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Spatial Variation in Surface Soil Total Carbon and Its Relationship with Soil Color in a River Floodplain Ecosystem of Northern Ghana

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Abstract

In this study, we aimed to identify the factors underlying the spatial variation of total carbon (TC) and its relationships with soil color parameters in the surface soil (0 to 15 cm in depth) of the White Volta River floodplain in northern Ghana. The 75 soil samples collected in 2014 from an area of about 3 km × 4 km in this floodplain showed a large variation in TC content (4.1-40.1 g kg^{-1}), and to cover this variation, 63 soil samples were additionally collected from two line transects (1419 and 1177 m long), across the same floodplain in 2015. TC content in these two transects ranged from 3.7 to 54.9 g kg^{-1}, and most of the carbon (> 75.9%) was in the heavy fraction (> 1.6 g cm^{-3}) of the soil in 2014. Soil TC content was significantly correlated with clay content and soil moisture content (r = 0.87 and 0.84, respectively; $P < 0.001$ for each) in 2015. Soil TC content decreased exponentially with the increase in downward gradient ($R^2 = 0.41$; $P < 0.001$) in 2015. Sloped areas, where the downward gradient was larger than 0.3%, had low soil TC content (ranging from 3.7 to 20.2 g kg^{-1} with a mean of 10.0 g kg^{-1}), while the other locations had high soil TC content (ranging from 5.5 to 54.9 g kg^{-1} with a mean of 26.1 g kg^{-1}) in 2015. Soil moisture content and clay content decreased exponentially with the increase in downward gradient (R^2 = 0.39 and 0.43, respectively; $P < 0.001$ for each) in 2015. Chromaticity values of soil color such as a*, b*, and C* decreased exponentially with the increase in soil TC content (R^2 = 0.68, 0.63, and 0.65, respectively; $P < 0.001$ for each), and would be better indices for the estimation of TC than the lightness of soil color (L*, $R^2 = 0.32$; $P < 0.001$) in the studied floodplain.

Discipline: Soils, fertilizers and plant nutrition
Additional key words: Africa, microtopography

Introduction

Low soil fertility is one of the main factors limiting crop yields in West Africa (Sanchez 2002, Vågen et al. 2005, Dingkuhn et al. 2006, Lal 2006). Soil fertility is the ability to supply essential plant nutrients and water in adequate amounts for plant growth in the absence of toxic substances that may inhibit plant growth, and soil organic carbon (SOC) plays a key role in the determination of soil fertility (Lal 2006). High SOC content improves the water holding capacity (Rawls et al. 2003), cation exchange capacity (Syers et al. 1970), and biotic activity of microorganisms (Powlson et al. 2001), and also enhances the soil structure (Haynes and Naidu 1998). Various studies have indicated that crop yield is limited by low SOC content in West Africa (Vågen et al. 2005, Lal 2006).

River floodplains in West Africa have relatively high levels of soil total carbon (TC) compared with upland areas (Abe et al. 2000). As the soils in this region are acidic (Abe et al. 2000) and do not contain much inorganic carbonates, soil TC is considered to be equal to SOC. Although rice cultivation there is still limited and the grain yield is low (Oteng and Sant'Anna 1999), there

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are growing expectations for more widespread use of non-utilized floodplain areas for agricultural production (Tsujimoto et al. 2017). Even though floodplains pose problems for crop production, such as the potential for submergence damage (Manzanilla et al. 2011, Dar et al. 2013), the utilization of floodplains for rice production is highly anticipated in West Africa (Buri et al. 1999). For example, our previous study demonstrated that the potential yield of rice grown under rainfed conditions in river floodplains in West Africa may exceed 5 t ha^{-1} (Katsura et al. 2016).

The floodplains in West Africa have high spatial variability in soil TC content. Buri et al. (1999) conducted a regional soil investigation at 62 sites in West Africa and found that the general soil fertility status including soil TC content differed widely depending on the ecological zone: soil TC content decreased from the south (equatorial forest, 14.4 g kg^{-1} of soil TC content at 0-15 cm depth) to the north (Sahel savanna, 6.2 g kg^{-1} of soil TC content at 0-15 cm depth). Tabi et al. (2012) investigated soil physicochemical properties including SOC content at several locations in the Logone and Chari floodplains in Cameroon, and found that there were large variations in SOC content at 0-25 cm depth, ranging from 4.6 to 21.2 g kg^{-1}.

Such a large variation in SOC or soil TC content is not limited to the regional scale. Tsujimoto et al. (2013) focused on a narrower area of a few square kilometers that included a floodplain of the White Volta River in the Northern Region of Ghana, and found that floodplains had higher soil TC content, with a maximum of 40.2 g kg^{-1}, compared to the marginal upland areas, with a maximum of around 10.0 g kg^{-1}. However, the factors causing spatial variation of soil TC content in a small area of a floodplain have not been well studied. Carbon in the light fraction of soil is partly decayed plant and animal products, whereas that in the heavy fraction comprises humic substances encrusted with clay particles (Six et al. 2000, Song et al. 2012). Erosion is one of the driving forces that cause spatial variation in soil TC content (Lal 2006), as clay particles are translocated to a lower position through erosion. Hence, the microtopography affects the spatial variation of soil TC content. Homma et al. (2003) showed that relative elevation is an important factor determining spatial variation in SOC and clay in a mini-watershed in Northeast Thailand. Tsujimoto et al. (2013) also found that soil TC content showed significant correlation with elevation and distance to the reservoirs in a floodplain of the White Volta River in the Northern Region of Ghana. However, they could not adequately explain the cause of large variations in soil TC content among locations close to water reservoirs, ranging from around 5.0 to 40.0 g kg^{-1}, by using such topography data as elevation, slope, etc. Tsujimoto et al. (2013) obtained topography data from geographic information system analysis using satellite images, which may not be suitable for understanding the large spatial variation of soil TC content in a small area. Therefore, a detailed field investigation of topography is necessary for further understanding of the factors underlying the spatial variation of soil TC content in small areas within a floodplain.

A simple technique for the estimation of soil TC content would also be useful in identifying suitable locations for crop cultivation, as its measurement requires labor or a special instrument. Soil color is one of the best options to estimate soil TC content (Konen et al. 2003, Viscarra Rossel et al. 2006, Moritsuka et al. 2014). However, no study has been conducted in a river floodplain in West Africa to investigate the spatial variability of soil color parameters and their relationship with soil TC content.

In this study, we focused on a river floodplain along the White Volta River in northern Ghana as a model case for West Africa. The objective of this study was to gain knowledge on the spatial variation in surface soil TC content and its relationship with microtopography, soil particle size distribution, and soil color for the selection of locations suitable for crop cultivation within a river floodplain.

Materials and methods

The research was conducted in an area of about 3 km × 4 km on a floodplain of the White Volta River in the Northern Region of Ghana (latitude 9.072°N-9.109°N; longitude 1.160°W-1.127°W) (Fig. 1). The study region is classified as a Guinea savanna ecosystem, which comprises vast, flat land areas of the Volta basin, a major rice-producing region of the country. Annual average temperature ranged from 27.8°C to 28.3°C, and rainfall ranged from 554 mm to 835 mm based on our measurements using the Hobo weather station (Onset Hobo Corporation, Bourne, MA, USA) from 2012 to 2014 in the study area (Katsura et al. 2016). The rainy season is from mid-June to mid-October. According to the previous survey by Tsujimoto et al. (2013), the pH of surface soils in the studied floodplain (n = 18) ranged from 5.4 to 7.6. The content of TC varied widely from 3.5 to 30.2 (g kg^{-1}) and showed a significant positive correlation with many other properties such as mineralized nitrogen N (1.4-141.1 mg kg^{-1}), cation exchange capacity (3.1-15.1 cmolc kg^{-1}), and clay content (10.6-31.5%). The soils in the studied area were classified as Petric Plinthosol according to the Soil Atlas of Africa (Jones et al. 2013).

In 2014, 75 soil samples were taken randomly from within the research area. In 2015, line transect surveys were conducted at two locations inside the research area perpendicular to the White Volta River (Fig. 1; Transects A and B). Each transect survey started from a point on the upland side before the first swamp was observed, and passed across a few swamps to the riverside. We collected 35 soil samples from Transect A, which was 1419 m long, and 28 samples from Transect B, which was 1177 m long; the average distance between each soil sampling point was about 40 m for both transects. A topographical survey including relative elevation and distance between surveying points was carried out with a surveying instrument (AT-FT; Topcon, Tokyo, Japan) from 90 and 68 points, including soil sampling points, along Transects A and B, respectively. Distances between the topographical surveying points ranged from 1 m to 35 m with a mean of 15.6 m, and from 3 m to 59 m with a mean of 16.8 m for Transects A and B, respectively. Each soil sampling point was categorized for descriptive purposes into one of two geographical groups based on the gradient between the soil sampling point and its nearest neighboring topographical surveying point. The classifications were "Slope" (where the downward gradient was larger than 0.3%) and "Others". The criteria for the downward gradient of 0.3% was set empirically based on relationship between soil TC content and downward gradients. If the downward gradient exceeded 0.3%, only one out of 39 soil samples had soil TC content larger than 2.0 g kg^{-1}. Conversely, if the downward gradient was lower than 0.3%, 13 out of 20 samples exceeded soil TC content of 2.0 g kg^{-1}. Negative values of downward gradient mean that the gradients to both sides were acclivitous.

Soil samples were collected from the top 0 to 15 cm in a natural ecosystem of the floodplain with no cultivation history. Samples were collected from the middle of June to early July. All soil samples were air-dried and sieved to pass through a 2-mm mesh. The soil TC content was determined using an automatic NC analyzer (Sumigraph NC-220F; SCAS, Tokyo, Japan). The particle size distribution (i.e., percentages of sand, silt and clay) was measured using a sieving and pipetting method (Gee and Bauder 1986). Soil samples collected in 2014 were separated into light and heavy fractions by a density fractionation method using a NaI solution with a specific gravity of 1.6 g cm^{-3} (Strickland and Sollins 1987), and the carbon content in the light fraction of soil was determined by using the automatic NC analyzer. Carbon content in the heavy fraction of soil was calculated by subtracting carbon content in the light fraction from TC.

Soil moisture content at the sampling points along the line transect surveys in 2015 was measured using a gravimetric method on July 2 and 6, 2015. Soil samples (100 mL) were collected from 0 to 51 mm depth by using a stainless-steel cylinder (DIK-1801; Daiki Rika Kogyo Co., Saitama, Japan), and the weight was measured before and after drying at 100°C for 48 h. The average values of

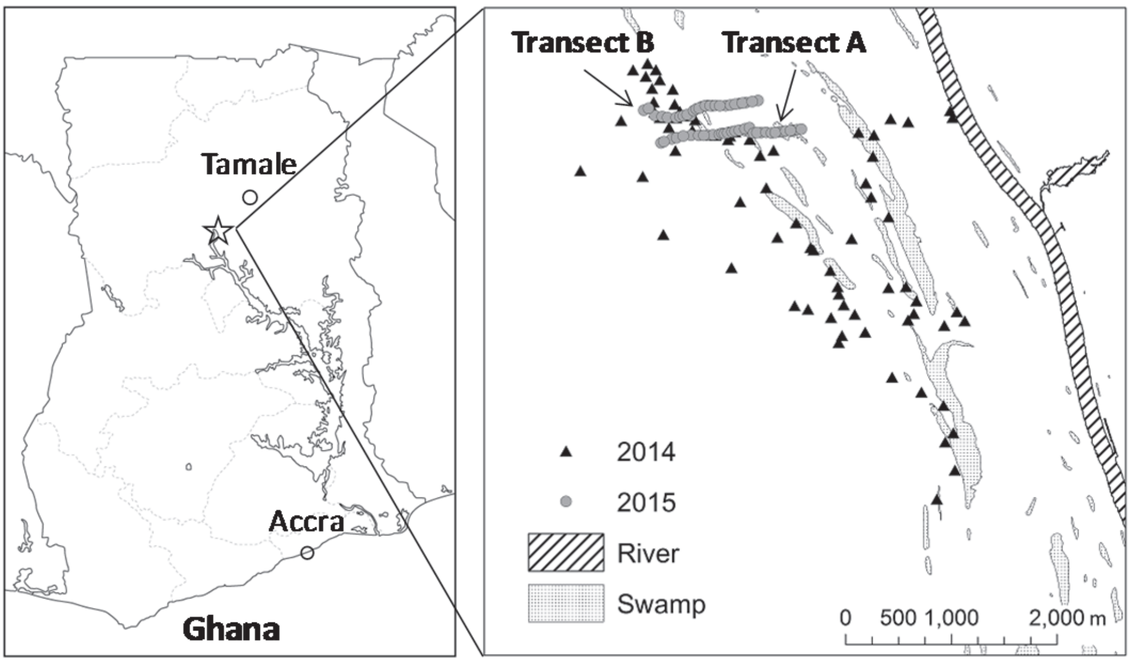

Fig. 1. Soil sampling points in 2014 and 2015 in a floodplain of the White Volta River in the Northern Region of Ghana

the two days of measurements were used for analysis.

To evaluate the relationship between soil TC content and soil fertility, aboveground plant biomass was measured. Plants within a 2 m × 2 m area with four replications were harvested from the area within a radius of about 4 meters from 58 of the 75 soil sampling points in early October 2014, and plants within a 1 m × 1 m area with four replications were harvested from 12 of the 63 soil sampling points in early October 2015. The size and percentage of plant sampling points were reduced due to a labor shortage in 2015. Harvested plants were oven dried at 100°C for 48 h and then weighed.

The color of air-dried, 2-mm sieved soil samples was measured by a soil color reader (SPAD-503; Konica Minolta, Tokyo, Japan) and expressed as a CIELAB color space. From the color parameters obtained from the CIELAB color space (L*, a* and b*), two additional parameters—chroma (C*) and hue angle (h)—were also calculated by the following formulas (Viscarra Rossel et al., 2008):

$$chroma\ (C^*) = \sqrt{(a^{*2} + b^{*2})} \quad (1)$$

$$hue\ angle\ (h) = \arctan\left(\frac{b^*}{a^*}\right)(degree) \quad (2)$$

The parameters among geographical groups were compared by using a Tukey-Kramer test or Mann-Whitney rank sum test, depending on the distribution patterns of each parameter. For non-linear regression, Dynamic Fit Wizard of SigmaPlot 13.0 was used.

Results

There were large variations in soil TC content even within a small area of the floodplain (Fig. 2). Soil TC content ranged between 4.1 and 40.1 g kg^{-1} in 2014, and between 3.7 and 54.9 g kg^{-1} in 2015, with no significant difference in soil TC content being observed in those years. According to the density fractionation of the soil samples collected in 2014, the ratio of carbon content in the heavy fraction (> 1.6 g cm^{-3}) to TC ranged between 75.9% and 97.7%, which meant that most of the carbon was in the heavy fraction of soil (Fig. 3). Soil TC content was significantly correlated with sand (r = −0.73 and −0.85 in 2014 and 2015, respectively), silt (r = 0.34 and 0.39 in 2014 and 2015, respectively), and clay contents (r = 0.76 and 0.87 in 2014 and 2015, respectively) (Table 1). When the data of both years were combined, sand, silt, and clay contents showed large variations ranging from 3.4% to 93.2%, 2.4% to 61.2%, and 2.5% to 82.4%, respectively. The values of the coefficient of variation of clay content were 64.6% and 78.7% in 2014 and 2015, respectively (Table 1). Soil TC content and aboveground plant biomass in the natural environment at the soil sampling point were significantly correlated, but the intercepts of the regression line differed significantly in both years (Fig. 4).

The topographical survey for Transects A and B in 2015 showed there were many small uphill and downhill areas around the swamps, with only a few meters'

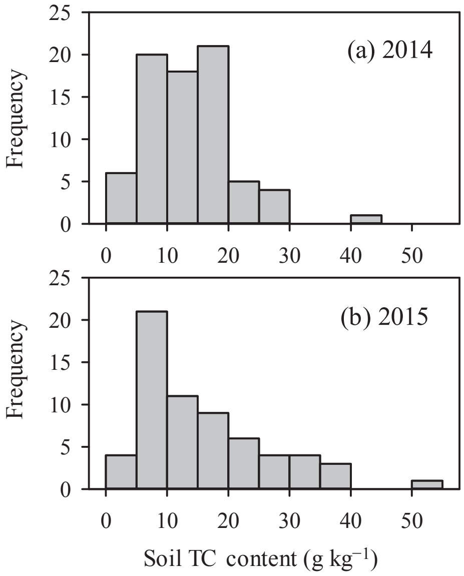

Fig. 2. Histogram of soil TC content in (a) 2014 (n = 75) and (b) 2015 (n = 63) in a floodplain of the White Volta River in the Northern Region of Ghana

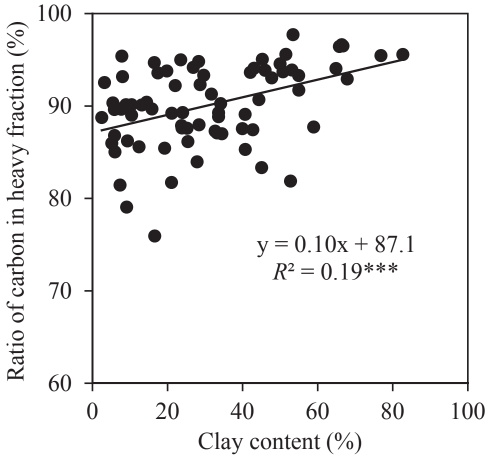

Fig. 3. Relationship between clay content and ratio of carbon in heavy fraction of soil (> 1.6 g cm^{-3}) to TC (n = 75) in 2014
***: $P < 0.001$

difference in elevation (Fig. 5). Soil TC content in Slope (10.0 g kg^{-1}) was significantly lower than that in Others (26.1 g kg^{-1}) (Table 2). Topographic parameters measured by the surveying instrument explained the variations in soil TC content (Fig. 6). There was a significant negative relationship between relative elevation and soil TC content (R^2 = 0.16; P < 0.01), and the relationship became more significant when data from Slope were excluded (R^2 = 0.33; P < 0.01) (Fig. 6 (a)). Even at the same elevation, Slope had lower soil TC content than Others (Fig. 6 (a)). The soil TC content showed significant exponential decay with downward gradients (R^2 = 0.41; P < 0.001) (Fig. 6 (b)). Soil moisture content and clay content were also affected by topographic parameters, and showed a significant exponential decay with downward gradients (R^2 = 0.39 and R^2 = 0.43, respectively; P < 0.001 for each) (Fig. 6 (c) and (d)). Both have a significant correlation with soil TC content (r = 0.84 and 0.87, respectively; P < 0.001 for each) (Fig. 6 (e) and (f)).

There were also large variations in soil color parameters among the samples even within a small area of the floodplain (Fig. 7). Soils in Slope had significantly larger values of L*, a*, b* and C*, and a significantly lower value of hue angle than those in Others (Table 3). All of the soil color parameters were significantly correlated with soil TC content. Among those parameters, chromaticity values such as a*, b* and C* had higher relationships with soil TC content than did lightness value (L*) and hue angle (h).

Discussion

The mean values of soil TC content were 13.7 g kg^{-1} in 2014 and 16.1 g kg^{-1} in 2015, and thus comparable to previously reported values of soil TC, ranging from 6.2 to 16.3 g kg^{-1} (averaged values of some arable lands in each floodplain), in floodplains in West Africa (Buri et al. 1999). Soil TC content of over 20.0 g kg^{-1} was frequently observed at some locations in the present study, which is comparable to or much higher than that in other rice growing environments in West Africa, including irrigated lowland rice fields, which generally have SOC or soil TC content ranging from 13.0 to 24.0 g kg^{-1} on average in some fields (Becker and Johnson 2001, Ofori et al. 2005).

In the present study, there was a significant positive relationship between soil TC content and plant biomass in the natural environment (Fig. 3). The variation in plant biomass would arise not only from variations in soil TC content but also from other factors such as water conditions. Tsujimoto et al. (2013), however, conducted

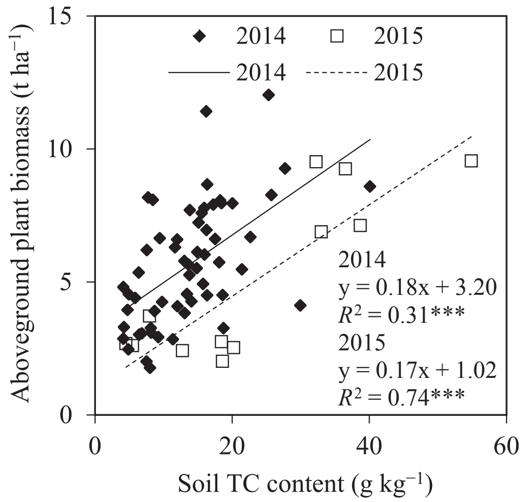

Fig. 4. Relationship between soil TC content and above ground plant biomass in a natural environment in 2014 (n = 58) and 2015 (n = 12)
***: P < 0.001

Table 1. Particle size distribution and correlation coefficient to soil TC content for the soil samples in 2014 (n = 75) and 2015 (n = 63)

	Average	Minimum	Maximum	Coefficient of variation (%)	Correlation coefficient to soil TC content
2014					
Sand	44.0	3.4	93.2	60.8	-0.73***
Silt	24.9	3.2	50.2	49.5	0.34**
Clay	31.1	2.5	82.7	64.6	0.76***
2015					
Sand	51.0	3.9	91.2	54.9	-0.85***
Silt	21.3	2.4	61.2	62.7	0.39**
Clay	27.7	2.5	78.7	77.0	0.87***

**: P < 0.01; ***: P < 0.001

pot experiments growing rice using soils from the same research area under flooded conditions to exclude the possible effects of water conditions, and showed a significant contribution of soil TC content to rice growth. These findings suggested that soil TC content could be an indicator of potential rice yield in the river floodplains in West Africa. Homma et al. (2003) demonstrated that soil TC content contributed to high rice yield in rainfed lowland paddies in Northeast Thailand.

At the same time, our study showed that there were large variations in TC even within a small area in the floodplain (Fig. 2). The average values of soil TC content in Slope (10.0 g kg^{-1}) were significantly smaller than in Others (26.1 g kg^{-1}) (Table 2), and downward gradients explained the variation of soil TC content much more than relative elevation (Fig. 6 (a) and (b)). On such slopes of 0.3%, soil TC content sharply decreased to less than 20.0 g kg^{-1} (Fig. 6 (b)). The previous study conducted in the same area found no significant relationship between soil TC content and slopes (Tsujimoto et al. 2013). However, Tsujimoto et al. (2013) used satellite images for the estimation of topography, and the resolution of a global digital elevation model used in this study—ASTER-GDEM ver. 2 with 30-meter postings, vertical accuracy of 0.5 m, and widely prevalent 1 x 1 degree tiles—was not sensitive enough to delineate small uphill and downhill inclines in the study area. Most of the carbon in the soil was in the heavy fraction (90.1% on average) of soil (> 1.6 g cm^{-3}) (Fig. 3). John et al (2005) also showed that the heavy fraction of soil in grasslands made a greater contribution to soil TC content (95.0%, 0-10 cm top soil), whereas in forest environments its contribution to soil TC content is only 65.0% (0-7 cm top soil). The differences in the contributions of carbon in light or heavy fractions to soil TC content between forest and grassland ecosystems would be caused by the litter quality and microbial activity in soil. Clay particles are easily translocated to, and accumulate in depressional sites by erosion (Lal 2005). Our results suggested that microtopography affected the soil moisture content (Fig. 6 (c)) and clay content (Fig. 6 (d)). Clay content also showed a large variation, and would contribute to the

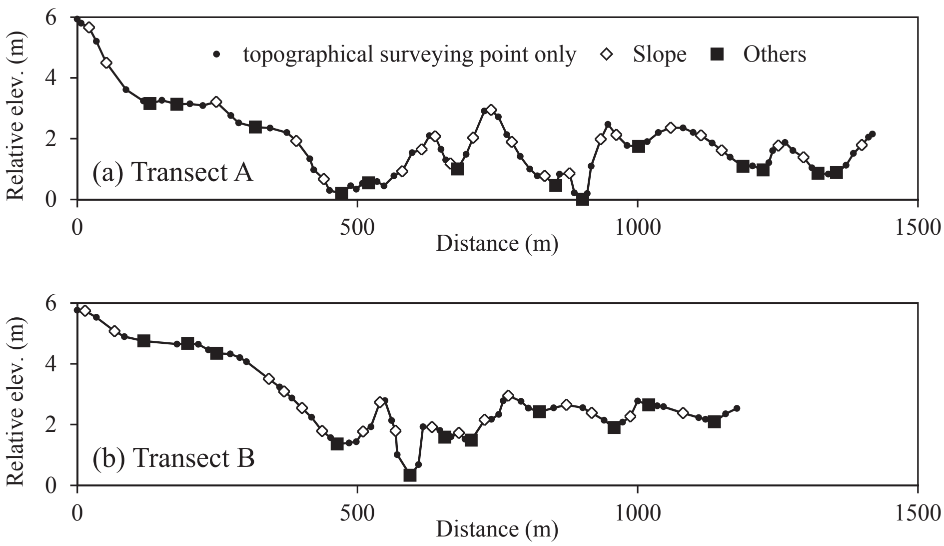

Fig. 5. Relative elevation of topographical surveying points in (a) Transect A and (b) Transect B, and soil sampling points in 2015

Soil sampling points were categorized into two topographical groups: Slope and Others. For further information, see the text.

Table 2. Average values of soil TC content and particle size distribution for each geographical group in 2015

	n	Soil TC content (g kg^{-1})	Sand (%)	Silt (%)	Clay (%)
Slope	39	10.0±4.1b	69.1±14.9a	15.2±9.3b	15.7±9.2b
Others	24	26.1±10.0a	21.8±17.5b	31.1±13.1a	47.1±21.2a

*Mean value with standard deviation. Values with the same letter are not significantly different from each other (Mann-Whitney rank sum test for soil TC content, Sand and Clay; Tukey-Kramer test for Silt, $P < 0.05$).

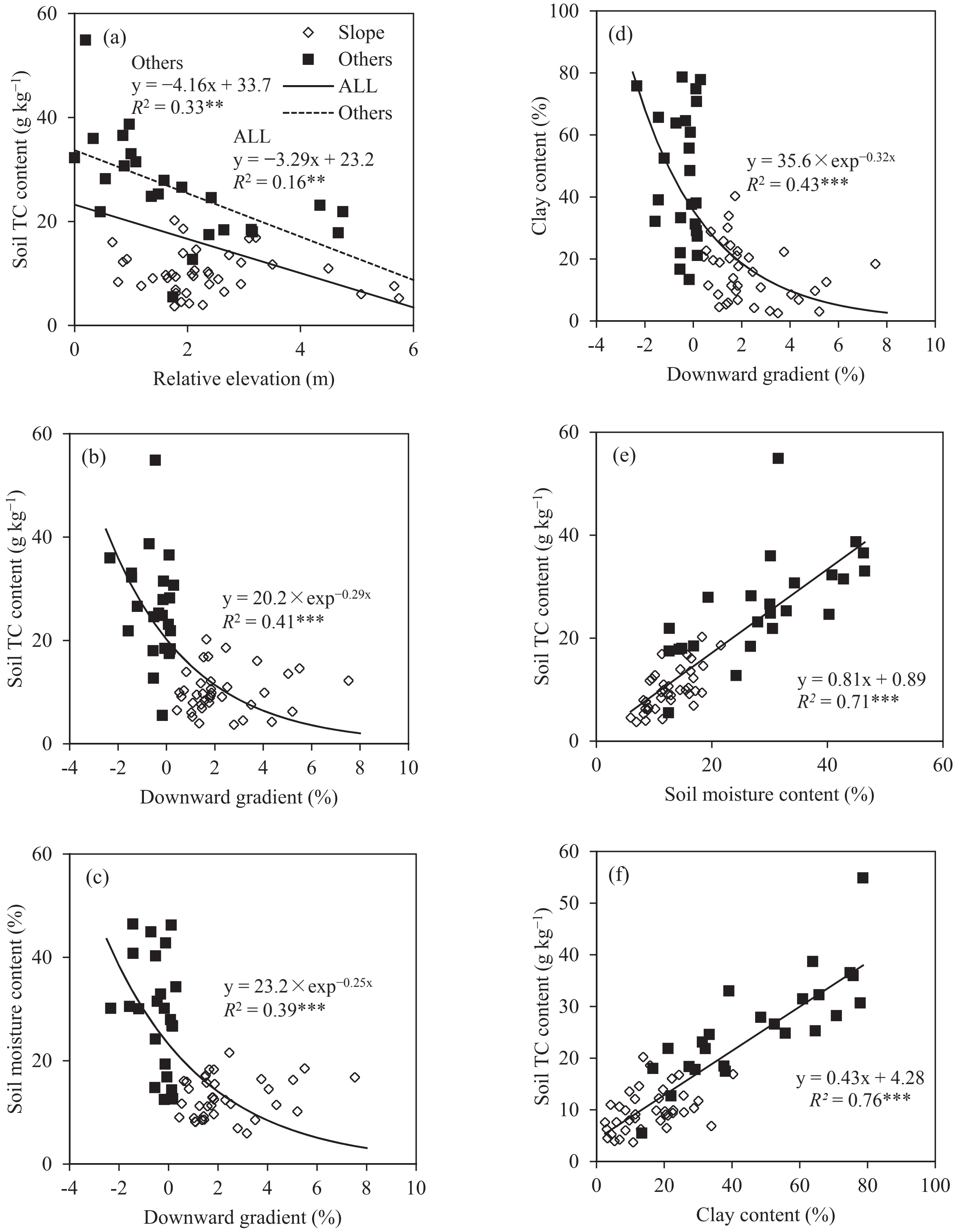

Fig. 6. Relationship between (a) relative elevation and soil TC content, (b) downward gradient and soil TC content, (c) soil moisture content and (d) clay content, (e) soil moisture content and soil TC content, and (f) clay content and soil TC content in 2015

Negative values of downward gradient mean that the gradients to both sides were acclivitous. For further information, see the text.

**: $P < 0.01$; ***: $P < 0.001$

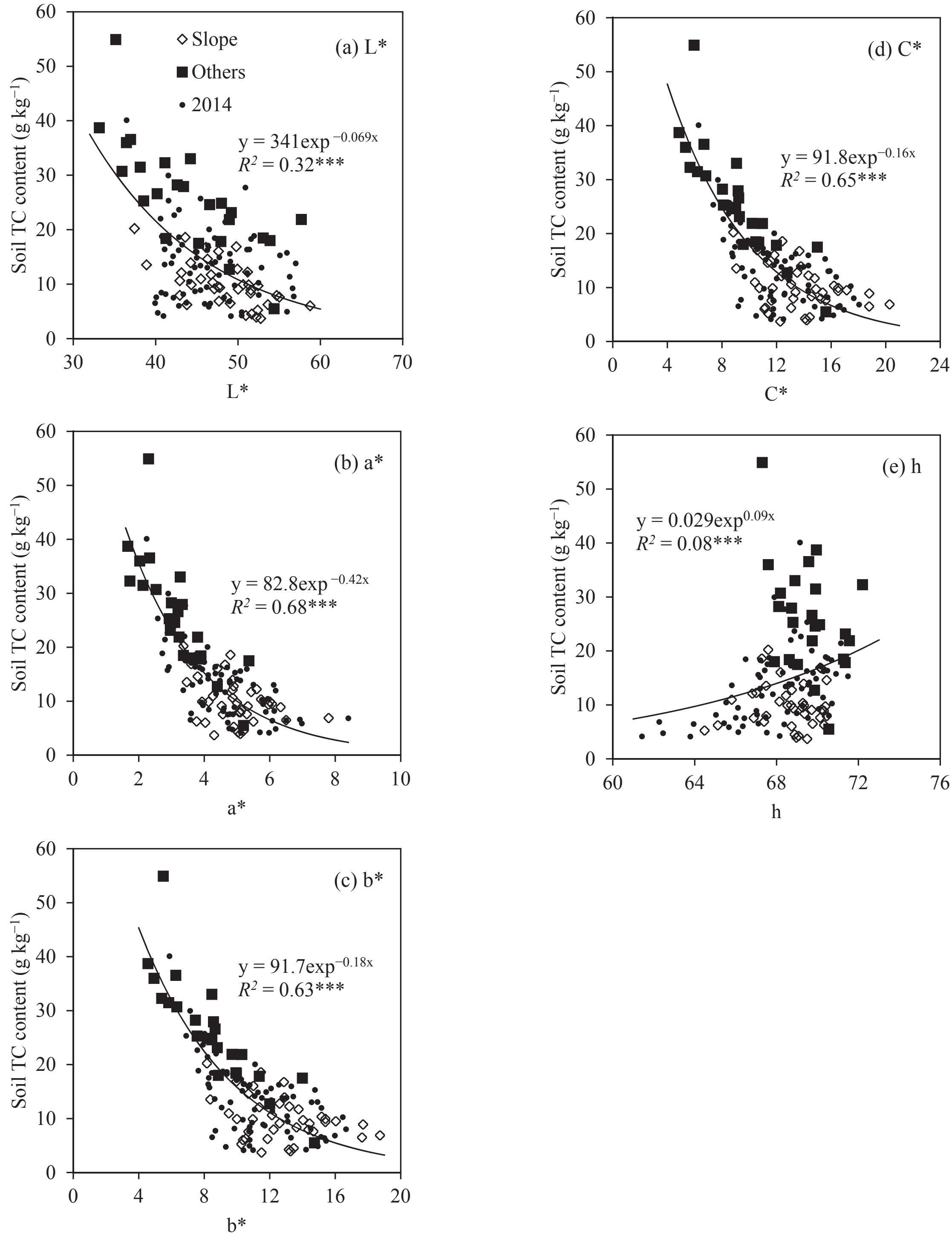

Fig. 7. Relationship between soil color parameters and soil TC content

L*: lightness coordinate; a*: red/green coordinate; b*: yellow/blue coordinate; C*: chroma coordinate; h: hue angle.
***: $P < 0.001$

Table 3. Average values of soil color parameters for each geographical group in 2015

	n	L*	a*	b*	C*	h
Slope	39	48.4±4.5a	5.0±0.9a	12.7±2.5a	13.7±2.6a	68.6±1.5b
Others	24	44.2±6.8b	3.2±1.0b	8.6±2.7b	9.1±2.8b	69.6±1.3a

L*: lightness coordinate; a*: red/green coordinate; b*: yellow/blue coordinate; C*: chroma coordinate; h: hue angle.
Mean value with standard deviation. Values with the same letter are not significantly different from each other (Mann-Whitney rank sum test for L*; Tukey-Kramer test for a*, b*, C* and h, $P < 0.05$).

topographical variation in soil TC content (Table 1 and Fig. 6 (f)). A similar case was observed in a previous study in rainfed lowland rice fields in Asia. Homma et al. (2003) showed the accumulation of clay in the lower part of a mini-watershed in Northeast Thailand.

There were significant relationships between soil moisture content and soil TC content in the present study (Fig. 6 (e)), which also suggested that clay particles were translocated to the depressions through erosion by either rainwater or flooding. This relationship also suggested that high crop yields could be expected in depressions, but at the same time, submergence-induced damage should be taken into account. It could be said that depressions are high-risk, high-return environments. The utilization of such environments would require such submergence stress measures as introducing a genotype with submergence tolerance (Xu 2006, Fukao et al. 2011) or crop management to avoid submergence stress, such as seed hydropriming (Matsushima and Sakagami 2013). In any case, an appropriate crop production strategy would be required depending on the microtopography.

Our results showed that soil color is another option to identify locations with high soil TC content (Table 3 and Fig. 7), as has been shown in a previous report (Moritsuka et al. 2014). The variation of soil color parameters in our study area was very large, and might be comparable to the variation observed on a nationwide scale. For example, L* ranged from 33.2 to 58.5 in our study, while Moritsuka et al. (2014) showed that L* of agricultural soils collected throughout Japan ranged from 32.1 to 68.6. Previous reports suggested an empirical rule that the lightness value (L*) has a strong negative relationship with SOC or soil TC content, and would be the best indicator for the estimation of SOC or soil TC content (Konen et al. 2003, Viscarra Rossel et al. 2006, Moritsuka et al. 2014). Schulze et al. (1993) reported that the humic acid fraction was responsible for the dark color of the soil. In some cases, an equally significant relationship was also observed between soil SOC content and Munsell chroma (Konen et al. 2003). In our study, chromaticity values such as a*, b* and C* had stronger relationships with soil TC content than did L*, and thus became better indicators for the estimation of soil TC content (Fig. 7). Many studies have reported that iron oxides are responsible for the chromaticity value of the soil color (Schwertmann 1993, Scheinost and Schwertmann 1999). In the case of our soil samples displaying a significant positive correlation between soil TC content and clay (Fig. 6 (f) and Table 1)), most of the total carbon in the heavy fraction is expected to be adsorbed on the surface of clay-sized iron oxides in the soil. The relatively constant hue angles of our samples (Fig. 7 and Table 3) further suggested that the colors of iron oxides were similar among the sampling points. Hence, the significant negative correlations between soil TC content and chromaticity values (Fig. 7) are presumably because the intrinsic reddish color of iron oxides was masked by soil carbon and diminished in accordance with an increase of soil TC content. Further study is required to determine whether these relationships between soil TC content and soil color parameters are applicable to other floodplains in West Africa.

Conclusions

A large variation in soil TC content was observed even within a small area in the floodplain ecosystem in the Northern Region of Ghana, which could be caused by the microtopography. When considering whether to start crop cultivation on floodplains in this area, different strategies would be required depending on the microtopography. In addition to the gradient ratio, the chromaticity value of soil color was a better indicator of soil TC content than the lightness of soil color. This was a case study from a single floodplain in northern Ghana. In order to apply the results to other floodplain areas in West Africa, further study is required.

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