content). In the case of the elevated landform, the high bulk density may be related to the hardening of the iron/quartz stone layer due to prolonged dry conditions which manifested in low moisture status (Annan-Efful *et al.* 2004). Similar to the present results, Boling *et al.* (2008) found that bulk density varied ap-

Table 4. Matrix of the correlation coefficients among the measured soil physical properties in all the landscape positions (n = 36)

	Sand	Silt	Clay	Bulk density	Total porosity	Moisture content	
	(%)					gravimetric	volumetric
Sand (%)	–						
Silt (%)	–0.77*	–					
Clay (%)	–0.47	–0.25	–				
Bulk density	0.68*	–0.77	0.03	–			
Total porosity	–0.68*	0.76	–0.02	1.00*	–		
Gravimetric moisture content	–0.65	0.85**	–0.18	–0.95**	0.95**	–	
Volumetric moisture content	–0.66	0.90**	–0.23	–0.88**	0.88**	0.96**	–

*, **significant at $P \leq 0.05$ and 0.1, respectively

preciably along some toposequences (slope range, 1.5–4.8%) in Indonesia. On the other hand, the very highly significant ($P \leq 0.001$) differences in the water-retention properties among the landforms in the present inland valley suggest a possibility of differences in their morphology (Olaleye *et al*. 2006).

Considering the effect of slope position across the three landforms, there were no differences in the structural and water retention properties, except for the volumetric moisture content which maintained the trend of decreasing from the mid through the bottom to the top slope position (Table 3). Recall that the volumetric moisture content was representative of the field soil moisture status at the time of sampling. These results signify therefore that although the bottom slope may have higher moisture retention capacity, the mid slope may benefit more from the hydrological processes at the field scale. In the prevailing hydrology of this rice field, the chances of having water at any point in time are higher in the mid slope than in the bottom slope.

Relationships among the soil properties

As shown by the correlation coefficients with their probability levels (Table 4), sand and silt were two fractions of the soil that had a significant ($P \leq 0.05$) inverse relationship with each other in the study site. The sand content also significantly ($P \leq 0.05$) correlated negatively with the bulk density. Yet, the soil gravimetric moisture content showed significant ($P \leq 0.01$) positive and negative correlation with the silt fraction and the bulk density, respectively. Since the sand fraction correlated negatively with these two variables (silt fraction and bulk density), it implies that sand fraction was the factor negating the enhancement in moisture status of this soil. Contrary to the results reported by Tsubo *et al.* (2007) in northeast Thailand and to our expectation too, the clay fraction had no influence on the soil moisture. This could be due to the high clay content of the soil. Unlike in the present situation, the study sites of Tsubo *et al.* (2007) were dominated by loamy sand and sandy loam soils, and so the little clay fraction in those

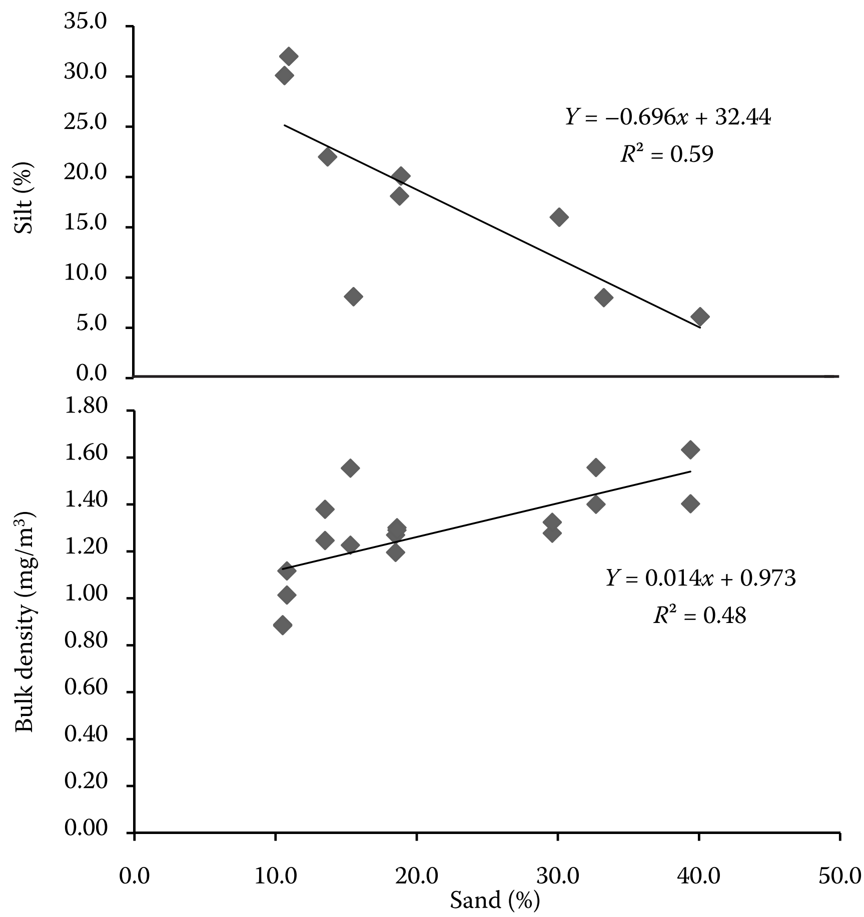

Figure 3. Relationship between each of silt content and bulk density with the sand content

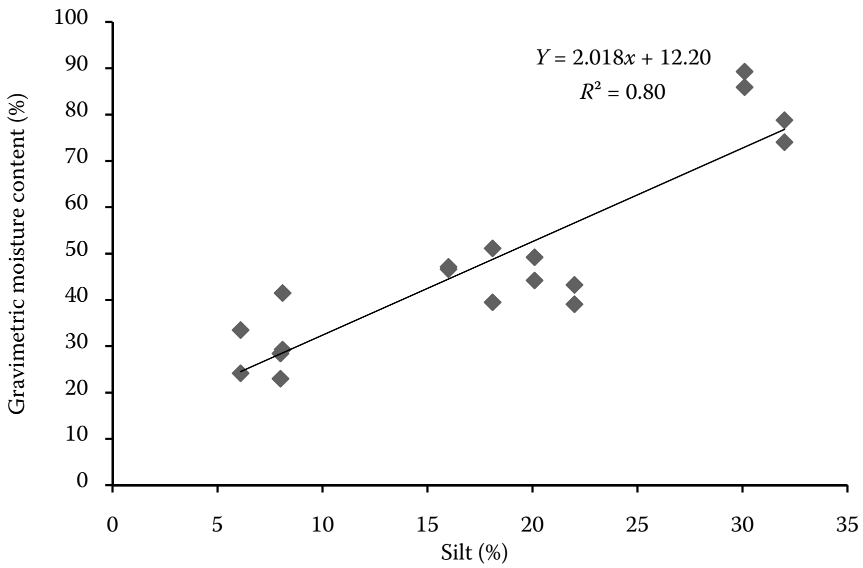

Figure 4. Relationship between gravimetric moisture content and silt content of the soil

soils exerted palpable influence in their moisture contents.

The linear relationships between the silt and the sand fractions of the soil, as well as between the bulk density and the sand fraction are shown in Figure 3. As indicated by the coefficients of determination (R^2), the silt fraction than the bulk density had greater share of the negative impact of the sand content of the soil. Furthermore, Figures 4 and 5 show the linear relationships between the gravimetric moisture content and the silt fraction and between the gravimetric moisture content and the bulk density, respectively. In spite of the comparatively low silt content of the soil, the silt fraction exerted strong influence on its gravimetric moisture content (R^2 = 0.80). The bulk density showed stronger influence on the gravimetric moisture content (R^2 = 0.90). The implication of these results for selection and management of the inland valley soils for *sawah* rice production is that while looking for sites with reasonable silt content, priority attention should be on managing the soil bulk density. Such is of paramount importance in especially inland valleys where there is – and in most cases there are – the need to enhance water retention in the soil. Interestingly, compared to the silt content of the soil (which is a textural attribute that is hardly influenced by management), the bulk density is a structural attribute of the soil that is readily responsive to management.

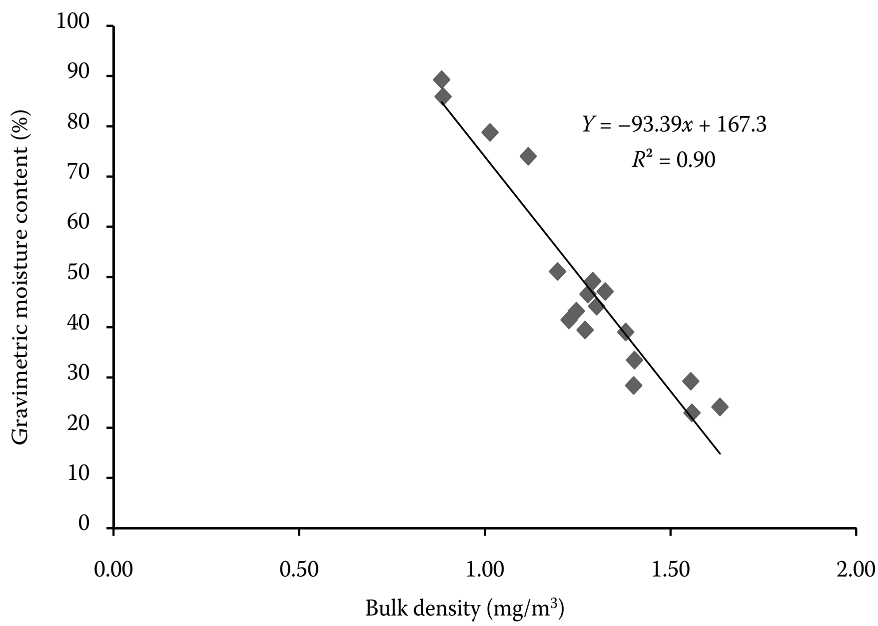

Figure 5. Relationship between gravimetric moisture content and bulk density of the soil

CONCLUSIONS

The landforms existing in the *sawah* rice field used for this study showed stronger influence than the slope positions on the monitored variables; including particle size distribution, bulk density, total porosity, gravimetric moisture content, and volumetric moisture content. Among the landforms, the depressed area maintained these soil properties at the most favourable levels compared to the elevated and the levee areas. More attention should therefore be paid to landforms than slope in site selection. The study also reveals that, with respect to water retention in a clayey inland-valley soil, the contributions of the silt content exceed by far those of the sand and/or clay contents. Bulk density was of prominent importance, as it had high control of the soil hydrophysical status – a major edaphic determinant of the suitability of an inland valley for *sawah* development. Therefore, variations in silt fraction and bulk density across a landscape of an inland-valley soil high in clay content could be used as a single but effective tool in site selection for sawah development and management.

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