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Assessing Soil Organic Carbon, Soil Nutrients and Soil Erodibility under Terraced Paddy Fields and Upland Rice in Northern Thailand

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Abstract: Terracing is the oldest technique for water and soil conservation on natural hilly slopes. In Northern Thailand, terraced paddy fields were constructed long ago, but scientific questions remain on how terraced paddy fields and upland rice (non-terraced) differ for soil organic carbon (SOC) stocks, soil nutrients and soil erodibility. Therefore, this study aims to evaluate and compare SOC stocks, soil nutrients and soil erodibility between terraced paddy fields and upland rice at Ban Pa Bong Piang, Chiang Mai Province, Thailand. Topsoil (0–10 cm) was collected from terraced paddies and upland rice fields after harvest. Results showed that SOC stocks were 21.84 and 21.61 Mg·C·ha^{-1} in terraced paddy and upland rice fields, respectively. There was no significant difference in soil erodibility between terraced paddies (range 0.2261–0.2893 t·h·MJ^{-1}·mm^{-1}) and upland rice (range 0.2238–0.2681 t·h·MJ^{-1}·mm^{-1}). Most soil nutrients (NH_4-N, NO_3-N, available K, available Ca and available Mg) in the terraced paddy field were lower than those in the upland rice field. It was hypothesized that the continuous water flows from plot-to-plot until lowermost plot caused dissolved nutrients to be washed and removed from the flat surface, leading to a short period for accumulating nutrients into the soil. An increase in soil erodibility was associated with decreasing SOC stock at lower toposequence points. This study suggested that increasing SOC stock is the best strategy to minimize soil erodibility of both cropping systems, while proper water management is crucial for maintaining soil nutrients in the terraced paddy field.

Keywords: soil organic carbon; soil erodibility; terraced paddy field; upland rice; Thailand

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1. Introduction

Globally, the soil organic carbon (SOC) pool has been a key challenging subject since it could generate either positive or negative feedback on atmospheric CO_2 changes [1–3]. As soil stores three-times more carbon than the atmosphere, many land uses have endangered soil degradation and also the related SOC sequestration potential [4,5], especially under agricultural systems [6]. In agricultural land, the SOC in soils is often depleted but also has the potential to sequester carbon (C) under agricultural practices [7,8]. In addition, SOC plays a role indicator of soil quality, as it contributes to soil biochemical and physical functions that are essential for plants and microorganisms [9]. Hence, agricultural management has become increasingly highlighted as a high-potential tool for mitigating climate changes and adapting to changing climate [10,11]. Concerning agriculture in mountainous areas, the slope gradient is the key factor affecting SOC dynamics and soil quality [12–14], while soil losses and soil erosion are highly correlated with slope steepness [15]. Budry and Curtis [16] and Tadele et al. [17] indicated that soil erosion causes land degradation that is the most serious problem for the farmer in tropical highlands, resulting in decreasing soil fertility and crop yield losses. Therefore, it is challenging to investigate the variation of SOC, soil nutrients and soil erodibility under different land management techniques in hilly and mountainous areas.

The most effective engineering measure for slope management is terracing, which, when well designed and appropriately maintained, has been reported to reduce soil and water loss [18–21]. Terracing is the oldest technique for water and soil conservation on natural hilly slopes [22,23], and some terraces were constructed in Southeast Asia more than 5000 years ago [24–27]. Under the terracing system, mountainous terrains are managed into narrow graduated steps to enable crop growing and management practices [28]. The terracing system plays a vital role in soil and water conservation not only by directly creating many microtopographical and specific hydrological pathways [29–31] but also by reducing slope gradient and connectivity of overland runoff [32,33]. In terraces, divided sections of cropland with gradient slopes also help farmers to alleviate flooding and erosion, while improving other ecosystem services, including food security [34], recreation [35] and C sequestration [36]. Previous studies, however, have found varying levels of SOC in different terraced sites. Xu et al. [37] revealed that mean SOC densities at the 0–60 cm soil depth in terraces were the highest when compared to forestland, grassland and sloping cropland. Meanwhile, Zhang et al. [38] presented the idea that soil erosion and cropping contributed to variations of SOC and TN losses along the sloping terrace. Inappropriate terraces, often randomly designed by local farmers, were also marked as having a higher risk of soil erosion and severe landslides caused by the unstable structure [39,40].

In Thailand, terraced paddy fields have been widely distributed in Northern Thailand under contribution by the Royal Development Project since 2003 [41]. Even though terraced paddy fields have been determined to be a highland sustainable agriculture approach [42], the surface runoff and soil and nutrient losses need to be examined [43]. However, the investigation of SOC stock, soil nutrients and soil erodibility under rice terraces is still lacking, indicating that it would be desirable to find out how terraced paddy field and upland rice differ in SOC stock, soil nutrients and soil erodibility. To fill these gaps, our study aims to evaluate and compare (1) SOC stock and soil nutrients and (2) soil erodibility between terraced paddy fields and upland rice as well as the different potentials of rice terraces among toposequences. This study could contribute to a clearer understanding of the relevant issues of hilly and mountainous areas.

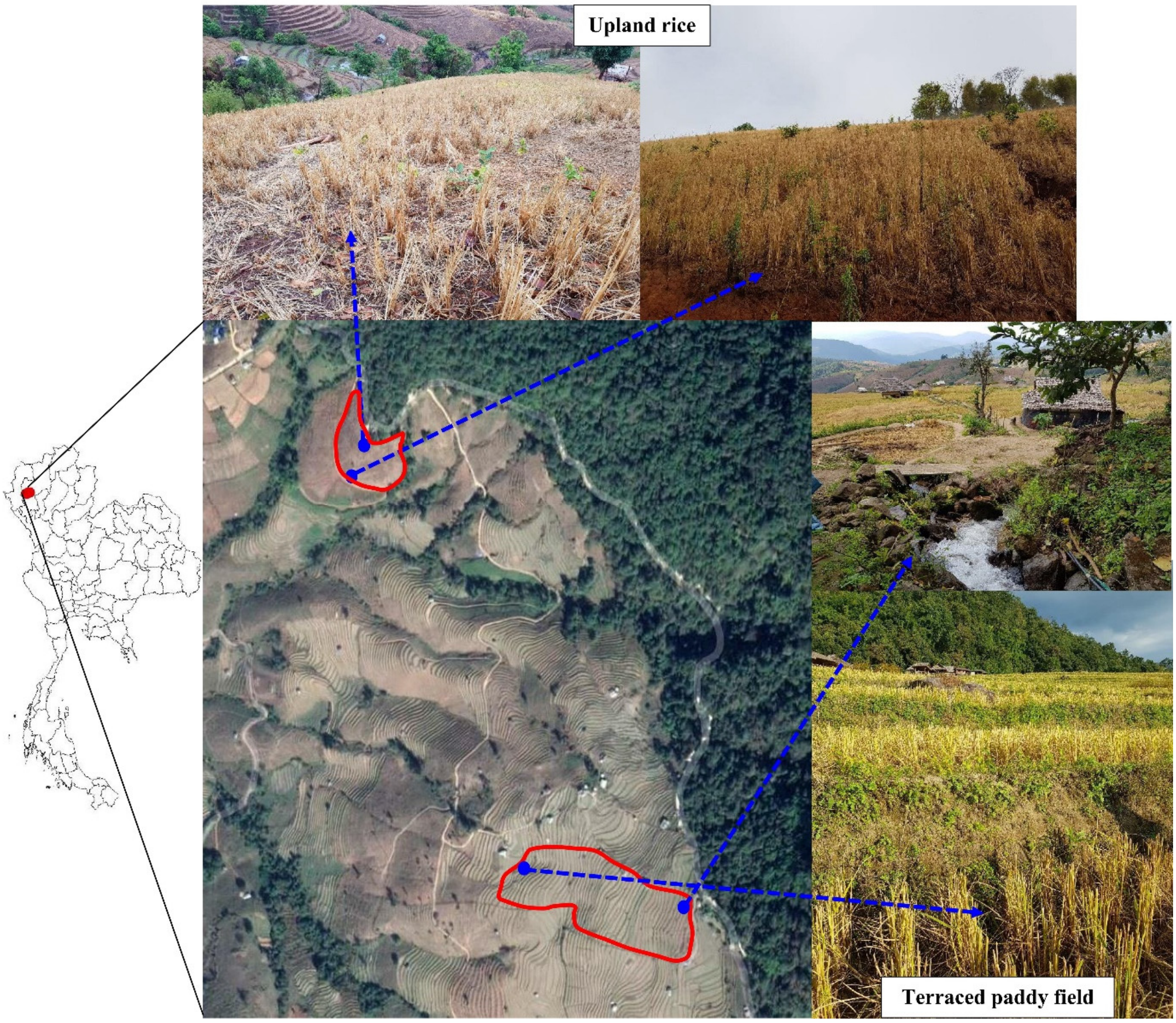
2. Material and Methods

2.1. Study Area and Site Selection

The study area was carried out at Ban Pa Bong Piang, Chang Khoeng Subdistrict, Mae Chaem District, Chiang Mai Province, Northern Thailand (Figure 1a). The rainy season of Chiang Mai Province is from May to October. The average annual temperature ranged between 20 and 35 °C, while the average annual rainfall ranged between 600 and >1000 mm. The topography of Ban Pa Bong Piang is relatively steep with an elevation of 800 to 1400 m above sea level (m a.s.l.). Most of the farmers are Karen people who mainly cultivate upland rice and terraced paddy fields once a year. Cultivation begins in June for land preparation, and then rice planting is in July. Harvest occurs around mid-October to the beginning of November, and then the land is left fallow from December to May.

In this study, the similarities of original geography, soil formation and microclimate conditions were well considered for site selection. A terraced paddy field located upstream of the natural water canal for cultivation was selected (18°32′02.8″ N, 98°26′48.8″ E). This terraced paddy field (level terrace type) was constructed since 1982 (40 years ago), and the terrace risers or walls were built of soil. Selecting this terraced paddy field avoided nutrient and sediment discharges from other terraced upland rice fields. Its elevation ranged between 975 and 1014 m a.s.l. with slopes of 5–17% (Figure 1b). The widths of the flat section of the terrace ranged from 3 to 5 m, and the heights of the terrace riser or wall were between 0.5 and 0.8 m.

Meanwhile, an upland rice field (non-terraced) was selected (18°32′22.2″ N, 98°26′34.7″ E) as the comparison field, with an elevation of 908–935 m a.s.l. and 19–26% slopes. Upland rice is as traditional rice cultivation in this area, which has been cultivated for more than 70 years. This field has only grown upland rice once a year, whereas most fields comprise the upland rice–maize system (Figure 1c).



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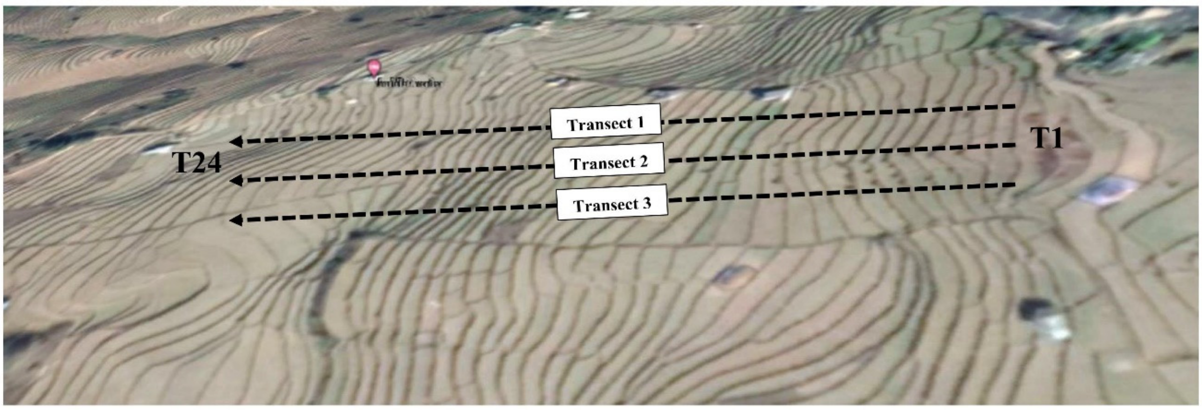

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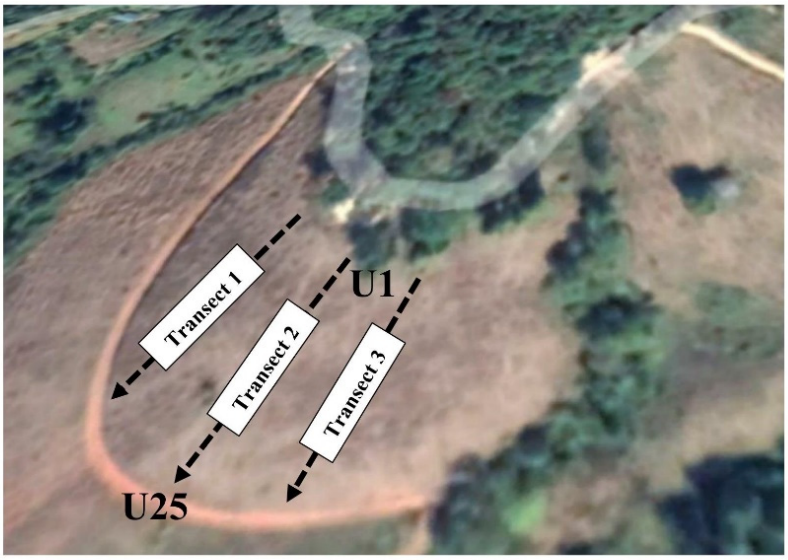


(**c**)

Figure 1. Study area. (**a**) Overall study area, (**b**) terraced paddy field and (**c**) upland rice. The aerial images were taken from Google maps on 25 February 2020. The photos were taken on 14 November 2020 by Noppol Arunrat.

2.2. Management Practices

Farm management practices were recorded from farm owners in November 2020. At the terraced paddy field, the transplanting method was used for rice cultivation. The nursery field was prepared in May. Rice seeds were placed into bags and soaked in water for 24 h, and then rice seeds in bags were drained and dried for 24 h in a shady area until small roots appeared at the end of the seeds. Then, pregerminating rice seeds were sown by hand in the nursery field. In June, puddling was prepared by a 15-horsepower tractor for all terraced paddy fields. The rice plants were removed from the nursery field and transplanted in terraced paddy fields by hand. The N, P_2O_5 and K_2O chemical fertilizers were applied using 46-0-0 (93.8 kg·ha^{-1}), 16-16-8 (156.3 kg·ha^{-1}), and 16-20-0 (156.3 kg·ha^{-1}). Harvesting was performed in October by hand. All rice residues were left in the field without burning.

Upland rice cultivation began in May with land preparation including removing weeds and vegetation. The no-tillage method was used due to the difficulty of using any machines on the hillslopes, whereas the drilling method was usually applied for planting. A hoe was used to dig the soil at a 10 cm depth, and then rice seeds were dropped by hand. The N, P_2O_5 and K_2O chemical fertilizers were applied, consisting of 16-20-0 (156.3 kg·ha^{-1}) and 16-16-8 (156.3 kg·ha^{-1}). Harvesting was performed in November by hand, and all rice residues were left in the field without burning.

2.3. Soil Sample Collection and Laboratory Analysis

Topsoil was collected at depth 0–10 cm on terraced paddy and upland rice fields after harvest in November 2020. At each field, three transects were designed with a distance of 7–8 m from one transect to another; then, the soil samples were collected from each point of each transect. At the terraced paddy field, the uppermost toposequence point was called T1, followed by T2, T3, . . . , and T24 (lowermost toposequence point), respectively (Figure 1b). At each point of each transect, the soil sample was collected using a mini shovel, then 1 kg of soil sample was packed into a plastic bag. Thus, 72 soil samples were obtained from the terraced paddy field. At the upland rice field, the uppermost toposequence point was called U1, followed by U2, U3 . . . , and U25 (lowermost toposequence point), respectively (Figure 1c). A total of 75 soil samples were gathered from the upland rice field. A compass was used to identify the slope gradient of each soil sample point. This is because the slope gradient influences the rate of runoff on the soil's surface, soil erosion and the movement of nutrients. Steel soil cores (5.0 cm width × 5.5 cm length) were used to collect soil samples from both fields for soil bulk density analysis.

At the laboratory, soil bulk density was measured by the dry weight per volume of soil core after drying in an oven at 105 °C for 24 h. All soil samples were air-dried at room temperature for 7–14 days, and then the dry soils were crushed and passed through a 2 mm sieve. Soil texture was determined by a hydrometer. Electrical conductivity (ECe) in saturation paste extracts was measured by an EC meter [44]. Soil pH was determined in a 1:2.5 soil to water mixture by a pH meter [45]. The cation exchange capacity (CEC) was determined by the NH_4OAc pH 7.0 method. Organic carbon (OC) was determined following the method described by Walkley and Black [46] using potassium dichromate ($K_2Cr_2O_7$) in sulfuric acid and reported as organic matter (OM) by multiplying with 1.724. Ammonium nitrogen (NH_4-N) and nitrate–nitrogen (NO_3-N) were measured by the KCL extraction method. Available phosphorus was determined based on the molybdate blue method (Bray II extraction) [47]. Available potassium, calcium and magnesium were extracted by NH_4OAc pH 7.0 and measured by atomic absorption spectrometry [48].

2.4. Soil Organic Carbon Calculation

The SOC stock was calculated using the following equation:

$$\text{SOC stock } = OC \times BD \times L, \tag{1}$$

where SOC is the soil organic carbon stock (Mg·C·ha^{-1}), *OC* is organic carbon (%), *BD* is bulk density (g·cm^{-3}) of soil and *L* is soil thickness (10 cm for this study).

2.5. Soil Erodibility Calculation

Among the estimators of the soil erodibility (*K*-value), the nomograph by Wischmeier et al. [49], the *K*-value in the Environmental Policy Integrated Climate (EPIC) model [50] and a formula proposed by Shirazi and Boersma [51] were widely used. Although there is no study in Thailand, several studies in China (e.g., Du et al. [52]; Wu et al. [53]; Chen et al. [54]; and Liu et al. [55]) achieved scientific results and revealed that the method of the EPIC model is reasonable to calculate *K*-value. Therefore, the *K*-value in our study area was calculated by following the EPIC model equation developed by Williams et al. [50] and Sharpley and Williams [56]:

$$\begin{aligned} K = \{0.2 + 0.3\exp[-0.256\mathrm{SA}(1-0.01\mathrm{SA})]\}\left(\frac{\mathrm{SI}}{\mathrm{SI}+\mathrm{CL}}\right)^{0.3}\left[1-\frac{0.25\mathrm{C}}{\mathrm{C}+\exp(3.72-2.95\mathrm{C})}\right] \\ \times\left\{1-\frac{0.7\left(\frac{1-\mathrm{SA}}{100}\right)}{\left(\frac{1-\mathrm{SA}}{100}\right)+\exp\left[-5.51+22.9\left(\frac{1-\mathrm{SA}}{100}\right)\right]}\right\}\times 0.1317 \end{aligned} \tag{2}$$

where SA is the fraction of sand (%), SI is the fraction of silt (%), CL is the fraction of clay (%), C refers to the organic carbon content (%) and 0.1317 is the conversion factor for United States business units (t acre h/100 acre/ft/tanf/in) to the international system of units. Thus, the unit of *K* value is t·h·MJ^{-1}·mm^{-1} (metric ton (t) × hour (h)/megajoule (MJ) × millimeter (mm)).

2.6. Statistical Analysis

The differences in soil properties between the terraced paddy and upland rice fields were compared by using independent *t*-tests. One-way ANOVA was employed to test for the differences in soil parameters within the group. The correlation between soil properties in terraced paddy samples and upland rice samples was separately investigated by Pearson's correlation coefficient. Meanwhile, principal components analysis (PCA) was applied to analyze the factors that influence the SOC stocks and soil erodibility under the terrace and upland rice paddies. The variables with high collinearity, correlation coefficients $|r| > 0.7$, were cut off in Pearson's correlation analysis. These statistical analyses and visualization were performed using R environment (v.4.0.2) with packages such as 'agricolae' [57], 'ggplot2' [58] and 'factoextra' [59]. Moreover, trend analysis was performed to analyze the variation of soil properties along the slope gradient using SPSS (v. 20.0).

3. Results and Discussion

3.1. Variation of Soil Properties under Terraced Paddy Field and Upland Rice

The proportion of topsoil textural composition of each sample of terraced paddy field and upland rice is shown in Figure 2. In the terraced paddy field, topsoils predominantly contained a high proportion of sand particles (49.3–67.1%), which varied significantly among different toposequences ($p < 0.01$, Table 1) from sandy loam to loam. Meanwhile, 29.1–47.9% of the sand proportions of topsoils varied from sandy clay loam to clayey loam in the upland rice field. Similarly, silt and clay contents were significantly different between the terraced paddy and upland rice fields ($p < 0.01$, Table 1), and higher average values were found under upland rice compared to terraced paddy fields (Table 1). In both cropping systems, there was a large difference in the particle size distribution depending on toposequence, as shown in Figure 3.

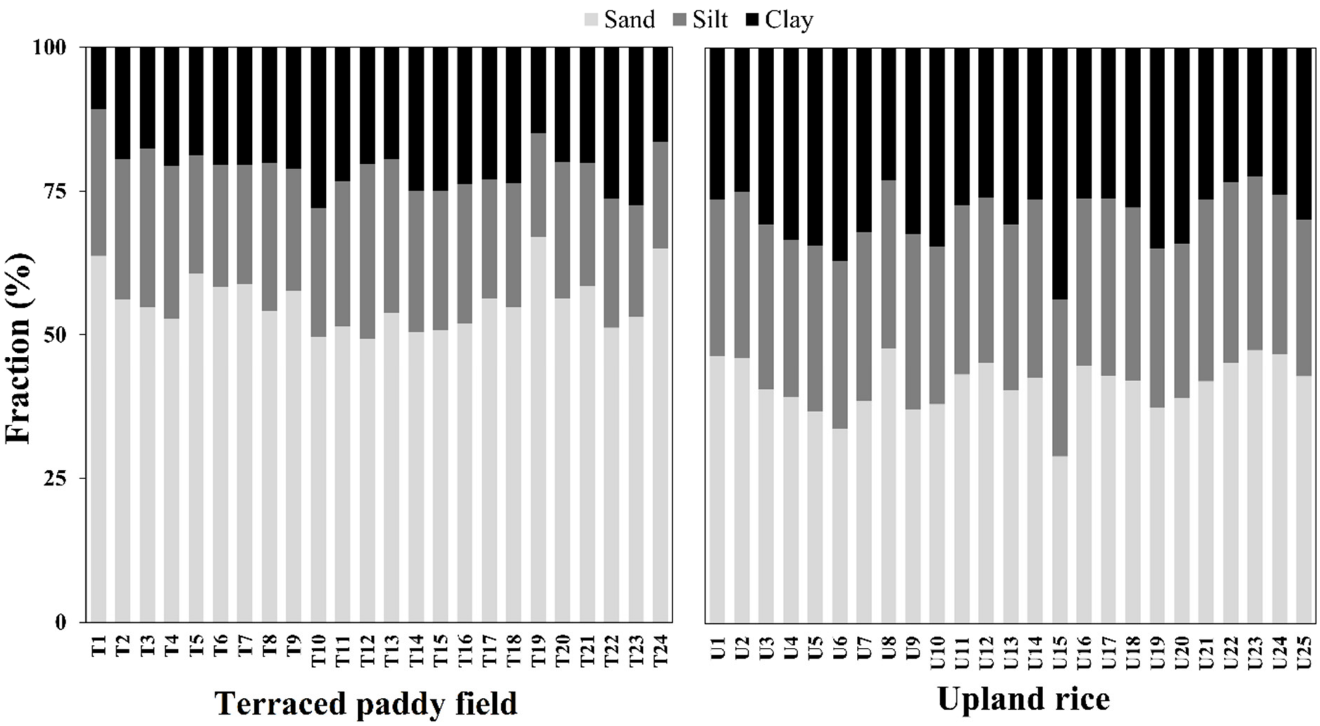


Figure 2. Particle size distribution for terraced paddy field and upland rice areas.

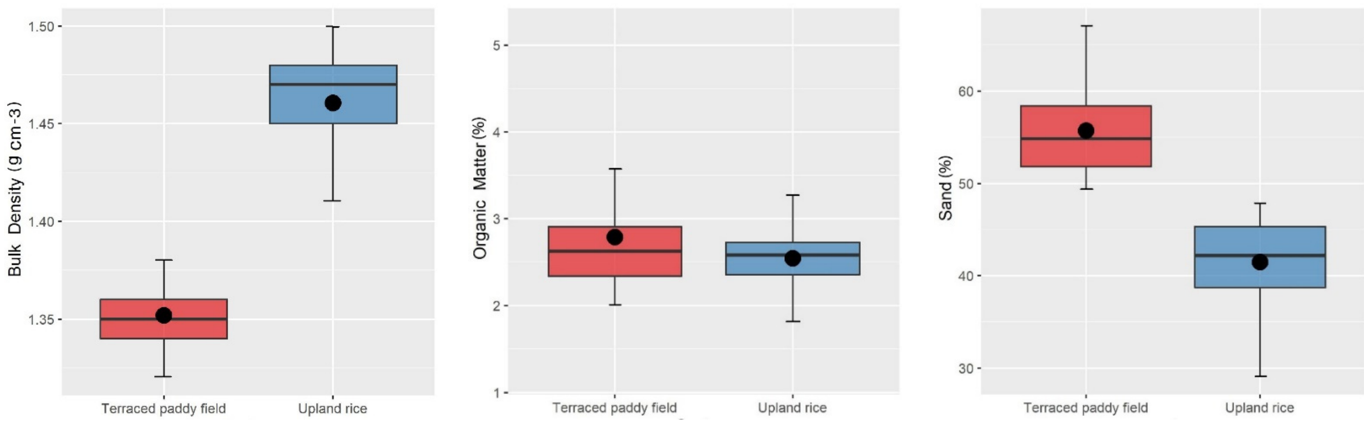
From the independent *t*-test in Table 1, the terrace paddy soils showed significantly higher values ($p < 0.05$) of OM, EC_e, available P and sand fraction than the upland rice soils. In addition, there were significantly lower ($p < 0.01$) values for bulk density, CEC, NH_4-N, NO_3-N, available K, available Ca, available Mg, silt fraction and clay fraction in terraced paddy than upland rice soils. However, there was no significant difference in pH, SOC and soil erodibility between these two cropping systems ($p > 0.05$).

In the same cropping system, more variation in soil properties for each toposequence was mostly found in terraced paddy soils rather than upland rice soils. Soil pH, OM, SOC, EC_e, CEC, available P, available Ca, available Mg, silt and clay contents as well as soil erodibility significantly fluctuated in different toposequence patches ($p < 0.05$) under terraced paddy cultivation (Table 1 and Figure 3). Meanwhile, significant differences ($p < 0.05$) of bulk density, NH_4-N, NO_3-N, available P, available K and available Mg were detected under the upland rice cultivation area (Table 1 and Figure 3). It is noteworthy that the available soil base elements responsively fluctuated under both upland rice and terrace paddy fields in different toposequences, especially available Ca (varied in ranges of 590.9–2302.2 mg·kg^{-1} and 198.7–984.2 mg·kg^{-1}, respectively, Figure 3).

Table 1. Independent *t*-test comparing soil properties between upland rice (n = 75) and terraced paddy field samples (n = 72).

Soil Properties	Upland Rice				Terraced Paddy Field				Between Group	
	Mean	Std	F	*sig.*	Mean	Std	F	*sig.*	*t* Value	*p* Value
pH	5.36	0.29	1.45	0.23	5.31	0.20	5.06	0.03	−1.15	0.25
Bulk density (g·cm^{-3})	1.46	0.03	4.60	0.04	1.35	0.01	3.43	0.07	−32.24	<0.01
Organic matter (%)	2.55	0.33	0.33	0.57	2.79	0.85	128.70	<0.01	2.29	0.02
Soil organic carbon (Mg·C·ha^{-1})	21.61	2.72	0.79	0.38	21.84	6.52	132.20	<0.01	0.28	0.78
Electrical conductivity (dS·m^{-1})	0.24	0.05	0.06	0.81	0.29	0.06	6.08	0.02	5.32	<0.01
Cation exchange capacity (meq·100 g^{-1})	13.87	1.75	0.07	0.79	8.50	1.45	145.70	<0.01	−20.21	<0.01
NH_4-N (mg·kg^{-1})	29.05	7.36	59.87	<0.01	22.85	6.68	0.59	0.45	−5.34	<0.01
NO_3-N (mg·kg^{-1})	17.44	4.52	14.16	<0.01	14.81	4.03	1.24	0.27	−3.72	<0.01
Available P (mg·kg^{-1})	2.57	0.97	8.83	<0.01	95.83	37.49	91.58	<0.01	21.54	<0.01
Available K (mg·kg^{-1})	215.25	48.84	23.97	<0.01	48.00	15.74	4.50	0.04	−27.71	<0.01
Available Ca (mg·kg^{-1})	1063.32	341.00	2.99	0.09	652.63	188.83	46.37	<0.01	−8.98	<0.01
Available Mg (mg·kg^{-1})	141.62	27.97	28.59	<0.01	28.28	7.52	5.85	0.02	−33.25	<0.01
%Sand	41.50	4.52	2.35	0.13	55.70	4.77	0.004	0.95	18.53	<0.01
%Silt	28.96	1.41	2.08	0.15	23.20	3.00	18.86	<0.01	−14.99	<0.01
%Clay	29.54	5.04	3.22	0.08	21.10	3.90	10.65	<0.01	−11.33	<0.01
Soil erodibility (t·h·MJ^{-1}·mm^{-1})	0.2402	0.0136	0.00	0.99	0.2351	0.0104	35.08	<0.01	0.17	0.86

The relative fluctuations of soil physical and chemical properties were reflected in the impact of patches heterogeneity and soil erodibility as well as practice management in these two areas. The fluctuation of soil physical and chemical properties in the terraced paddy field indicated the high variation of soil characteristics among plots from the uppermost to lowermost toposequence plots. Cui et al. [60] also found that the available K and available P were low in the fallow period compared with the tillage period, whereas OM was higher in the fallow period than that in the tillage period.



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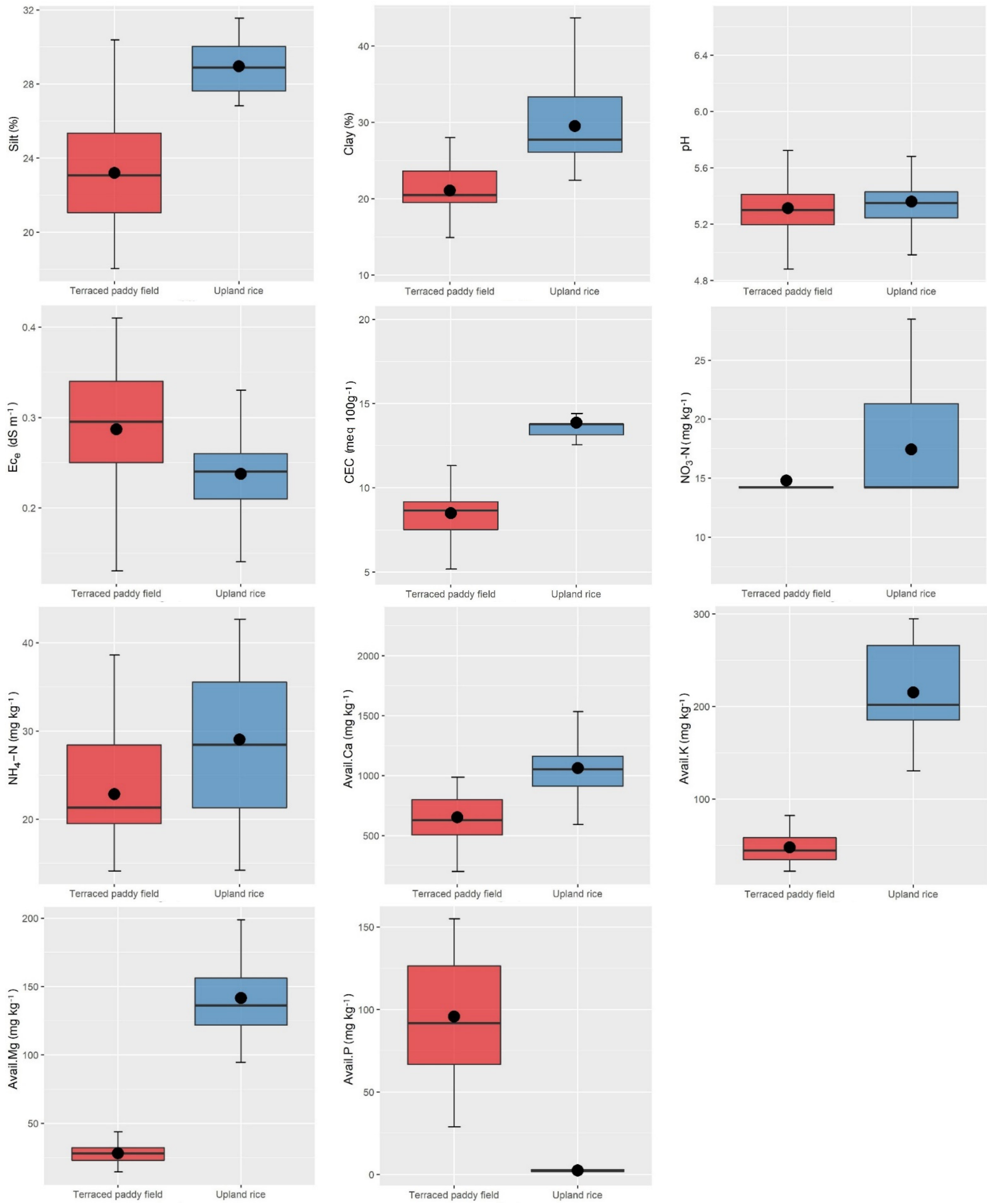
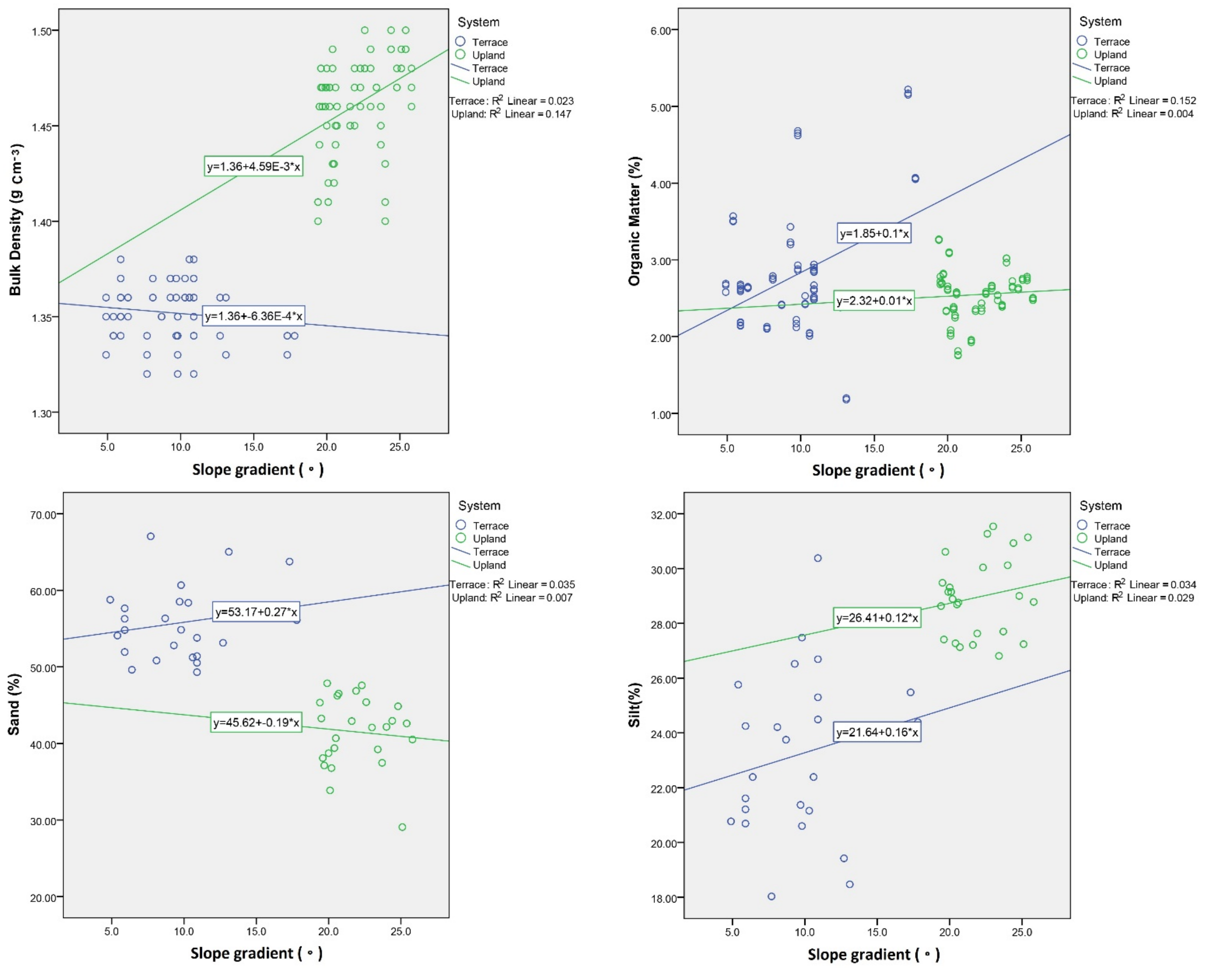


Figure 3. Comparison of soil physical and chemical properties between terraced paddy field and upland rice.

Based on trend analysis (Figure 4), there were no significant trends of soil physical and chemical properties with the topographic slopes. It is implied that the slope gradients did not influence to the variation of soil physical and chemical properties of both upland rice and terraced paddy fields. The trend line of the terraced paddy field showed that OM, silt content, pH, ECe, CEC, NH_4-N, available Ca, available K and available P decreased from the uppermost toposequence downwards the slope. Meanwhile, the trend line of upland rice field indicated that bulk density, OM, silt and clay contents, available K and available P decreased from the top slope to the lowermost toposequence point. This is mainly due to the transportation of nutrients and sediments from upstream to downstream locations under the plot-to-plot irrigation system, which detected the significant differences ($p < 0.01$) of silt and clay particles among terraced paddy soils (Table 1). This is consistent with Miyamoto et al. [61] and Mori et al. [62], who observed that fine particles in the surface were washed and transported downstream by surface flow. Terracing does not always increase soil nutrient status, as found in the present study, as most soil nutrients (NH_4-N, NO_3-N, available K, available Ca and available Mg) in the terraced paddy field were lower than the upland rice field (Table 1). Probably, the continuous water flows from plot-to-plot until downstream locations cause dissolved nutrients to be washed and removed from the flat surface (cultivation section), indicating a short period for accumulating nutrients into the soil that results in lower remaining nutrients in the soil. The draining of water at least 7 days before harvesting is another hypothesized cause for the reduction in soil nutrients. Schmitter et al. [63] suggested that soil fertility in rice paddy terraces can be maintained by balancing sediment inputs of different sources. However, continuous observation is needed to estimate any significant trends of these two cropping systems in our study area.



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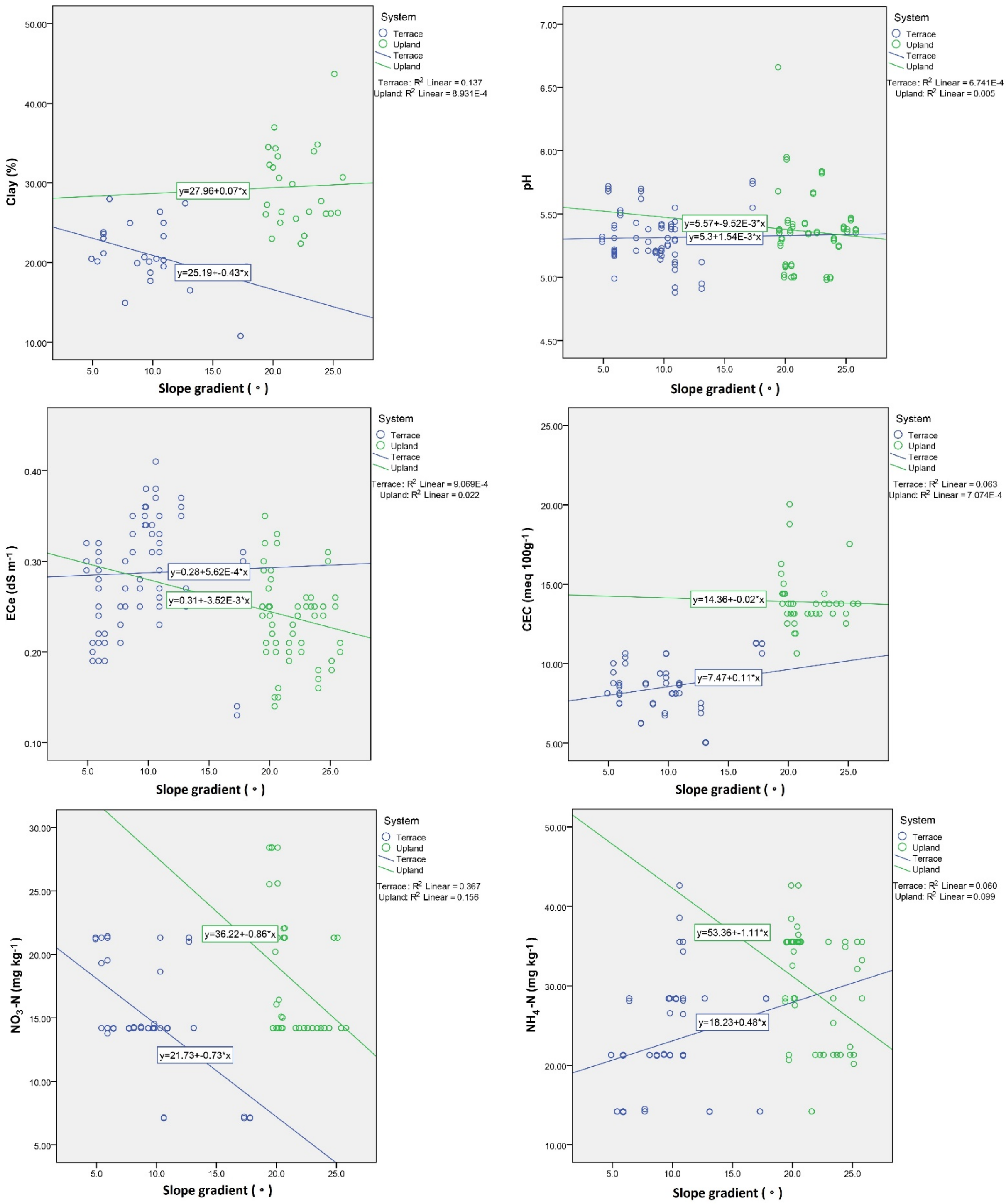

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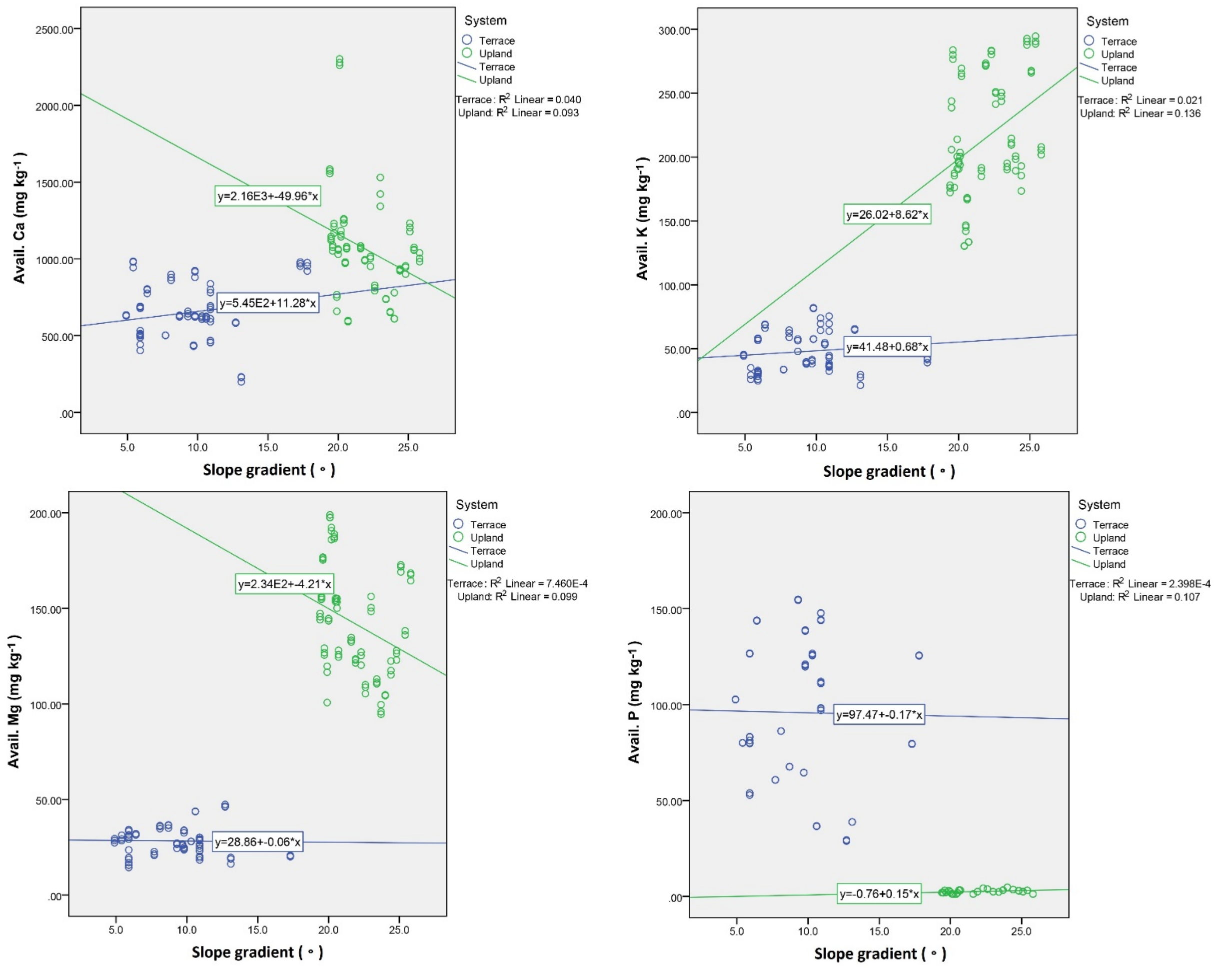
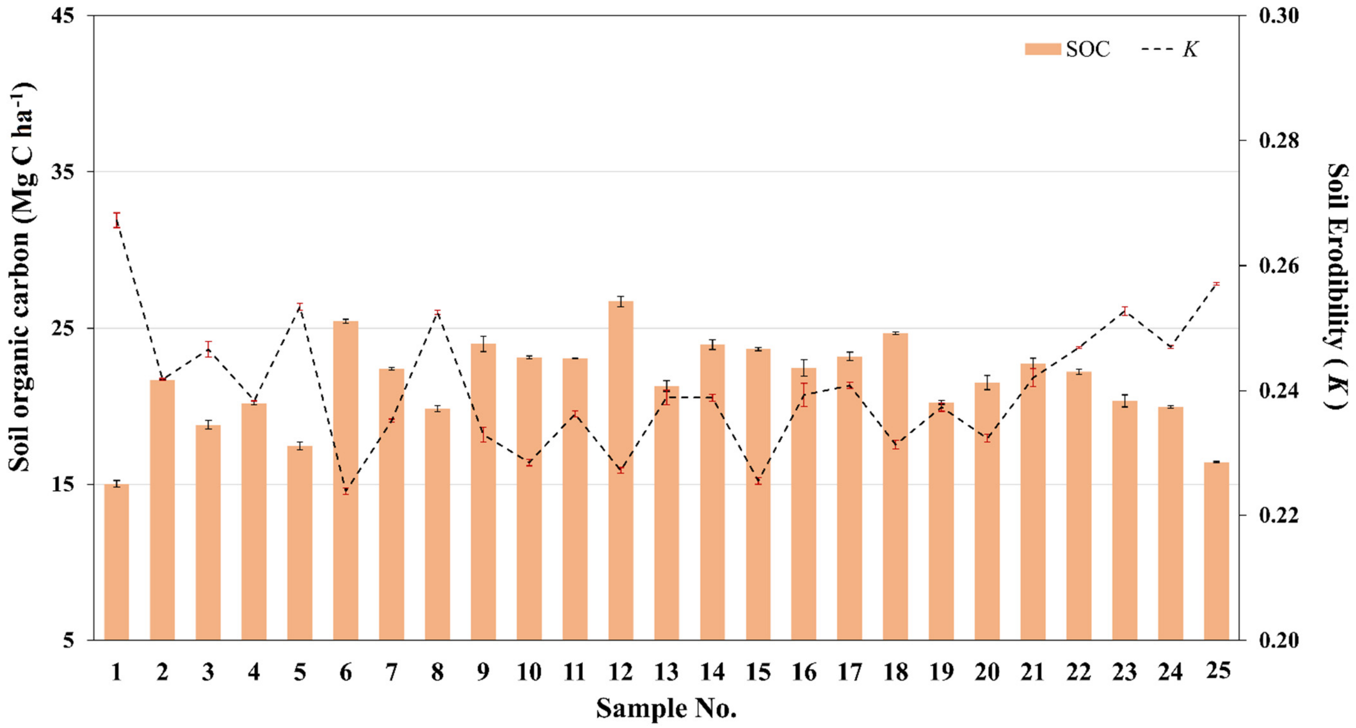


Figure 4. Trend analysis charts of soil physical and chemical properties between terraced paddy field and upland rice.

3.2. Soil Organic Carbon Stock under Terraced Paddy Field and Upland Rice

The OM fraction was significantly higher ($p < 0.01$) in terraced paddy soils (2.8 ± 0.9%) than in the upland rice soils (2.6 ± 0.3%) (Table 1). There was no significant difference in SOC stocks in both cropping systems, which was because the combination of OM and bulk density variations caused insignificant differences of SOC stocks between both systems. In the upland rice system, the lowest SOC stock (15.0 ± 0.2 Mg·C·ha^{-1}) was found in U1, which is the uppermost toposequence plot (Figure 4). Meanwhile, the sample soil at U12 had the greatest SOC content (26.7 ± 0.1 Mg·C·ha^{-1}) (Figure 5a). However, significant variations of SOC among different toposequences were not detected under upland rice soils. In the terraced paddy field, conversely, SOC stock shows significant differences among toposequence patches ($p < 0.01$, Table 1). It was found that T1, which is the uppermost toposequence plot, contained the largest SOC stock (40.2 ± 0.4 Mg·C·ha^{-1}) (Figure 5b). Meanwhile, the lowest SOC stock was found in T24 (9.3 ± 0.2 Mg·C·ha^{-1}), which was located at the lowest toposequence (Figure 5b). This can be explained by previous evidence of the effect of toposequence on soil properties. Baskan et al. [64] revealed that soil properties in different topographic positions were significantly different in terms of pedogenic processes shaped by the movement and transport of soil particles. In this study, a higher level of SOC content in upper terraces compared to the upland site indicates its potential on SOC sequestration from the above position. De Blécourt et al. [65] quantified SOC stock changes induced by terrace construction in the area of forest conversion to rubber plantation. They found that topsoil removal at the cut section caused a reduction in SOC stocks in the youngest plantation, and then the recovery of SOC stocks came from roots and litter and deposition of topsoil materials from the upper slope.



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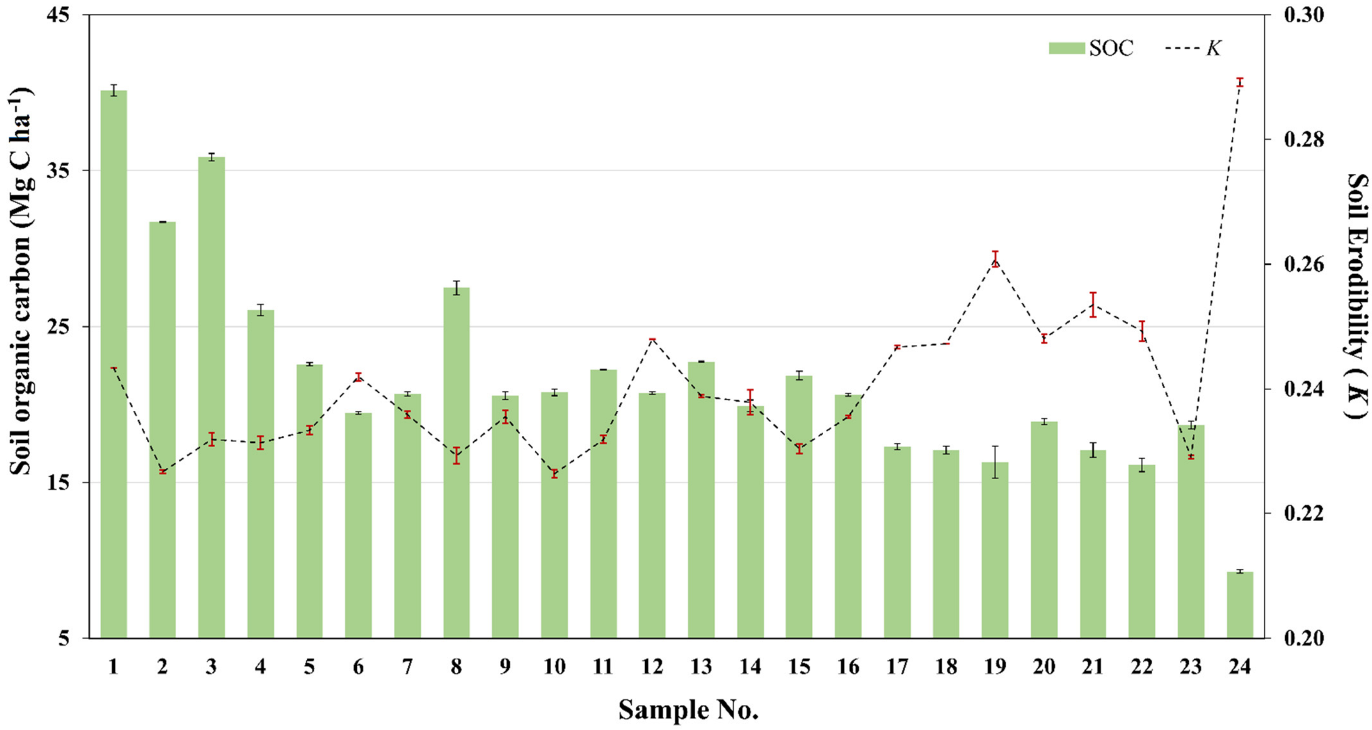

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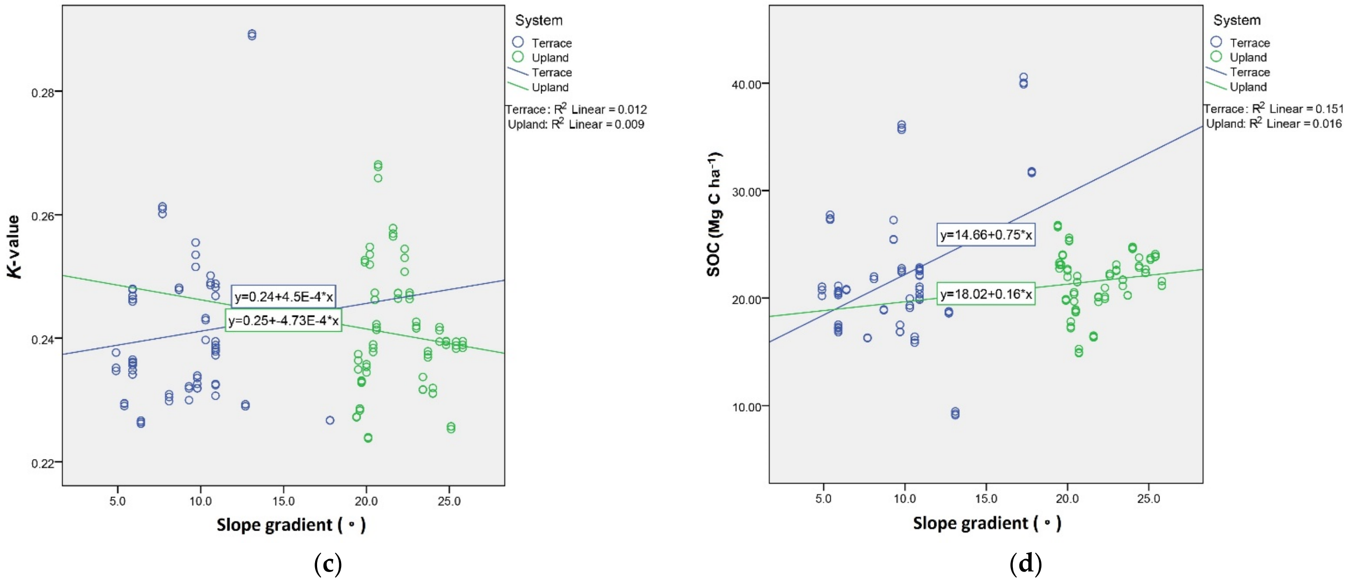

Figure 5. Soil organic carbon (Mg·C·ha^{-1}, bar area) and *K*-value (line) of under different toposequences, and trend analysis charts of soil organic carbon and *K*-value. (**a**) Upland rice area, (**b**) terraced paddy field, (**c**) trend analysis chart of *K*-value and (**d**) trend analysis chart of SOC stock.

As presented in Table 1, SOC stocks in the terraced paddy and upland rice fields were 21.84 and 21.61 Mg·C·ha^{-1}, respectively, but a significant difference was not detected. Previous studies [37,66,67] have reported that terracing can reduce SOC loss by modifying hillslopes to small flat fields, which was supported by the findings of the present study. During the dry period after harvest, the rice straw remaining in the terraced field is a great practice to improve SOC sequestration as well as restoring soil nutrients with fewer losses from the field, which is conserved by the structure of terracing, such as stair-rice paddy. Moreover, flooding in the terraced paddy field supplies suspended particles and soluble nutrients to the fields [68], while puddling facilitates the incorporation of organic inputs into the soil and creates low breakdowns of OM [69]. On the other hand, the loss in upland rice may be higher than terraced paddy fields due to having no riser or wall to slow down erosion, together with fewer weeds and plants to cover the soil after harvest. Chen et al. [70] reported higher SOC in the surface layer (0–20 cm) than the deeper soil layer (20–100 cm), indicating that protection of surface soil of terraced field is the key to enhancing SOC [33,71]. As the meta-analysis by Chen et al. [72] points out, terraces in China increased 32.4% of SOC sequestration compared with sloping areas. Tadesse et al. [73], Arunrat et al. [74] and Arunrat et al. [75] suggested that the application of manure, crop residues and soil conservation could increase SOC. However, SOC stock in the present study reflects a visual tendency, but no significant difference was found, highlighting that continuous investigation is necessary to conserve soil nutrients and SOC sequestration.

3.3. Soil Erodibility under Terraced Paddy Field and Upland Rice

Soil erodibility is used to calculate the *K*-value in the universal soil loss equation (USLE) and the revised universal soil loss equation (RUSLE), which is an important factor for soil erosion assessments as well as soil and water conservation planning [76,77]. In the present study, there was no significant difference in *K*-values, ranging from 0.2261–0.2893 t·h·MJ^{-1}·mm^{-1} and 0.2238–0.2681 t·h·MJ^{-1}·mm^{-1} between terraced paddy and upland rice soils ($p > 0.05$, Table 1), respectively. In upland rice soil, the difference in *K*-values across different toposequences was not significant ($p > 0.05$, Table 1). We found that the *K*-value was slightly higher when SOC content dropped, especially in U1 and U25 (Figure 5a). As noted previously, the finer particles tended to be dominantly exported by erosion [78]; thus, SOC was relatively eroded [79,80]. Conversely, soil erodibility was significantly variable under the terraced paddy soil ($p < 0.01$, Table 1). The highest *K*-value was, as expected, detected in T24 (lowermost location point), which contained the lowest SOC stock (Figure 5b). This can probably be explained by particle distribution differences being reduced due to the terracing technique. Moreover, SOC stock was possibly conserved under terracing cultivation by its contribution to plant root distribution [61], and its impact varied strongly among management practices [81]. This is because puddling in land preparation and transplanting method for rice planting caused a decrease in bulk density and enhanced root length density [82]. However, our findings merely reflect a tendency that was not a significant difference between upland rice and terrace paddy soils.

As a significant difference of soil erodibility under terraced paddy soil was detected ($p < 0.01$) (Table 1), it indicated the high fluctuation of soil erodibility among flat sections across the terraced paddy field. Moreover, the trend analysis chart of *K*-values along the topographical gradients between terraced paddy field and upland rice can be observed in Figure 5c. This is because each flat section of the terraced paddy field contains a different proportion of sand, silt, clay and OC contents, and vice versa under upland rice (Table 1). Thus, maintaining the fractions of sand, silt and clay contents as well as improving OC contents is the primary important factor to control the erodibility of both cropping systems. Among these factors, increasing OC content seems to be the most possible strategy and does not disturb current farmer's management practices by retaining rice straw and stubbles, applying animal manure and reducing tillage. Once SOC is increased, the benefits can result in the stability of soil aggregates and enhanced soil structure, resulting in resistance to erosion [83]. Moreover, terraces have the potential to reduce sediment yield and runoff [84] as well as increase water infiltration, soil moisture and soil water holding capacities in several areas [21,71]. It can be observed in Figure 5d that SOC stocks decreased from the uppermost toposequence to the downward slope.

It should be noted that the *K*-value of the EPIC model is dependent on soil particle size and organic carbon, which may not be sufficient to estimate soil erodibility with the different climate and cropping systems. For example, the studies of Zhang et al. [85], Chen et al. [20] and Zhang et al. [86] have developed a database of K factors for China's agricultural soils to reduce the biases of soil loss estimation. Therefore, the study of the feasibility of combining methods (e.g., *K*-value from nomographs method [49], *K*-value of EPIC model method [50] and the soil geometric mean diameter method [51]) to provide accurate estimations of *K*-values in Thailand is required for future studies. Moreover, it should be constructed as Thailand's database of K factor and K factor maps.

3.4. Correlation Coefficient Matrix and PCA Analysis

The Pearson's correlation matrix among soil physicochemical properties is presented in Table 2. In terraced paddy soils, SOC showed a high positive correlation with both CEC (0.88, $p < 0.05$) and available Ca (0.85, $p < 0.05$). Available Ca had significant positive correlation with pH ($r = 0.80$, $p < 0.05$). Meanwhile, it was found that the available Ca positively correlated with CEC ($r = 0.78$, $p < 0.05$) and pH ($r = 0.75$, $p < 0.05$) in upland rice soils. A significant negative correlation was also found between clay and sand contents in upland rice soils and terraced paddy soils ($r = -0.96$ and -0.78, respectively). Interestingly, the negative values of correlation coefficients of the relationship between SOC or CEC and clay content were found in the upland rice field, indicating that clay minerals might not be active (Table 2).

These results, together with principal component analysis, explained 62.6% of the total variance (Figure 6, PC1: 46.3% and PC2: 16.3%) and allowed a better understanding of the correlation between the physicochemical properties of the soils collected in different cropping systems. Additionally, factor loading analyses showed that the first 6 of 16 PCs can explain 90.5% of the total variance with eigenvalue greater than 0.7. The significant loading factors with 10% of the highest factor loading in each significant PCs are underlined in Table 3. Three variables, available Mg, CEC and sand content, were obviously weighted in PC1. Meanwhile, in PC2, SOC, soil erodibility and toposequence were considered significant. In contrast, PC3 was strongly related to EC, NH_4-N and NO_3-N. Both EC and NO_3-N were significantly included in PC4 and PC5. While pH and EC were considered in PC4 and PC5, respectively. In PC6, soil erodibility, clay content and bulk density were significantly weighted.

Table 2. Pearson's correlation matrix of soil properties in terraced paddy field samples (*n* = 72, white background) and upland rice (*n* = 75, grey background).

Variable	pH	BD	SOC	EC_e	CEC	NH_4-N	NO_3-N	P	K	Ca	Mg	%Sand	%Silt	%Clay
pH		**−0.24 ***	**0.45 ***	0.18	**0.54 ***	−0.08	**0.24 ***	−0.18	**0.23 ***	**0.75 ***	**0.41 ***	−0.01	**0.31 ***	−0.08
BD	−0.14		−0.13	0.06	**−0.24 ***	0.01	**−0.26 ***	0.14	**0.44 ***	**−0.30 ***	−0.10	0.00	0.17	−0.05
SOC	**0.52 ***	**−0.33 ***		**0.36 ***	**0.66 ***	0.02	**0.28 ***	0.17	0.21	**0.47 ***	0.09	**−0.25 ***	**0.43 ***	0.10
ECe	**−0.42 ***	0.16	**−0.30 ***		0.15	**0.24 ***	**0.51 ***	0.11	**0.40 ***	**0.23 ***	0.10	0.11	0.13	−0.14
CEC	**0.49 ***	−0.13	**0.88 ***	**−0.25 ***		−0.08	**0.37 ***	**−0.29 ***	0.18	**0.78 ***	**0.48 ***	**−0.65 ***	**0.02 ***	**0.57 ***
NH_4-N	−0.17	**0.30 ***	−0.09	**0.66 ***	0.12		**0.27 ***	−0.17	**−0.32 ***	0.15	**0.39 ***	0.09	0.12	−0.11
NO_3-N	−0.17	0.09	**−0.35 ***	0.05	**−0.38 ***	−0.23		−0.04	0.05	**0.37 ***	**0.37 ***	−0.07	−0.29	0.14
P	−0.13	−0.07	**0.44 ***	−0.08	**0.61 ***	0.15	−0.04		**0.25 ***	**−0.53 ***	**−0.66 ***	**0.40 ***	**0.36 ***	**−0.46 ***
K	**0.31 ***	−0.15	**0.33 ***	**0.30 ***	**0.39 ***	**0.37**	−0.11	**0.25 ***		0.02	−0.01	−0.04	0.25	−0.03
Ca	**0.80 ***	−0.19	**0.82 ***	**−0.32 ***	**0.83 ***	−0.03	**−0.32 ***	**0.31 ***	**0.41 ***		**0.70 ***	**−0.39 ***	**0.12 ***	**0.32 ***
Mg	**0.40 ***	**0.13 ***	−0.02	**0.45 ***	0.03	**0.44 ***	0.02	**−0.34 ***	**0.54 ***	**0.28 ***		**−0.51 ***	**−0.19 ***	**0.51 ***
%Sand	−0.09	−0.41	−0.04	**−0.24 ***	**−0.34 ***	**−0.54 ***	−0.01	**−0.33 ***	**−0.28 ***	**−0.27 ***	**−0.45 ***		**0.23 ***	**−0.96 ***
%Silt	0.16	**0.02 ***	**0.59 ***	−0.06	**0.62 ***	0.20	**−0.32 ***	**0.57 ***	0.15	**0.51 ***	−0.02	**−0.58 ***		**−0.48 ***
%Clay	−0.01	0.49	**−0.41 ***	**0.34 ***	−0.07	**0.50 ***	**0.25 ***	−0.03	**0.23 ***	−0.07	**0.56 ***	**−0.78 ***	−0.06	

* Correlation is significant at 0.05 probability level ($p < 0.05$); BD = bulk density; SOC = soil organic carbon; ECe = electrical conductivity; CEC = cation exchange capacity; P = available P; K = available K; Ca = available Ca; Mg = available Mg.

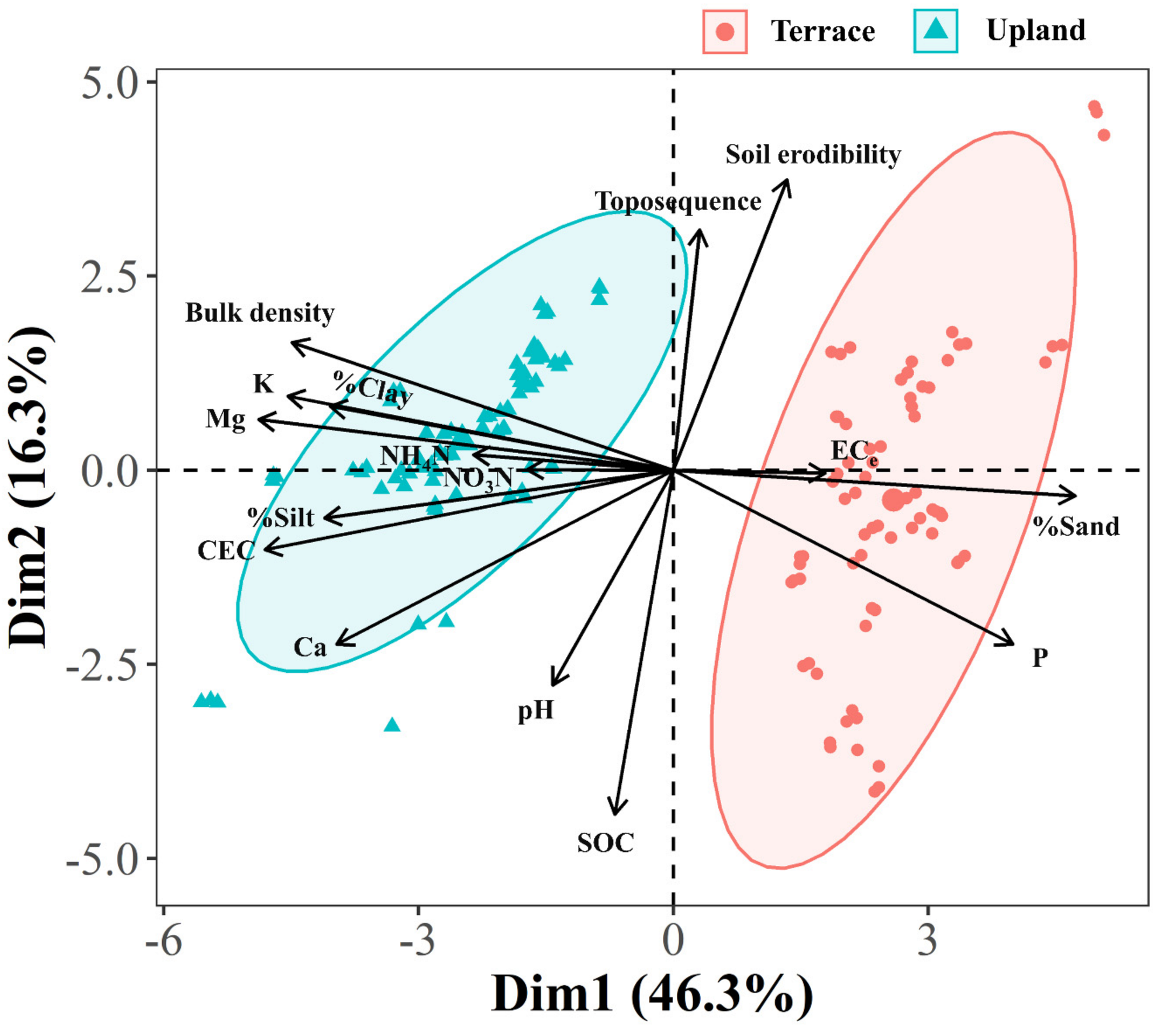

Figure 6. Principal component analysis (PCA) and the loading values of soil properties and toposequences for terraced paddy field samples (red area) and upland rice samples (blue area).

Table 3. Principal components (PCs), eigenvalues, percentage of variance explained by the PCs (% Var.) and cumulative percentage of variance explained by PCs of soil properties and toposequences for terraced paddy field and upland rice samples.

	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
Eigenvalue	7.408	2.607	1.502	1.196	0.909	0.866
Var. (%)	46.301	16.296	9.386	7.473	5.681	5.415
Cum. var. (%)	46.301	62.598	71.984	79.457	85.138	90.553
Factor loading/eigenvector						
Toposequence	0.022	**0.378**	0.266	**0.442**	**−0.409**	0.310
pH	−0.103	−0.337	0.276	**0.493**	−0.186	**−0.330**
Bulk density	−0.325	0.201	0.051	−0.124	−0.053	−0.009
SOC	−0.050	**−0.541**	0.158	−0.169	−0.141	0.044
ECe	0.129	−0.005	**−0.537**	0.263	**−0.552**	0.003
CEC	**−0.348**	−0.125	0.065	−0.007	0.011	0.049
NH_4-N	−0.170	0.024	**−0.506**	−0.286	−0.327	−0.291
NO_3-N	−0.125	0.001	**−0.396**	**0.445**	**0.494**	−0.239
P	0.289	−0.273	−0.120	−0.107	0.015	0.175
K	−0.329	0.116	0.087	0.032	−0.139	−0.003
Ca	−0.287	−0.273	0.055	0.198	−0.034	−0.205
Mg	**−0.353**	0.080	−0.033	−0.004	0.061	−0.157
%Sand	**0.342**	−0.040	0.087	0.052	−0.029	−0.298
%Silt	−0.297	−0.075	0.110	−0.285	−0.245	−0.027
%Clay	−0.292	0.101	−0.185	0.099	0.186	**0.426**
Soil erodibility	0.097	**0.457**	0.201	−0.149	−0.001	**−0.529**

BD = bulk density; SOC = soil organic carbon; ECe = electrical conductivity; CEC = cation exchange capacity; P = available P; K = available K; Ca = available Ca; Mg = available Mg.

As shown in Figure 6, the result of PC1 shows the direct correlation among some properties (bulk density, available Mg, CEC, available K, available Ca, percent clay, percent silt, NH_4-N and NO_3-N), which were inversely correlated with percent sand, available P and EC_e. A negative relationship between bulk density and sand content was detected. It indicated that upland rice soils were in higher bulk density, while the terraced paddy field had more sand content. It was clear that the upland rice and terraced paddy fields were different in the relationship between bulk density and sand content. Lower sand content and higher bulk density can make soil more fertile, while in the higher sand content area, more nutrients are expected to be gathered by irrigation. These results suggested that terraced paddies might be constructed to increase soil fertility rather than to reduce soil erosion in low upland crop production fields on natural hilly slopes. A strong correlation between the soil erodibility and toposequence was detected, indicating that higher soil erodibility occurred at lower toposequence points. As expected, by using the *K*-values of the EPIC model method, the correlation between soil erodibility and SOC was the opposite, meaning that a decrease in SOC stock was related with increasing soil erodibility (Figure 6). This is in line with the studies of Shabani et al. [87] and Ostovari et al. [88], who found a significant negative correlation between soil erodibility and OM.

3.5. Recommendations for Further Study

The findings of our study were investigated from a specific area, which may not be stated with high confidence about the differences between terraced paddy and upland rice fields, especially SOC stock and soil erodibility. Our study can be simply stated that SOC stocks and soil erodibility were not significantly different between the terraced paddy and upland rice fields in our study area. Therefore, more research should be conducted to validate the results in our study for providing appropriate management practices for these two systems. In future studies, experimental measurements should be conducted by measuring nutrient movement characteristics in terraced paddy and upland rice fields as well as soil erosion, water runoff and infiltration.

4. Conclusions

This study investigated hillslope cultivation fields that have been continuously managed as terrace paddy fields and upland rice cultivation, with the aim to explain how SOC sequestration, erodibility and physiochemical properties of topsoils are affected by terracing management. More variation in soil properties for each toposequence was found in terraced paddy soils rather than upland rice soils. Most soil nutrients (NH_4-N, NO_3-N, available K, available Ca and available Mg) in the terraced paddy field were lower than in the upland rice field. SOC stocks in the terraced paddy and upland rice fields were 21.84 and 21.61 $Mg{\cdot}C{\cdot}ha^{-1}$, respectively, but a significant difference was not detected. Similarly, there was no significantly difference in soil erodibility between terraced paddies (range 0.2261–0.2893 $t{\cdot}h{\cdot}MJ^{-1}{\cdot}mm^{-1}$) and upland rice (range 0.2238–0.2681 $t{\cdot}h{\cdot}MJ^{-1}{\cdot}mm^{-1}$). Higher soil erodibility and lower SOC stock were found at the lower toposequence points of both cropping systems.

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