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Influence of Land-Use Systems and Topographic Variables on Soil Physical Indicators in the Chittagong Hills, Bangladesh

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Abstract

This study evaluates the influence of land-use systems and topographic variables on soil physical indicators in the Chittagong Hills, Bangladesh. A total of 81 topsoil samples (0 - 20 cm depth) were collected from nine land-use types, spanning altitudes from 26.43 m to 106.35 m and slope lines from 26.07% to 77.30%. Soil structure varied from blocky to granular, and soil textures ranged from sandy loam to sandy clay loam, with color ranging from dark grayish-brown to reddish-brown, exhibiting significant variation across land-use sites. One-way analysis of variance (ANOVA) results revealed significant differences ($p < 0.05$ to $p < 0.001$) in soil physical indicators across land-use practices. Moisture-related indicators such as moisture content (MC), field capacity (FC), maximum water holding capacity (MWHC), total porosity, and soil organic matter (SOM) were highest in natural forest and agroforestry systems compared to acacia forest, young teak forest, mature teak forest, and shifting cultivation. Dry and moist bulk density (DBD and MBD) were highest in the acacia forest, teak forest, and shifting cultivation site. Pearson correlation analysis confirmed strong positive relationships between slope, altitude, sand content, bulk density (BD), but negative correlations with FC, MWHC, total porosity (TP), silt, SOM ($p < 0.01$). Among soil physical indicators, strong positive correlations were observed between sand content, DBD, and MBD, while strong negative correlations were observed between silt content, MC, FC, MWHC, TP, and SOM. Regression analyses indicated significant negative relationships of FC and SOM with altitude and slope, whereas MWHC was negatively associated with altitude only. Sand content showed significant positive relationships with both topographic variables, while dry and moist bulk density were positively associated with slope only. The study concludes that variations in the land-use practices along altitude and slope gradients drive the soil physical indicators and soil OM, with steeper slopes showing compacted, coarser soils and lower SOM. Such findings emphasize the role of natural forests and agroforestry systems in preserving soil physical health, whereas shifting cultivation and monoculture plantations lead to soil degradation. Considering climate change variables, future research should focus on the effects of temperature and rainfall on soil physical properties and SOM to conserve the forest ecosystems.

Keywords

Land-Use Practice, Altitude, Slope, Soil Physical Indicators, Chittagong Hills

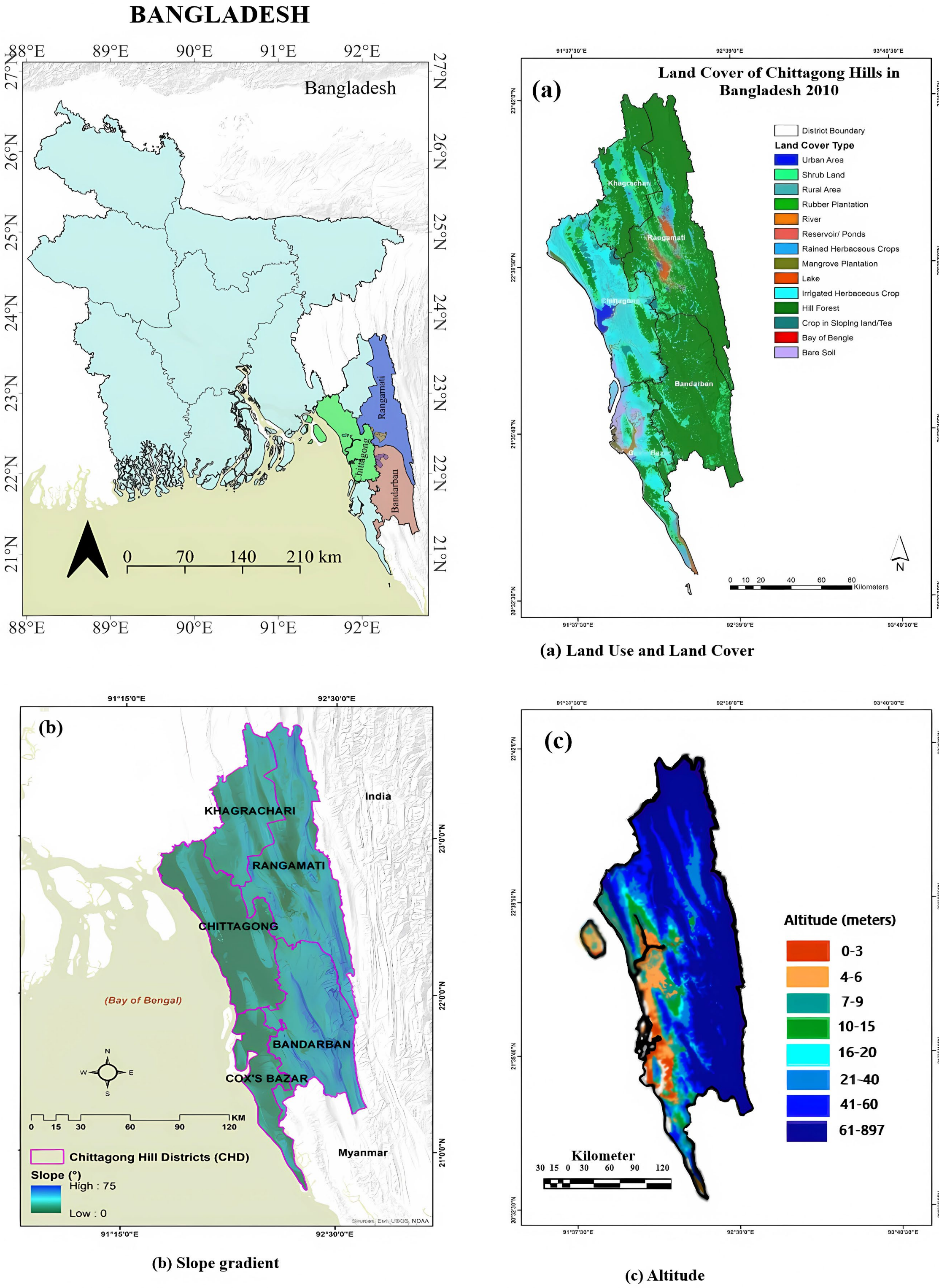
1. Introduction

Soil is one of the most critical land resources, enabling agricultural development and sustaining ecological integrity amid global climate change. In addition to food, fuel, and fiber production, soil provides vital ecosystem services, including nutrient cycling, water purification, and carbon sequestration [1]. Currently, soil health such as soil quality, nutrient cycling, and soil fertility is affected by climate change, population growth, and unsustainable land-use practices. However, healthy soils are essential for maintaining ecosystem functions, supporting soil microorganisms involved in nutrient cycling, preventing erosion, and preserving soil organic matter [2] [3]. Specifically, soil physical indicators provide valuable information about hydrologic characteristics, such as water infiltration and retention, which directly influence water availability to plants. These indicators are related to nutrient availability through their influence on rooting volume and soil aeration [4]. Intensive cultivation of farmland has resulted in sediment loss, soil erosion, and increased runoff; moreover, ploughing rugged topography and steep landscapes is a common practice in the highlands, which aggravates soil erosion [5].

The need for agricultural land and food production has led to forced land-use and land-cover changes (LUCC), which have impacted soil properties [6], particularly in areas such as the Chittagong Hills in Bangladesh. The uniqueness of these Hills lies in their varied topographic and ecological characteristics, which support a diversity of land-use practices that are fundamental to local income, agricultural development, and ecosystem services. These diverse land-use practices include agroforestry, shifting cultivation (*Jhum*), mixed fruit gardening, timber plantations (monocultures such as teak and acacia), and natural forest systems. Depending on the type of land-use, soil physical, chemical, and biological properties are affected [7], which can interact to influence soil quality and the capacity of forest land to provide ecosystem services. The region is still significant for agriculture, with more than 35 crop species produced annually, with fruit plantations occupying more than 30% of the land area [8] [9]. According to Rahman *et al.* [10], different types of crops, fruits, and timber species are grown in various agroforestry systems on steep slopes in CHT. Recently, agroforestry and other tree-based systems have gradually replaced traditional land-use systems such as Jhum cultivation. However, research indicates that monoculture plantations, such as teak plantations, are associated with severe degradation and increased soil erosion [11]. Besides, deforestation and unsustainable land-use practices have further degraded soil health, endangering the ecological balance of the region. Therefore, regional variation of soil properties is closely related to different forest management practices [12], while at the same time depending on many environmental factors, such as local topography including position, elevation, slope and aspect, organic matter content, climate and forest [13]-[16]. For example, soil properties are driven by environmental factors such as topography, altitude, and climate [17]. Similarly, Kalivas *et al.* [18] noted that soil-forming processes and their properties are partly controlled by topography. In regions like the Chittagong Hills, where slopes often exceed 40%, topography plays a vital role in soil degradation. Steep slopes make the land highly susceptible to erosion, leading to the loss of topsoil and organic matter, and to changes in soil physical properties, especially during periods of high rainfall [19] [20].

Many studies have examined the interactions among land-use, topography, and soil health, and some have concluded that soil characteristics are significantly influenced by slope gradient and elevation [21] [22], especially soil water-holding capacity and organic matter. Soil degradation is a key concern in the Chittagong Hills, an area that would benefit from a targeted soil research approach. However, previous research (e.g., [23]) called for extensive investigation of soil properties, while Chowdhury *et al.* [24] suggested agroforestry as a potential solution to this problem. Monoculture of teak trees was reported to adversely affect soil health and vegetation, calling for further research [25] [26]. It suggests that opting for teak, gamar and rubber plantations could be a more favorable land cover than original shifting cultivation. However, further research is needed to fully understand the impacts of fast-growing species on soil and ecosystem health. No existing research has specifically addressed the combined effects of land-use change and environmental variables on soil physical indicators and soil organic matter (SOM). Therefore, this study aims to fill this gap by examining the impact of land-use changes and environmental variables on key soil physical indicators in the Chittagong Hills. This study explicitly investigates how land-use, altitude, and slope affect soil physical indicators and soil organic matter (SOM). The findings can inform sustainable land management strategies, improved soil conservation practices, and future research in the context of global climate change.

We hypothesize that natural forest soils maintain better soil physical properties, higher soil organic matter and lower compaction than monoculture forests, shifting cultivation and degraded agroforest systems, with variability influenced by altitude and slope position. To test this hypothesis and address the research objectives outlined above, the following sections describe the study site, land-use systems, experimental design, sampling strategy and analytical methods used to assess soil physical health indicators, soil organic matter and related topographic variables under nine different forest soil conditions.



(a) Land Use and Land Cover

(b) Slope gradient

(c) Altitude

Figure 1. Location map of study area (Chittagong, Bandarban and Rangamati): (a) Land-use/Land cover; (b) Slope gradient (degree); (c) Altitude (meter).

2. Materials and Method

2.1. Description of the Study Area

The study was carried out in nine hills located at six different union in Chittagong, Bandarban and Rangamati districts of Chittagong division, in the south eastern zone of Bangladesh (**Figure 1**). There were three sites in Chittagong (agroforest system (AFS), acacia forest (AF) and young teak forest (YTF)), 3 sites in Bandarban (shifting cultivation (SC), multi-strata agroforest system (MAFS) and mature teak forest (MTF)), and 3 sites in the Rangamati district (multi-story fruit garden (MSFG), mixed mature timber forest (MMTF) and natural forest (NF)). The study area extends from 22°15′59.78″N to 22°50′57.84″N latitude and from 91°47′51.71″E to 92°19′57.56″E longitude. The study area's climate is a tropical monsoonal type, with heavy rainfall and high humidity during the monsoon season from May to August [27]. The region experiences an average annual rainfall of 2735 mm (107.7 inches) and an average temperature of 25.1˚C.

2.2. Soil and Topography

The soils of the study area are predominantly derived from parent materials of tertiary geological origin, consisting primarily of sandstones and, in some locations, semi-consolidated to consolidated shale or shale fragments [28]. The weathering processes in the region are quite harsh owing to strong oxidation, leaching, and surface runoff. Therefore, soils are generally coarse-textured. The hill soil (*Dystric cambisols*) is mainly yellowish brown to reddish brown loam and naturally moderate to strongly acid [29]. The mean altitude of the study areas is quite variable, ranging from 26.43 to 106.36 meters above sea level. This geological formation has contributed to the development of steep and variable slopes, with gradients ranging from 26.07% to a maximum of 77.30% in some locations. These slopes are particularly prone to very severe landslides and soil erosion, especially during the rainy season when most of the yearly rainfall occurs [28]. This continuous loss of soil reduced soil fertility [30].

2.3. Land-Use Practices

Research was conducted across nine sites, each representing distinct hills with varying slopes, elevations, land-use and vegetation types. These sites were classified into nine land-use categories: agroforest system (AFs), acacia forest (AF), young teak forest (YTF), shifting cultivation (SC), multi-strata agroforestry system (MAFS), mature teak forest (MTF), multi-story fruit garden (MSFG), mature mixed timber forest (MMTF), and natural forest (NF) (**Figure 2**).

At the time of sampling, the agroforestry sites (AFs and MAFS) were under intensive year-round mixed cropping, incorporating fruit and timber production trees such as *Mangifera indica* (mango), *Artocarpus heterophyllus* (jackfruit), *Elaeocarpus serratus* (jalpai), *Albizia procera* (white Koroi), *Acacia auriculiformis* (acacia), *Tectona grandis* (teak), *Psidium spp.* (guava), *Carica spp.* (papaya), and *Citrus limon* (lemon) etc. The monoculture plantation forests (Acacia and Teak stands) were predominantly covered by *Acacia auriculiformis* and *Tectona grandis*, both showing minimal ground litter and canopy cover. The shifting cultivation sites (SC) were characterized by diverse seasonal Jhum crops, including *Vigna unguiculata* (long bean), *Abelmoschus esculentus* (okra), *Ananas comosus* (pineapple), *Carica papaya* (papaya), *Musa acuminata* (banana), *Solanum melongena* (brinjal), *Curcuma longa* (turmeric), *Lablab niger* (bean), and *Zea mays* (maize) etc. The multi-story fruit garden (MSFG) were dominated by a variety of fruit-bearing trees such as *Punicagranatum* (pome granate), *Litchi chinensis* (lychee), *Mangifera indica* (mango), *Psidium spp*., *Ziziphus mauritiana* (apple jujube), *Manilkara zapota* (sapodilla), *Citrus maxima* (pomelo), *Citrus sinensis* (sweet orange), and *Citrus reticulate* (mandarin) etc.

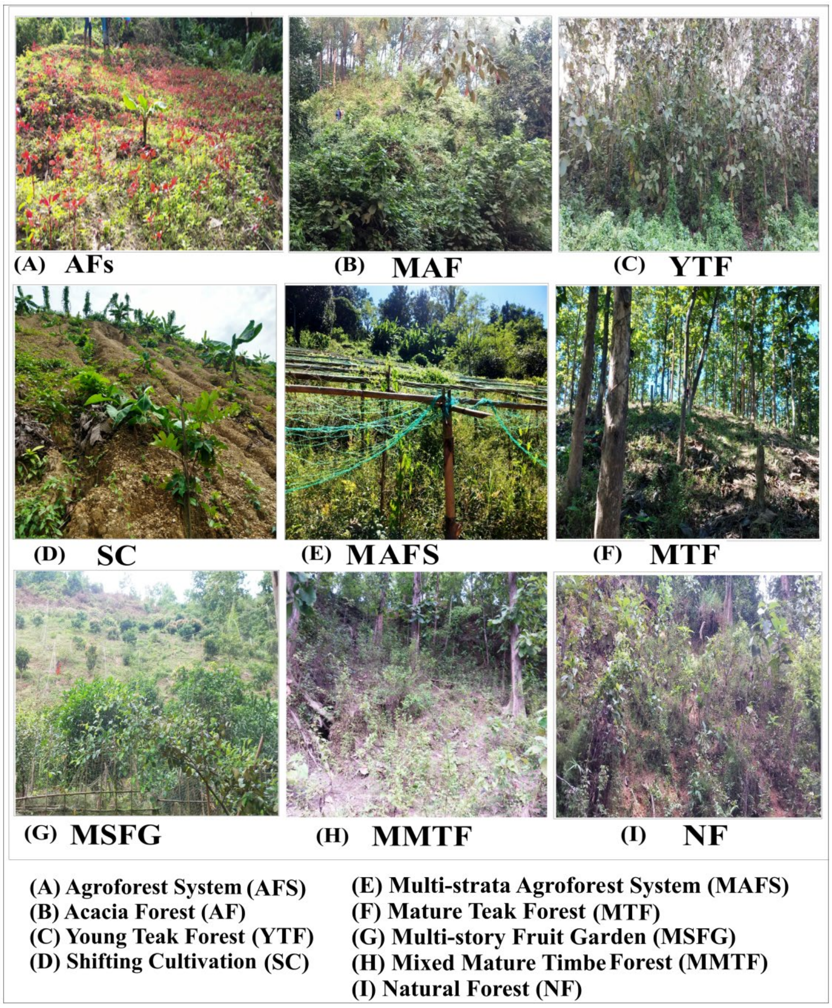


Figure 2. Study area land-use types: AFS—Agroforest system, AF—Acacia forest, YTF—Young teak forest, SC—Shifting cultivation, MAFS—Multi-strata agroforestry system, MTF—Mature teak forest, MSFG—Multi-story fruit garden, MMTF—Mature mixed timber forest, NF—Natural forest.

Mixed mature timber forest (MMTF) featured a diversity of timber species, including *Tectona grandis* (teak), *Swietenia mahagoni* (mahogany), *Acacia auriculi-*

formis (acacia), *Gmelina arborea* (gamar), along with understory vines and shrubs. Finally, the natural forest (NF) was dominated by native species such as *Swintonia floribunda* (chundul), *Swintonia helferi* (civit or mylum), *Baccaurea ramiflora* (lotkon), *Syzygium fruticosum* (putijam), *Bombaxceiba* (kapok tree), *Ficus rumphii* (pakur), *Artocarpus lacucha* (deuya/monkey Jack), *Ficus carica* (dumur), *Bambusa spp.* (bamboo), and other indigenous shrubs and climbers.

2.4. Experimental Design, Soil Sampling and Preparation

A multistage stratified field sampling design was employed to investigate the effects of land-use systems and topographic positions on soil properties in the Chittagong Hills of Bangladesh. In the first stage, three representative districts including Chittagong, Bandarban, and Rangamati were selected as the study areas. In the second stage, nine representative land-use systems were identified across the selected districts. Each land-use site was subsequently stratified into three topographic positions (upper, middle and bottom) to capture spatial variability associated with altitude and slope. At each topographic position, three sampling points were selected from relatively homogeneous areas. Consequently, a total of 81 surface soil samples (9 land-use systems × 3 topographic positions × 3 sampling points) were collected from the 0 - 20 cm soil layer, representing the most biologically active horizon. All sampling locations were geo-referenced using a handheld GPS.

Each of the 81 soil samples was analyzed individually in the laboratory. For statistical analyses, the measurements obtained from the three sampling points within each slope position were averaged to generate one representative value. This resulted in a final dataset of 27 observations (9 land-use systems × 3 slope positions), which was used for all subsequent statistical analyses, including one-way ANOVA, Pearson correlation and simple linear regression. The values presented for each land-use system in **Table 1** and **Table 2** represent the mean ± standard deviation of the three slope-position observations.

Before analysis in the laboratory, visible plant residues and debris were removed from collected soil samples. All samples were then air-dried at room temperature for seven days. Once dried, the soils were sieved through a 2 mm stainless steel mesh to ensure uniform particle size before laboratory analysis. The sieved samples were then stored in plastic containers at room temperature.

2.5. Analysis of Soil Physical Indicators

Soil colour was determined using the Munsell soil colour chart on moist soil, and soil structure was observed immediately after excavation in the field. Soil texture was analyzed using the hydrometer method, as described by Bouyoucos [31] and Piper [32]. The percentage of sand, silt and clay were used to determine the textural classes of the soil samples using the USDA-soil textural triangle [33].The moisture content (MC) was determined using the gravimetric method and calculated with Equation (1).

$$\mathrm{MC}(\%)=\frac{\text{Weight of moist soil}-\text{Weight of oven dry soil}}{\text{Weight of oven dry soil}}\times 100 \quad (1)$$

Field capacity (FC), maximum water holding capacity (MWHC), moist bulk density (MBD), dry bulk density (DBD) and total porosity (TP) were determined using the core sampling method. The collected samples were saturated, allowed to drain under gravity for 24 - 48 hours (for FC), and then oven-dried. MWHC was calculated after full saturation and drainage. These parameters were calculated using Equations (2) and Equation (3), respectively.

$$\mathrm{FC}(\%)=\frac{W_2-W_3}{W_3-W_1}\times 100 \quad (2)$$

$$\mathrm{MWHC}(\%)=\frac{W_4-W_3}{W_3-W_1}\times 100 \quad (3)$$

W_1 = weight of core, W_2= weight of soil at field capacity + core, W_3 = weight of dry soil + core, W_4 = weight of saturated soil + core, W_5 = weight of moist soil, V = volume of core.

MBD and DBD were calculated using Equation (4) and Equation (5), respectively.

$$\mathrm{MBD}\left(\mathrm{g}\cdot\mathrm{cm}^{-3}\right)=\frac{W_5-W_1}{V} \quad (4)$$

$$\mathrm{DBD}\left(\mathrm{g}\cdot\mathrm{cm}^{-3}\right)=\frac{W_3-W_1}{V} \quad (5)$$

Finally, total porosity (TP) was calculated based on previously measured BD and PD values, following Equation (6); [34]:

$$\mathrm{Porosity}(\%)=\left(1-\frac{\mathrm{BD}}{\mathrm{PD}}\right)\times 100 \quad (6)$$

SOC was determined using the wet oxidation method of Walkley and Black, [35], and in order to calculate soil organic matter (SOM), the percentage of organic carbon was multiplied by 1.724.

2.6. Statistical Data Analysis

Before statistical analysis, the normality of all variables was assessed using the Shapiro-Wilk test, with a p-value > 0.05 indicating that the data did not significantly deviate from a normal distribution. To obtain one representative observation for each topographic position, the three soil samples collected within each position were averaged, yielding 27 observations (9 land-use systems × 3 topographic positions) for subsequent statistical analyses. One-way analysis of variance (ANOVA) was then performed to evaluate differences in soil physical properties among the land-use systems. Duncan's Multiple Range Test (DMRT) was used for post hoc comparisons, with statistical significance considered at $p < 0.05$, $p < 0.01$, and $p < 0.001$. Pearson correlation analysis and simple linear regression were applied to examine relationships between soil physical properties and topographic variables (altitude and slope). These methods were selected to identify overall patterns and associations within the dataset. However, because the sampling design was hierarchical, with slope positions nested within representative hill sites, the analyses do not explicitly account for the nested structure of the data. Therefore, the findings are interpreted as exploratory associations among the sampled sites rather than as formal hierarchical inference. All statistical analyses were performed using Microsoft Excel 2010 and IBM SPSS Statistics 27.0.

3. Results and Discussion

3.1. Soil Structure and Color across the Land-Use Sites

Granular soil structures were observed in agroforestry systems, multi-strata agroforestry systems, mature mixed timber forests, and natural forests (**Table 1**), owing to their rich organic matter and favorable moisture conditions. These land-use practices maintain well-structured, healthy soils with strong water-retention capacity, in sharp contrast to the compact or blocky structures often associated with monoculture plantations. The acacia forest showed a single-grain structure due to sandy loam texture, which was linked to low aggregation and water retention and increased erosion. Blocky soil structures were observed in young teak forest, shifting cultivation area, mature teak forest, and multi-story fruit garden (**Table 1**). The low and sparse canopy cover in teak forests increased soil erosion [36], while the erosional effects of shifting cultivation further degrade the soil properties [37]-[40], which collectively contribute to the formation of these blocky soil structures. Cultivation practices along hill slopes in upland agriculture and shifting cultivation with the burning of vegetation degrade soil structure, reduce aggregate stability and make soils more prone to runoff and increases erosion risks as observed in other studies [41]-[44].

Walia and Rao, [45], explained that soil color depends on its chemical composition, mineralogy, topography, and moisture regimes. **Table 1** showed that under moist conditions, a dark grayish-brown color was observed in the agroforest system, mixed mature timber forest and natural forest due to litter decomposition in natural ecosystems and the application of organic manure in the agroforest system [46]. Dark brown soils in the multi-strata agroforest system suggest medium OM, whereas lighter brown soils in the mature teak forest reflect low OM. Yellowish-brown soils in acacia forest and shifting cultivation suggest low OM and potential leaching. Multi-story fruit garden and young teak forest soils are colored dark reddish-brown, probably because of the presence of iron oxide, consistent with lower organic matter. The present results agree with those of Huq and Shoaib, [15], Biswas *et al.* [28], and Mamun *et al.* [46], who reported yellow-brown to reddish-brown and grey soils on the steeper slopes of the hill.

3.2. Soil Textural Classes across the Land-Use Sites

Soil samples collected from young teak forest, shifting cultivation, multi-strata agroforestry system, mature teak forest, multi-story fruit garden and mature mixed timber forest were sandy clay loam in texture, whereas those of agroforest system, acacia forest, and natural forest represented clay loam, sandy loam and loam respectively (Table 1). According to the USDA Soil Classification of Soil Textures, the soils in this study area are primarily classified as moderately fine-textured loamy soils, with a range from sandy loams to sandy clay loams. Previous studies on different forest land uses in the Chittagong Hill Tracts (CHTs), including agroforestry, teak forests, plantation forests, shifting cultivation, and natural forests, have observed similar soil textures [24] [28] [47].

Table 1. Distribution of means for soil particle size (sand, silt, and clay), color, structure and textural classes at 0 - 20 cm soil depth across different land-use sites.

LUS	Sand%	Silt %	Clay %	TC	Structure	Soil color
AFs	37.12 ± 1.00*	27.35 ± 0.64	35.53 ± 0.55**	CL	Granular	Dark Grayish Brown
AF	66.13 ± 5.69*	21.81 ± 4.02	12.06 ± 1.73***	SL	Single grain	Yellowish Brown
YTF	55.57 ± 3.79	17.77 ± 6.11	26.67 ± 2.52	SCL	Crumb	Dark Radish Brown
SC	57.87 ± 4.04	17.87 ± 6.66	24.26 ± 2.65	SCL	Blocky	Yellowish Brown
MAFS	55.26 ± 3.00	23.07 ± 4.04	21.67 ± 1.15	SCL	Blocky	Dark Brown
MTF	52.08 ± 3.61	20.56 ± 2.65	27.36 ± 2.00	SCL	Blocky	Brown
MSFG	52.33 ± 4.51	21.00 ± 3.46	26.67 ± 2.52	SCL	Blocky	Dark Radish Brown
MMTF	53.63 ± 7.02	16.60 ± 5.00	29.77 ± 2.08	SCL	Granular	Dark Grayish Brown
NF	46.25 ± 2.08	34.19 ± 1.10	19.56 ± 1.54	L	Granular	Dark Grayish Brown
Mean	52.92 ± 8.42	22.25 ± 6.37	24.84 ± 6.59	-	-	-
F-value	10.696	5.176	34.044	-	-	-
p-value	<0.000***	=0.002**	<0.000***	-	-	-

Values represent the mean ± standard deviation of the three laboratory-analyzed samples collected at each topographic position. Significance levels are marked as $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$. SD—Standard deviation, AFs—Agroforest system, AF—Acacia forest, YTF—Young teak forest, SC—Shifting cultivation, MAFS—Multi-strata agroforestry system, MTF—Mature teak forest, MSFG—Multi-story fruit garden, MMTF—Mature mixed timber forest, NF—Natural forest; TC—Textural Class; CL-Clay loam, SL-Sandy loam, SCL-Sandy clay loam and L-Loam.

One-way ANOVA was applied to compare the mean differences in sand, silt and clay content between each site. The analysis results showed that the percentages of sand, silt, and clay were significantly different at ($p < 0.001$) with land-use sites (Table 1). Post-hoc analysis showed that the mean sand percentage under the agroforest system and acacia forest showed significant differences ($p < 0.05$), whereas no significant differences ($p > 0.05$) were found among the young teak forest, shifting cultivation, multi-strata agroforestry system, mature teak forest, multi-story fruit garden, mixed mature timber forest, and natural forest sites regarding the percentage of sand. Relative to the other systems, the mean percentage of sand was highest under the acacia forest (66.13%) and lowest under the agroforest system (37.12%). The overall mean sand content was 52.92%. The percentage of mean sand was recorded in the order of AF > SC > YTF > MMTF > MAFS >

MSFG > MTF > NF > AFs in the different land-use sites (**Table 1**). On the contrary, no significant differences ($p > 0.05$) were observed among the different land-use sites in terms of silt percentage. The mean percentage of silt was highest in the natural forest (34.19%), and the lowest mean value was recorded in the mature mixed timber forest (16.60%). The overall mean value of silt was 22.25%. The percentage of silt in different land-use sites was recorded in the following order: NF > AFs > MAFS > AF > MSFG > MTF > SC > YTF > MMTF (**Table 1**). Finally, clay content showed significant differences under the agroforest system ($p < 0.01$) and the acacia forest ($p < 0.001$), whereas no significant differences ($p > 0.05$) were observed for young teak forest, shifting cultivation, multi-strata agroforestry system, mature teak forest, multi-story fruit garden, mature mixed timber forest, and natural forest sites in terms of clay percentage. The highest mean percentage of clay was recorded in the agroforest system (35.53%), and the lowest mean value was recorded in the acacia forest (12.06%). In addition, the mean clay content was 24.84%. The percentage of clay was recorded among different land-use sites in the following order: AFs > MMTF > MTF > YTF > MSFG > SC > MAFS > NF > AF (**Table 1**). Soils with more sand than silt and clay tend to be well-drained, but they may not provide nutrients for prolonged fertility, as sand does not hold nutrients or moisture as well. The parent material from which these hill soils are formed is sandstone, which is the dominant parent material of these soils, resulting in sandy textures that dominate in hill soils [48]. According to Singh *et al.* [43], variation in texture is greatly influenced by land-use and vegetation composition. Although soil texture is an inherent property, it can be altered by pedogeologic processes such as erosion, deposition, illuviation, and weathering, which are themselves influenced by management practices [49] [50] who reported higher sand content in monoculture (eucalyptus) plantation compared to natural forest. In contrast, the lower clay content in eucalyptus plantations compared to forest areas indicates that soil degradation and erosion processes have contributed to the loss of finer clay particles.

3.3. Moisture Content, Field Capacity and Maximum Water-Holding Capacity across the Land-Use Sites

The analysis of variance (ANOVA) results showed that soil moisture-related indicators, such as moisture content (MC), field capacity (FC), and maximum water-holding capacity (MWHC), were significantly different ($p < 0.001$) among the land-use sites (**Table 2**). Post-hoc test of MC revealed that natural forest and multi-story fruit garden showed significant differences ($p < 0.05$). In contrast, no significant differences ($p > 0.05$) were found among the agroforest system, acacia forest, young teak forest, shifting cultivation, multi-strata agroforestry system, mature teak forest and mixed mature timber forest sites regarding the percentage of MC. The highest mean percentage of MC was recorded in soils under natural forest (33.47%), while the lowest mean MC value was recorded in soils under the multi-story fruit garden (14.01%). In addition, the overall mean MC was 23.37%

(**Table 2**). The percentage of MC in different land-use sites was recorded in the following order: NF > AFs > MAFS > MMTF > AF > MTF > SC > YTF > MSFG (**Table 2**).

Similarly, the post-hoc test for FC demonstrated that the natural forest showed significant differences ($p < 0.05$), whereas no significant differences ($p > 0.05$) were observed among the agroforest system, acacia forest, young teak forest, shifting cultivation, multi-strata agroforestry system, mature teak forest, multi-story fruit garden, and mixed mature timber forest sites in terms of FC percentage. Soils under the natural forest had the highest mean FC (36.38%), and soils under the multi-story fruit garden had the lowest mean FC (14.55%). Also, the overall mean FC was 23.88% (**Table 2**). The percentage of FC in different land-use sites was recorded in the following order: NF > AFs > MMTF > MAFS > AF > SC > MTF > YTF > MSFG (**Table 2**).

In this study, higher MC and FC were observed in natural forests and agroforestry systems, which resulted in increased water retention capacity due to organic matter enrichment, greater plant coverage, and well-textured and structured soil properties. These findings align with those of Chowdhury *et al.* [24], Fentie *et al.* [51], and Gebrekidan *et al.* [52], who reported higher MC in plantation sites of forests compared to other land uses. Comparatively, multi-story fruit garden, shifting cultivation, and mature teak forest reported lower MC as well as lower FC, presumably due to erosion, slope, height, soil texture and lesser organic matter. Likewise, Salim *et al.* [53] observed higher MC in the case of a mixed plantation site due to a higher layer of litter over the ground, which forms a protective layer against evaporation. In contrast, a lower MC was observed at the plantation site under Acacia, attributed to the sandy loam soil texture.

The post-hoc analysis of MWHC showed that the young teak forest ($p < 0.01$), multi-strata agroforestry system ($p < 0.05$), mature teak forest ($p < 0.01$), and mixed mature timber forest ($p < 0.001$) differed significantly from one another. No significant variations ($p > 0.05$) were observed among the agroforest system, acacia forest, shifting cultivation, multi-strata fruit garden, and natural forest sites regarding MWHC percentage. The highest MWHC was recorded (43.56%) under mixed mature timber forest, and the lowest MWHC was recorded (32.09%) under young teak forest. Besides, the total means MWHC was 37.15% (**Table 2**). The percentage of MWHC in different land-use sites was recorded in the following order: MMTF > NF > AFs > MAFS > MSFG > AF > SC > MTF > YTF (**Table 2**).

Chowdhury *et al.* [54] found higher MWHC in forested sites than in orange orchid as well as in teak forest in CHTs, which confirms the results of this study. Moreover, Mamun *et al.* [46] have also found that higher MWHC of natural forest may occur due to higher OM as well as dense litter. However, a lower MWHC of monoculture plantation or in mixed fruit orchard may occur due to deficiency in ground floor vegetation, compaction and over-erosion. These findings confirm the current study results. The water-holding capacity was closely related to the mechanical composition of the soil, like other factors. The clay loam and loam soils tended to have higher water holding capacity than other textural classes. Huq and Shoaib [15] stated that brown hill soils have a low water-holding capacity due to their permeable, friable, and loamy texture.

3.4. Soil Bulk Density and Porosity across the Land-Use Sites

The ANOVA results revealed that both moist and dry bulk density (BD) of soils were highly significantly different ($p < 0.001$) across land-use sites (**Table 2**). In contrast, the post-hoc test denoted significant differences in DBD ($p < 0.05$) for the acacia and natural forests, but no significant differences ($p > 0.05$) among the other land-use sites. The highest mean DBD was recorded under the acacia forest (1.48 g/cm^3), whereas the lowest mean DBD was recorded under the natural forest (1.30 g/cm^3). The overall mean DBD was 1.39 g/cm^3. The DBDg/cm^3 in different land-use sites was observed in the following order: AF > MTF > YTF > SC > AFs > MSFG > MAFS > MMTF > NF (**Table 2**).

The post-hoc test for MBD exposed a significant difference ($p < 0.01$) in the natural forest, while the other land-use sites showed no significant differences ($p > 0.05$). The highest MBD was recorded in mature teak forest and acacia forest (1.73 g/cm^3), whereas the lowest MBD was recorded in natural forest (1.54 g/cm^3). The overall mean MBD was 1.65 g/cm^3. The MBDg/cm^3 was recorded in the order of MTF > AF > AFs > SC > YTF > MAFS > MSFG > MMTF > NF in different land-use sites (**Table 2**).

These findings align with previous studies, such as Chowdhury *et al.* [24], who reported that higher DBD is found in agroforestry systems. In contrast, Mamun *et al.* [46], observed the highest BD in *Tectona grandis* plantations and the lowest in natural forests. Besides, numerous researchers have reported that the bulk density of an agricultural site is higher than that of a natural forest site [55]. This difference in BD could be because of the greater organic matter content of natural forest as opposed to agricultural sites, which undergo continuous removal of organic matter with minimal addition to cultivated land [56]. In the present study, agroforest system, acacia forest, shifting cultivation, multi-strata agroforestry systems, and multi-story fruit gardens exhibited higher BD, which may also be attributed to erosion, continuous agricultural activities, and frequent tillage or machinery use [50]. Salim [53] observed that higher BD in the monoculture forest systems and lower BD in the mixed plantations, which indicates that lower BD is associated with higher organic matter content, which serves as a key indicator of improved soil quality. The lower BD found in the natural forest might be due to the result of less disturbance and high plant residues input in forest soil [57] as well as this lower BD in forest soils results in an improved soil structure and increased water holding capacity [58]. Besides, many other studies, e.g. Amponash [11] and Mongya [59] found that replacing virgin forests with high-value plantation species led to a rapid degradation in soil physical properties, including an increase in surface BD compared to virgin forest soils. Besides land-use changes, soil density depends on many other factors such as elevation, slope gradient, soil texture, SOM, climatic variables, etc.

Similarly, ANOVA results also showed that mean total porosity (TP) was significantly different among land-use sites ($p < 0.001$) (Table 2). Post-hoc analysis revealed that only the acacia forest showed significant differences in TP ($p < 0.05$), whereas no significant differences were observed among other land-use sites in terms of the percentage of TP. The highest mean TP was recorded under natural forest (56.18%), and the lowest mean TP was recorded under acacia forest (44.75%). In addition, the overall mean TP was 50.17 g/cm^3. The percentage of TP in different land-use sites was observed in the following order: NF > MMTF > MAFS > AFs > MSFG > SC > MTF > YTF > AF (Table 2).

Table 2. Distribution of mean (±SD) soil physical indicators (0 - 20 cm depth) across different land-use types in Chittagong Hills.

	Soil Physical Indicators						
LUS	MC (%)	FC (%)	MWHC (%)	DBD (g/cm^3)	MBD (g/cm^3)	TP (%)	SOM (%)
AFs	28.32 ± 1.92	28.47 ± 2.20	39.84 ± 0.35	1.40 ± 0.02	1.71 ± 0.01	51.88 ± 0.59	4.28 ± 0.61
AF	23.45 ± 3.51	23.79 ± 4.76	35.72 ± 1.16	1.48 ± 0.02*	1.73 ± 0.01	44.75 ± 1.66*	2.45 ± 0.34
YTF	17.84 ± 1.26	19.32 ± 5.49	32.09 ± 1.07**	1.44 ± 0.01	1.66 ± 0.02	46.63 ± 0.18	2.12 ± 0.16
SC	18.48 ± 2.05	21.84 ± 4.22	35.68 ± 0.37	1.42 ± 0.01	1.66 ± 0.01	48.02 ± 1.24	1.14 ± 0.28
MAFS	27.61 ± 3.17	23.80 ± 3.99	37.38 ± 0.21*	1.34 ± 0.02	1.64 ± 0.02	52.90 ± 0.67	3.54 ± 0.15
MTF	21.78 ± 1.49	20.59 ± 6.25	33.98 ± 0.26**	1.44 ± 0.04	1.73 ± 0.02	47.21 ± 1.16	1.66 ± 0.77
MSFG	14.01 ± 1.77*	14.55 ± 3.95	35.91 ± 1.00	1.36 ± 0.01	1.60 ± 0.02	49.30 ± 0.65	2.99 ± 0.13
MMTF	25.34 ± 1.09	26.18 ± 4.72	43.56 ± 0.58***	1.33 ± 0.02	1.59 ± 0.02	54.64 ± 0.94	4.43 ± 0.24
NF	33.47 ± 2.33*	36.38 ± 2.36*	40.22 ± 0.49	1.30 ± 0.01*	1.54 ± 0.02**	56.18 ± 1.58	5.42 ± 0.40**
Total mean	23.37 ± 6.10	23.88 ± 6.97	37.15 ± 3.43	1.39 ± 0.10	1.65 ± 0.06	50.17 ± 3.87	3.11 ± 1.40
F-value	22.592	5.932	75.830	28.985	60.096	40.332	37.340
p-value	<0.000***	<0.000***	<0.000***	<0.000***	<0.000***	<0.000***	<0.000***

Values represent the mean ± standard deviation of the three laboratory-analyzed samples collected at each topographic position. Significance levels are marked as *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$. SD—Standard deviation, AFs—Agroforest system, AF—Acacia forest, YTF—Young teak forest, SC—Shifting cultivation, MAFS—Multi-strata agroforestry system, MTF—Mature teak forest, MSFG—Multi-story fruit garden, MMTF—Mature mixed timber forest, NF—Natural forest, MC—Moisture content, FC—Field capacity, MWHC—Maximum water holding capacity, DBD—Dry bulk density, MBD—Moist bulk density, TP—Total porosity, SOM—Soil organic matter.

In this study, both natural forest and mixed plantation forest showed higher porosity than the acacia forest, because of the large amount of litter input and rich soil organic matter (SOM) that enhances soil porosity. These factors contribute to lower BD and greater pore space, thereby facilitating improved air and water movement through the soil [60] [61]. In contrast, acacia forest, shifting cultivation and teak plantations sites showed low pore space due to the soil texture (sandy clay, sandy clay loam), lower SOM content and erosion process. These results are consistent with the findings of [46] [59] [62]. Generally, compacted soils have lower porosity and greater BD, while looser soils have more porosity and lower BD [63]-[65].

3.5. Soil Organic Matter across the Land-Use Sites

The ANOVA results showed that soil organic matter (SOM) content was significantly different among land-use sites ($p < 0.001$) (**Table 2**). Post-hoc analysis revealed that only the natural forest showed significant differences in SOM ($p < 0.01$).In contrast, no significant differences ($p > 0.05$) were observed between the other land-use sites in the percentage of SOM. The highest mean SOM (5.42%) was recorded under the natural forest, and the lowest mean SOM was recorded under the shifting cultivation (1.14%). The overall average SOM was 3.11%. The SOM content was observed in the order of NF > MMTF > AFs > MAFS > MSFG > AF > YTF > MTF > SC in different land-use sites (**Table 2**).

In line with these findings, the natural forest site in this study, which had high litter input, exhibited higher SOM, whereas the acacia plantation, with lower litter fall, showed reduced SOM [53] also, it was reported that mixed plantation forests are the most effective system, as they increase SOM and improve soil structure, which aligns with the present study findings. A relatively high level of SOM was observed in natural forestland, followed by grazing and farmland [66], and also noted that as forestland changes to farmland and grazing land uses, SOM decreases. Zeng *et al.* [67] highlighted that forest soils with higher SOM serve as reservoirs of essential plant nutrients. Similarly, Sevgi and Tecimen [68] observed that the production and return of large amounts of litter in natural forests contribute to higher SOM content. According to Demelash and Stahr [69], Hailu *et al.* [70], and Hishe *et al.* [71], soil OC is higher on conserved land than on non-conserved land.

3.6. Topographic Variables (Altitude and Slope) across the Land-Use Sites

As illustrated in **Table 3**, significant topographic variables (altitude and slope) were observed across different land-use types in the study area of the Chittagong. Specifically, altitude ranged from 10.78 meters in mature mixed timber forest to a maximum of 130.01 meters in multi-strata agroforestry systems. Similarly, slope gradients varied considerably, from a gentle incline of 5.78% in natural forests to a steep slope of 107.54% in the acacia forest. Multi-strata agroforestry systems situated at Talukdar Para, Bandarban, take the lead with the highest mean elevation (106.35 m) and slope (77.30%), indicative of typical upland cultivation practices in Bangladesh. On the contrary, the mean altitude (26.43 m) and slope (26.07%) of the mature mixed timber forest in Kaptai, Rangamati, indicate much less steep terrain. Mean altitudes across the sites range from 26.43 to 106.35 m in the following order: MMTF < NF < YTF < AF < AFs < SC < MSFG < MTF < MAFS (**Table 3**). In order from gentlest to steepest slope as follows: MMTF < NF < YTF < MTF < MSFG < AFs < SC < AF < MAFS (**Table 3**).

The study indicates that variations in altitude and slope across different land-use types are affecting soil drainage, erosion and fertility, which corroborates previous studies in hilly terrains of Bangladesh. According to Biswas *et al.* [28], the increase in altitude, along with the steepness of the slope, leads to better-drained soil, making it prone to erosion. On the other hand, steep slopes (e.g., MAFS at 77.30%) are problematic for soil retention. Shoaib *et al.* [72] reported that soil erosion was higher in areas of shifting cultivation (40 - 45 $t \cdot ha^{-1} \cdot yr^{-1}$) and on slopes (33% - 42%) than on gentle slopes (15%), highlighting the necessity for sustainable land-use planning.

Table 3. Topographic variables (altitude and slope) across different land-use sites.

LUS	Altitude (m)				Slope (%)			
	Hill top	Hill middle	Hill bottom	Mean ± SD	Hill top	Hill middle	Hill bottom	mean ± SD
AFs	53.05	41.23	28.02	40.77 ± 12.52	95.04	68.55	9.68	57.76 ± 43.69
AF	54.23	40.67	22.09	39.00 ± 16.14	107.54	72.05	28.47	69.35 ± 39.60
YTF	52.43	34.17	19.33	35.31 ± 16.58	65.67	49.43	19.07	44.72 ± 23.65
SC	81.76	65.96	37.26	61.66 ± 22.56	84.15	75.76	30.17	63.36 ± 29.05
MAFS	130.01	110	79.04	106.35 ± 25.68	100.54	90	41.36	77.30 ± 31.57
MTF	119.6	99.13	78.15	98.96 ± 20.73	84.15	61.96	25.36	57.16 ± 29.67
MSFG	98.56	78.55	50.21	75.77 ± 24.29	84.15	58.8	29.43	57.46 ± 27.38
MMTF	40.33	28.18	10.78	26.43 ± 14.85	49.43	19.09	9.68	26.07 ± 20.77
NF	44.55	30.46	18.62	31.21 ± 12.98	65.21	32.46	5.78	34.48 ± 29.77
		F-value		7.461		*F*-value		0.822
		p-value		0.000		*p*-value		0.594

Values represent the mean ± standard deviation of the three samples collected at each topographic position. AFs—Agroforest system; AF—Acacia forest; YTF—Young teak forest; SC—Shifting cultivation; MAFS—Multi-strata agroforestry system; MTF—Mature teak forest; MSFG—Multi-story fruit garden; MMTF—Mature mixed timber forest; NF—Natural forest.

3.7. Pearson Correlation Coefficient Analysis between the Soil Physical Indicators and Topographic Variables

The Pearson correlation between soil physical indicators and topographical variables of different land-use sites demonstrated strong and significant relationships at the 95% and 99% confidence levels at $p < 0.05$ and $p < 0.01$, respectively (**Table 4**).

The analysis results revealed a strong, significant positive relationship between altitude and slope ($r = 0.679$, $p < 0.01$), indicating that higher-elevation areas in the study region are generally associated with steeper slopes. On the other hand, both soil FC ($r = -0.585$, $p < 0.01$), MWHC ($r = -0.405$, $p < 0.05$), and SOM ($r = -0.430$, $p < 0.05$) showed significant negative correlations with altitude, suggesting a lower water-holding capacity at higher altitudes [73], and similar studies have shown that SOM is significantly correlated with altitude [74]-[76]. Sand content ($r = 0.434$, $p < 0.05$), DBD ($r = 0.407$, $p < 0.05$), and MBD ($r = 0.431$, $p < 0.05$) were strongly positively correlated with slope. In contrast, silt content ($r = -0.395$, $p < 0.05$), FC ($r = -0.561$, $p < 0.01$), TP ($r = -0.421$, $p < 0.05$), and OM ($r = -0.424$,

$p < 0.05$) showed negative correlations with slope, indicating that the highest TP at lower topography [73]. These results suggest that steeper slopes generally contain higher sand fractions than clay and silt [77] [78]. They also found that the soil textural fractions of sand, silt, and clay differed significantly with respect to the slope gradient. In addition, steeper slopes tend to develop denser soils with reduced water retention and lower OM content [70] [79]. Silt content ($r = -0.634$, $p < 0.01$), clay content ($r = -0.664$, $p < 0.01$), MC ($r = -0.473$, $p < 0.05$), FC ($r = -0.529$, $p < 0.01$), MWHC ($r = -0.437$, $p < 0.05$), TP ($r = -0.598$, $p < 0.01$) and OM content ($r = -0.572$, $p < 0.01$) showed significant negative correlations with sand content but DBD ($r = 0.467$, $p < 0.05$) was strongly positively correlation with sand content.

Table 4. Pearson correlation coefficient between the soil physical indication and topographical variables of study soils.

Indicators	Altitude (m)	Slope (%)	Sand (%)	Silt (%)	Clay (%)	MC (%)	FC (%)	MWHC (%)	DBD g/cm³	MBD g/cm³	TP (%)	SOM (%)
Altitude (m)	1											
Slope (%)	0.679**	1										
Sand (%)	0.261	0.434*	1									
Silt (%)	−0.337	−0.395*	−0.634**	1								
Clay (%)	−0.007	−0.173	−0.664**	−0.157	1							
MC (%)	−0.327	−0.345	−0.473*	0.718**	−0.089	1						
FC (%)	−0.585**	−0.561**	−0.529**	0.788**	−0.086	0.896**	1					
MWHC (%)	−0.405*	−0.360	−0.437*	0.344	0.225	0.642**	0.617**	1				
DBD g/cm³	0.142	0.407*	0.467*	−0.446*	−0.165	−0.497**	−0.503**	−0.685**	1			
MBD g/cm³	0.300	0.431*	0.239	−0.325	0.009	−0.269	−0.378	−0.534**	.892**	1		
Porosity (%)	−0.237	−0.421*	−0.598**	0.518**	0.263	0.708**	0.662**	0.825**	−0.924**	−0.756**	1	
SOM (%)	−0.430*	−0.424*	−0.572**	0.624**	0.128	0.756**	0.712**	0.800**	−0.784**	−0.633**	0.869**	1

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).

These results suggest that an increase in sand content reduces silt and clay content, as well as the percentages of MC, FC, MWHC, pore space, and soil organic matter in the study soil. Additionally, silt content exhibited significant positive correlations with MC ($r = 0.718$, $p < 0.01$), FC ($r = 0.788$, $p < 0.01$), TP ($r = -0.598$, $p < 0.01$) and OM ($r = -0.598$, $p < 0.01$), highlighting the increased water retention capacity, pore space and high organic content retention than sandy soils. In contrast, dry BD ($r = -0.446$, $p < 0.05$) showed a negative correlation with silt content. Similarly, FC ($r = 0.896$, $p < 0.01$), MWHC ($r = 0.642$, $p < 0.01$), TP ($r = 0.708$, $p < 0.01$) and OM content ($r = 0.756$, $p < 0.01$) were strongly positively correlated with MC, indicating the role of MC, which increases organic matter content in soil. Besides, MC and FC showed negative correlations with DBD ($r = -0.497$, $p < 0.01$; $r = -0.414$, $p < 0.05$), indicating that soils with higher moisture levels tend to have lower compaction. But FC showed a strong positive correlation with MWHC ($r = 0.617$, $p < 0.01$), TP ($r = 0.662$, $p < 0.01$), and SOM ($r = 0.712$, $p < 0.01$), suggesting that higher field moisture is associated with improved soil structure. MWHC exhibited a strong negative correlation with DBD ($r = -0.685$, $p < 0.01$) and MBD ($r = -0.534$, $p < 0.01$), reflecting that soils with higher water retention tend to have lower bulk densities. On the contrary, MWHC was significantly positively correlated with TP ($r = 0.817$, $p < 0.01$) and SOM ($r = 0.780$, $p < 0.01$), suggesting that soils with higher pore space and greater organic matter content retain more water. Both dry and moist BD exhibited strong negative correlations with TP ($r = -0.924$, $p < 0.01$ and $r = -0.756$, $p < 0.01$, respectively) and SOM ($r = -0.784$, $p < 0.01$ and $r = -0.633$, $p < 0.01$), indicating that the study soils are more compacted [80]. Moreover, several authors have demonstrated that soil organic matter is negatively correlated with soil bulk density, i.e., soil bulk density decreases with increasing soil organic matter content [81]-[83]. Dry BD showed a strong positive correlation with MBD ($r = 0.892$, $p < 0.01$), and TP was strongly positively correlated with SOM ($r = 0.828$, $p < 0.01$), confirming that higher organic matter content is associated with greater pore space.

3.8. Linear Regression Analysis between Slope, Altitude and Soil Physical Indicators

Regression analyses between altitude, slope, and soil physical indicators were conducted using 27 averaged observations, representing the mean values of three sampling points within each slope position across the nine land-use systems. Therefore, the reported relationships describe overall associations among the sampled sites. Linear regression analysis showed that several soil physical indicators were significantly associated with both slope and altitude (**Figure 3** and **Figure 4**). The moisture-related parameter FC, showed statistically significant negative relationships with both altitude ($R^2 = 0.342$, $p < 0.001$) and slope ($R^2 = 0.314$, $p < 0.01$), accounting for 34.20% and 31.40% of the variance, respectively. Similarly, MWHC also showed a significantly negative relationship with altitude ($R^2 = 0.164$, $p < 0.05$) but no significant relationship with slope ($p > 0.05$), explaining 16.40% and 13% of the variance, respectively. However, DBD and MBD accounted for 16.60% ($R^2 = 0.166$, $p < 0.05$) and 18.60% ($R^2 = 0.186$, $p < 0.05$) of the variance, indicating moderate but significant effects associated with slope position (**Table 5**). These results highlight that soils become more compacted with increasing elevation and slope position. Porosity exhibited an inverse relationship with both altitude ($R^2 = 0.056$) and slope ($R^2 = 0.177$, $p < 0.05$), explaining 5.60% and 17.70% of the variance. This finding is consistent with those of Dagnachew *et al.* [84], Hailemariam *et al.* [85], & Tanto and Laekemariam [86], who reported that porosity values often decrease as slope gradient increases. Soil OM explained 18.00% of the variation ($R^2 = 0.180$, $p < 0.05$) with slope and 18.51% of the variation ($R^2 = 0.1851$, $p < 0.05$) with altitude (**Table 5**). Sand and silt content exhibited significant relationships with slope, accounting for 18.90% (R^2

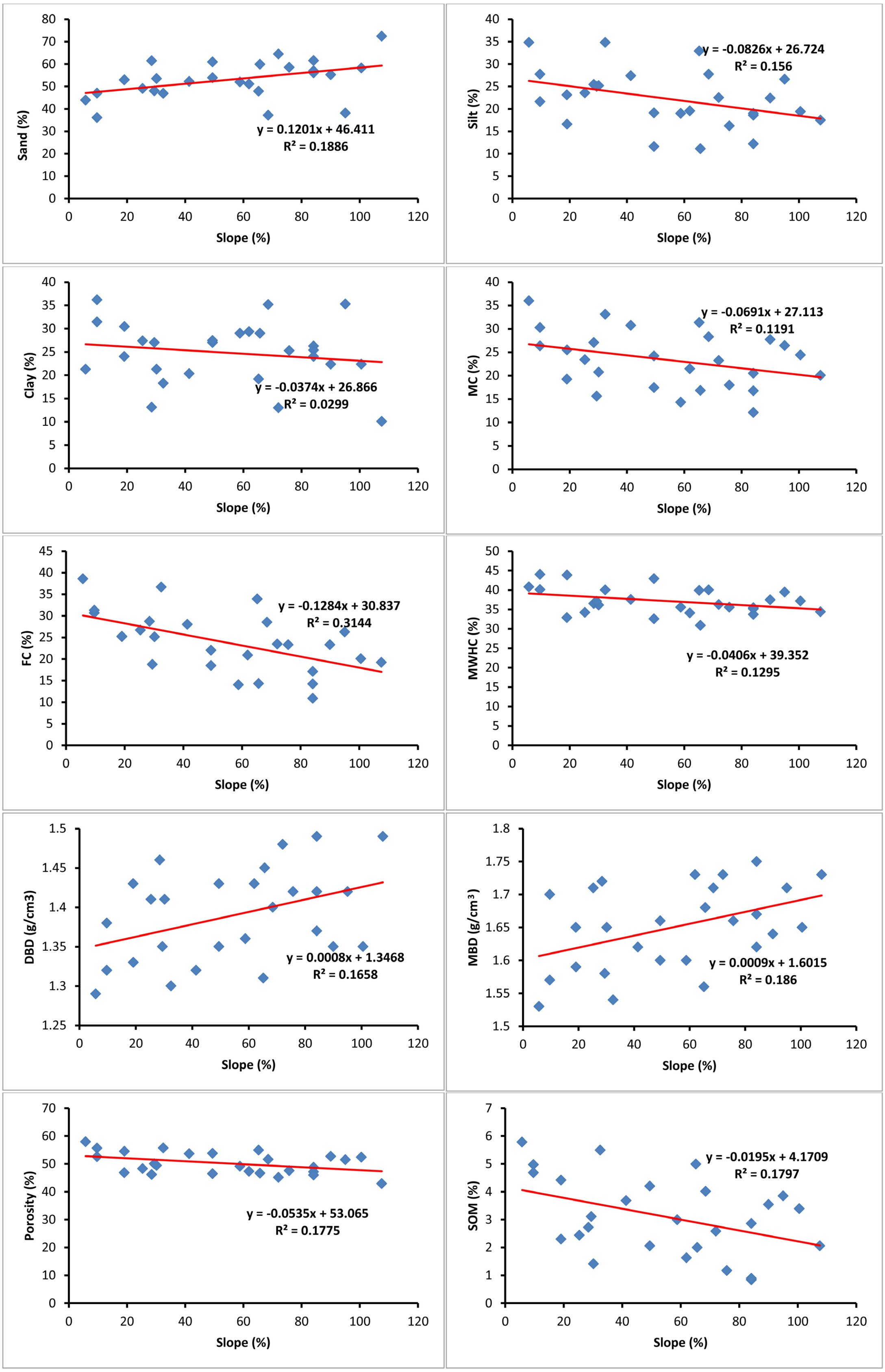


Figure 3. Linear regressions showing the effect of altitude on soil physical properties in the Chittagong Hills.

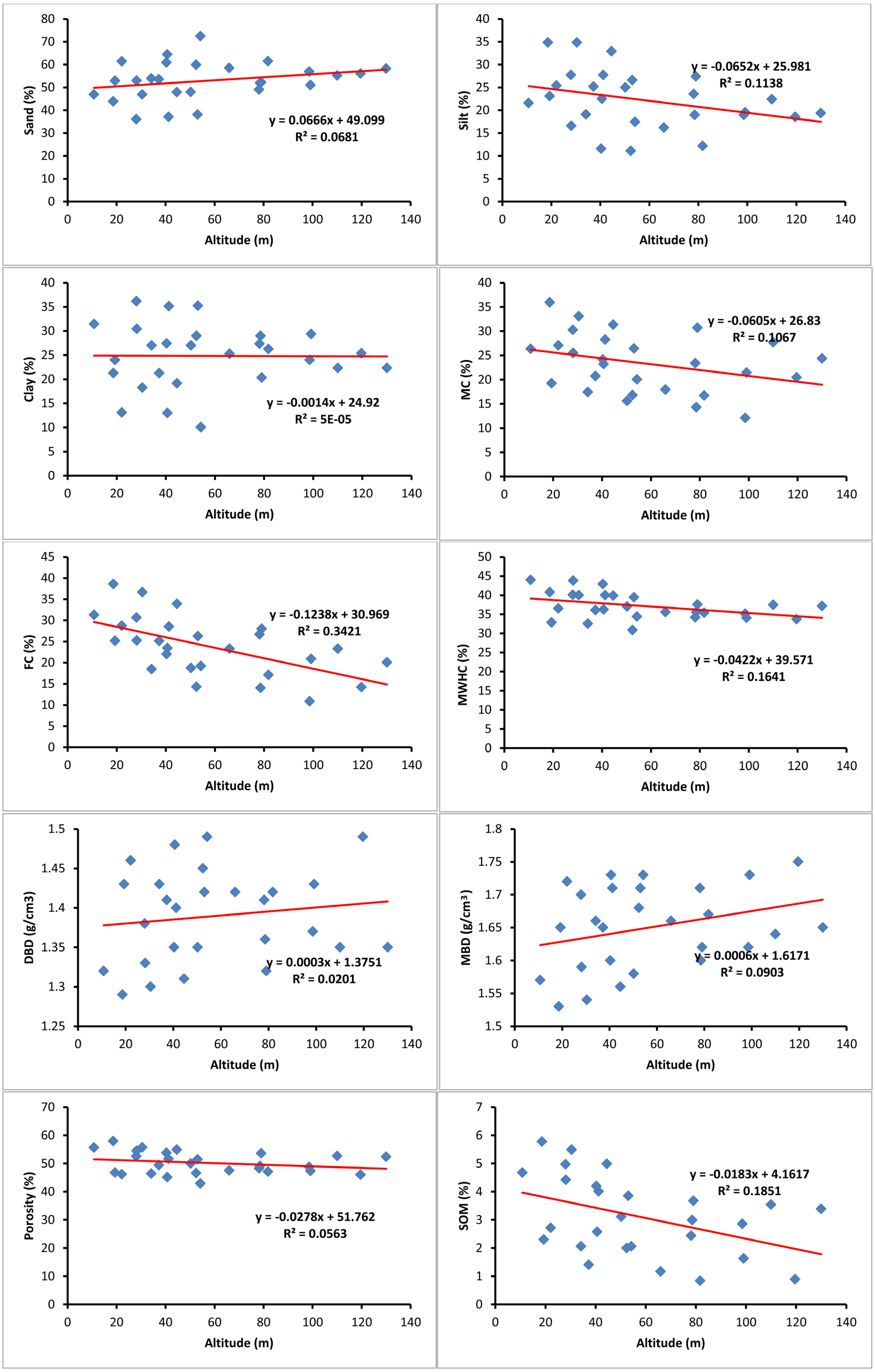


Figure 4. Linear regressions showing the effect of slope on soil physical indicators in the Chittagong Hills.

Table 5. Linear regression analysis between soil physical indicators and topographical variables (altitude and slope) in the Chittagong Hills.

Soil Physical Indicators	Altitude				
	Multiple *R*	R^2	Adjusted R^2	*F*	Sig
Sand (%)	0.260	0.068	0.031	1.826	0.189
Silt (%)	0.338	0.114	0.078	3.210	0.085
Clay (%)	0.000	0.000	−0.040	0.001	0.972
Moisture Content (%)	0.327	0.107	0.071	2.986	0.096
Field Capacity (%)	0.585	0.342	0.316	12.999	0.001
Maximum Water Holding Capacity (%)	0.405	0.164	0.131	4.908	0.036
Dry Bulk Density (g/cm^3)	0.142	0.020	−0.019	0.514	0.480
Moist Bulk Density (g/cm^3)	0.300	0.090	0.054	2.481	0.128
Porosity (%)	0.237	0.056	0.019	1.491	0.233
Soil Organic Matter (%)	0.430	0.185	0.152	5.676	0.025
Soil Physical Indicators	**Slope**				
	Multiple *R*	R^2	Adjusted R^2	*F*	Sig
Sand (%)	0.435	0.189	0.156	5.813	0.024
Silt (%)	0.395	0.156	0.122	4.622	0.041
Clay (%)	0.173	0.030	−0.009	0.770	0.389
Moisture Content (%)	0.345	0.119	0.084	3.381	0.078
Field Capacity (%)	0.560	0.314	0.287	11.463	0.002
Maximum Water Holding Capacity (%)	0.361	0.130	0.095	3.719	0.065
Dry Bulk Density (g/cm^3)	0.407	0.166	0.132	4.969	0.035
Moist Bulk Density (g/cm^3)	0.431	0.186	0.153	5.713	0.025
Porosity (%)	0.421	0.177	0.145	5.394	0.029
Soil Organic Matter (%)	0.424	0.180	0.147	5.484	0.027

Note: Regression analyses were based on 27 averaged observations obtained by averaging three laboratory-analyzed samples collected within each topographic position of each land-use system.

= 0.189, $p < 0.05$) and 15.60% ($R^2 = 0.156$, $p < 0.05$) of the variance, respectively. In contrast, sand, silt and clay content showed non-significant relationships with altitude, explaining between 0.01% and 11% of the variance ($p > 0.05$). Similarly, no significant relationship was found between clay content and slope ($p > 0.05$). Moisture content showed negative but non-significant relationships with both altitude and slope gradient ($p > 0.05$). Both dry and moist BD also showed positive, but non-significant relationships with altitude ($p > 0.05$). The results of this study are consistent with those of Hailu *et al.* [70] and Bogale *et al.* [79], who observed the highest organic matter in soils at lower slope gradients compared to those at higher slopes. The presence of greater OM content at lower slope positions contributed for lower BD [84] [87]. Overall, these findings indicate that soil health indicators were moderately to weakly associate with variations in topographic conditions across the sampled landscape. Among the two topographic variables, slope exhibited slightly stronger associations than altitude for most soil physical indicators. However, because land-use systems and topographic conditions were not independently replicated, these relationships likely reflect the combined influence of terrain characteristics and land-use practices.

Overall, a limitation of the present study is that the statistical analyses were conducted using one-way ANOVA, Pearson correlation, and simple linear regression to evaluate overall differences among land-use systems and associations with topographic variables. Although these methods were appropriate for identifying general patterns, the hierarchical sampling design, in which slope positions were nested within representative hill sites, was not explicitly accounted for in the statistical models. Furthermore, because each land-use system was represented by a single hill site with distinct altitude and slope characteristics, the independent effects of land use and topography could not be fully separated. Therefore, the findings interpreted as site-specific associations rather than definitive causal relationships. Future studies should employ replicated sites and mixed-effects models to strengthen statistical inference.

4. Conclusions

This study assessed the associations between land-use systems, topographic variables and soil physical indicators across representative hill landscapes of the Chittagong Hills, Bangladesh. The results showed that soil physical properties, including field capacity (FC), moisture content (MC), maximum water-holding capacity (MWHC), dry and moist bulk density (DBD and MBD), total porosity (TP) and soil organic matter (SOM), varied among the sampled land-use systems. In general, natural forest and mixed mature timber forest sites were associated with more favorable soil physical conditions, characterized by higher moisture retention, greater porosity, and higher soil organic matter. In contrast, shifting cultivation and monoculture plantation sites exhibited comparatively poorer soil physical characteristics.

Regression and correlation analyses indicated that increasing altitude and slope were generally associated with coarser soil texture, lower moisture-related properties, and reduced soil organic matter, while sand content showed positive relationships with both topographic variables. However, only those relationships supported by statistically significant analyses were interpreted as significant, whereas non-significant relationships were considered indicative trends. Because the sampled land-use systems occurred under different topographic conditions, the observed patterns likely reflect the combined influence of land-use management and terrain characteristics rather than the independent effect of either factor alone.

The findings highlight the importance of conserving natural forests and promoting sustainable land-use practices, such as mixed timber forests and multistrata agroforestry systems, to maintain favorable soil physical conditions in the

Chittagong Hills. Nevertheless, the present study was based on representative sites for each land-use system; therefore, the results should be interpreted as associations within the sampled landscape rather than definitive evidence of causal effects. Future studies incorporating replicated sites across similar land-use systems and applying hierarchical statistical approaches would enable clearer separation of land-use and topographic influences on soil quality. In addition, long-term investigations considering projected climate change, particularly changes in rainfall and temperature, would further improve understanding of soil degradation processes and support sustainable land management in the Chittagong Hills, Bangladesh.

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Author Contributions

The first author performed all the research with the supervision of the second author. The first author wrote the research concept and experimental design; carried out the experiments; collected data; and performed data analysis, with continuous input from the second author. First author drafted the manuscript and it was revised with input and guidance from the second author.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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