Soil Physical Quality as a Basis for Sustainable and Climate-Resilient Land Use in Suboptimal Drylands of Aceh Besar, Indonesia

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Abstract. The productivity of tropical dryland soils is constrained not only by limited water availability and low soil fertility but also by unfavorable soil physical properties, which are critical for achieving sustainable and climate-resilient agriculture. This study identified the characteristics and physical constraints of soils under several land use types (LUTs) in dryland areas of Aceh Besar Regency, Indonesia. Undisturbed and disturbed soil samples for physical analysis were collected using sample rings at a depth of 0–20 cm. Each LUT consisted of 5–8 sample plots (20 m × 20 m), with five soil samples taken from each plot. The results showed that soil physical properties in suboptimal drylands vary across land uses. Soil texture, bulk density, porosity, permeability, aggregate stability index, and water holding capacity (WHC) under forest vegetation, cultivated forests, and dryland agricultural systems were relatively better than those in uncultivated areas. In contrast, uncultivated lands exhibited several physical constraints, including coarse texture, high bulk density (1.51 ± 0.01 Mg m^{-3}), low porosity (49.13 ± 5.21%), moderately rapid permeability (21.48 ± 3.12 cm h^{-1}), unstable soil aggregates (0.43 ± 0.0021), and low WHC. Improving soil physical quality is essential for enhancing productivity and strengthening climate resilience in dryland systems. This can be achieved through the application of organic amendments such as biochar, compost, manure, and mulch (cover crops), which contribute to sustainable soil management and improved ecosystem functioning.

1 Introduction

Suboptimal drylands are a land resource with strategic potential to support agricultural development, particularly in tropical regions like Indonesia. However, various serious biophysical constraints result in relatively low productivity when managed conventionally. The main constraints include limited water availability, low soil fertility, and soil conditions that are less conducive to plant growth. Suboptimal drylands generally rely on seasonal rainfall with long dry periods, often experiencing water deficits during the dry season [2,11]. Furthermore, the soils in these areas are generally acidic, have low cation exchange capacity, low organic matter content, and are poor in macro- and micronutrients [2,15].

In Aceh Besar, Aceh Province, Indonesia, suboptimal drylands cover a significant area and have the potential to support sustainable agricultural development. While drylands in Aceh Besar reportedly cover over 239,484.63 ha, their utilization for food crops remains limited due to soil quality constraints [14]. Soils in this region generally develop from a variety of parent materials with low fertility, limited organic matter content, and diverse particle size distributions. Furthermore, variations in soil order, such as Entisols, Inceptisols, Oxisols, Ultisols, and Andisols, influence the physical and chemical characteristics of the soil [13]. Several studies indicate that suboptimal drylands in Aceh Besar were originally tropical forest and scrubland, and some have been utilized for dryland farming systems in the form of dry fields and mixed gardens, while others have been left as unproductive wastelands [2,14]. Climate factors, with uneven rainfall distribution throughout the year, also exacerbate land conditions, particularly groundwater availability, which is strongly influenced by soil physical properties, including soil structure, porosity, bulk density, and soil organic matter [1,3,5]. Therefore, a comprehensive understanding of the relationship between land use and soil physical properties is necessary as a basis for more effective land management.

Soil physical properties are important indicators of soil quality because they play a direct role in regulating water movement, aeration, and the development of plant root systems [1,3,11,12]. Under natural conditions, such as primary forests, soils have a stable structure, high porosity, and good infiltration capacity due to their high organic matter content and biological activity [1,3,6]. However, the conversion of primary forests to secondary forests or other land uses can cause significant changes in soil physical properties. Secondary forests exhibit a recovery process through the accumulation of organic matter and microbial activity, although they do not yet fully match the conditions of primary forests. These changes are strongly influenced by the intensity of disturbance and the duration of the succession process [10]. In Aceh Besar, land-use changes from forest to agricultural land or mixed gardens have been reported to reduce soil aggregate stability and organic carbon content, resulting in a decline in overall soil quality [2,14].

Besides forests, abandoned land and dryland agriculture are the two dominant land use types in suboptimal dryland areas. Abandoned land, which is generally former agricultural land, exhibits varying characteristics depending on the duration of abandonment and environmental conditions. In some cases, natural succession processes can improve soil physical properties, such as increasing porosity and organic matter, but in others, degradation occurs due to erosion and nutrient loss [7,8]. Conversely, dryland agriculture is the most intensive land use and often places significant pressure on soil quality. Intensive tillage practices, low organic matter inputs, and minimal application of conservation techniques can lead to increased bulk density, decreased porosity, and disrupted infiltration and water retention systems [4,5,9]. As a result, the soil becomes more compacted and less able to supply water to plants [9,11,12]. These conditions further exacerbate the water constraints that are a key characteristic of suboptimal drylands.

Although various studies have examined the influence of land use on soil properties, studies that comprehensively compare soil physical properties across the main land use types, primary forest, secondary forest, abandoned land, and dryland agriculture in Aceh Besar are still limited. Furthermore, few studies have integrated soil physical property analysis with soil quality indices and biomass as indicators of land sustainability. Therefore, this study is crucial to fill this gap by analyzing soil physical properties and soil quality indices across various land use types in Aceh Besar as a basis for formulating adaptive and sustainable land management strategies.

2 Materials and Methods

This research was conducted in Aceh Besar Regency, Aceh Province (Indonesia), in a suboptimal dryland. The study area of Aceh Besar Regency can be seen in Figure 1. Soil analysis was conducted at the Soil Physics Laboratory, Faculty of Agriculture, Universitas Syiah Kuala, Indonesia.

Fig. 1. Map of the Aceh Besar District, Aceh, Indonesia

2.1 Research methods

This research was conducted using a descriptive method based on survey results, field observations, and laboratory analysis. Field observations aimed to identify soil profiles for determining USDA Soil Taxonomy subgroups [13]. Soil sampling for analysis of physical and other soil properties was necessary to identify the soil profile. The study locations examined include suboptimal dryland areas in Aceh Besar District. The locations of which are divided into 4 (four) land use types (LUT), namely: (i) areas with natural forest vegetation (Nf) consisting of 2 types: primary forest (HPr) and secondary forest, (ii) cultivated forest areas (Cf) consisting of 3 types: pine forest, eucalyptus forest, and teak forest, (iii) uncultivated area (Ua) consisting of 4 types: forest shrubs, shrubs, grassland area, and bare land, and (iv) dryland farming (Df) consisting of 3 types: mixed gardens, moor, and rainfed. These areas are determined from spatial analysis using GIS software. The types of land use in the study area can be seen more clearly in Table 1.

Table 1. Land use types and study areas in suboptimal drylands of Aceh Besar

Land Use Type (LUT)	Utilization unit	Area (ha)	Number of sample locations
Natural Forest (Nf)	1-Primary forest	77,894.98	9
	2-Secondary forest	23,558.37	8
Cultivated Forest (Cf)	3-Pine forest	53.85	3
	4-Eucalyptus fores	307.14	3
	5-Teak forest	58.50	3
Uncultivated Area (Ua)	6-Forest bushes	6,513.47	5
	7-Shrubs	96,962.20	10
	8-Grassland area	80.50	3
	9-Bare land	14,211.93	8
Dryland Farming (Df)	10-Mixed garden	15,052.09	8
	11-Moor	313.03	3
	12-Rainfed	4,478.57	5
Total area		239,484.63	68

2.2 Soil sampling and analysis techniques

Two types of soil samples were collected: (i) intact soil samples with sample rings (measuring 7.4 cm x 4 cm) used to determine bulk density (BD) and porosity, and (ii) disturbed soil samples taken with a soil auger for analysis of the distribution of soil fractions (soil texture), permeability, water holding capacity (WHC), and aggregate stability index. All soil samples were taken from the topsoil at a depth of 0–20 cm. Soil sample analysis was conducted at the Soil and Plant Research Laboratory and the Soil Physics Laboratory, Faculty of Agriculture, Universitas Syiah Kuala, Darussalam, Banda Aceh. The soil physics measurement and analysis methods are shown in Table 2, while the soil analysis procedures used the Soil Research Center guidelines [12].

Table 2. The soil physics measurement and analysis methods

No.	Soil Physics Parameters	Unit	Analysis Method	Reference value
1.	Texture	%	Pipette method	Medium
2.	Bulk density	$Mg\ m^{-3}$	Gravimetric	0.9-1.1
3.	Porosity	%	Saturation method	<50
4.	Permeability	$cm\ h^{-1}$	Permeameter	2.0-12
5.	Aggregate stability index	-	Dry Sieve	>0.5
6.	Water holding capacity (WHC)	%	Pressure Plate Apparatus	>25

2.3 Data Analysis

Data from field observations and laboratory analysis were processed statistically using descriptive statistics, and to determine the differences in soil characteristics between land use types (vegetation), analysis of variance (F test) was used at the $P < 0.05$ level, followed by LSD analysis (0.05).

3 Results and Discussion

3.1 Description of Study Area

Based on survey results, the suboptimal dryland area in Aceh Besar Regency, Aceh Province, Indonesia, is estimated to cover more than 239,000 hectares **[14]**. Based on land use, this suboptimal dryland can be divided into four types: natural forest (primary and secondary forest), cultivated forest (pine, teak, and eucalyptus), unmanaged or fallow land (grassland and shrubland), and dryland agricultural areas (dry fields and mixed gardens). Several examples of land use types in the study area can be seen in Figure 2.

The study area is located in a humid tropical climate zone with an average annual rainfall ranging from 1,450 to 2,100 mm and an average annual temperature of 26–28 °C. The landscape is highly variable and is dominated by areas with slopes greater than 25%, comprising several soil orders, including Entisols, Inceptisols, Ultisols, and Andisols **[13]**. The suboptimal dryland farming system is characterized by poor soil quality and several fertility constraints, including acidic soil conditions (pH 4.5–6.5), low organic carbon and total nitrogen contents, and low cation exchange capacity **[2,15]**. Extensive research has been conducted on the chemical characteristics, soil quality, and carbon dynamics of these suboptimal drylands **[2,14]**; however, information regarding their soil physical properties remains limited. Land conversion from primary forest to other land uses is expected to alter soil physical quality, thereby affecting plant growth **[1,10]**.

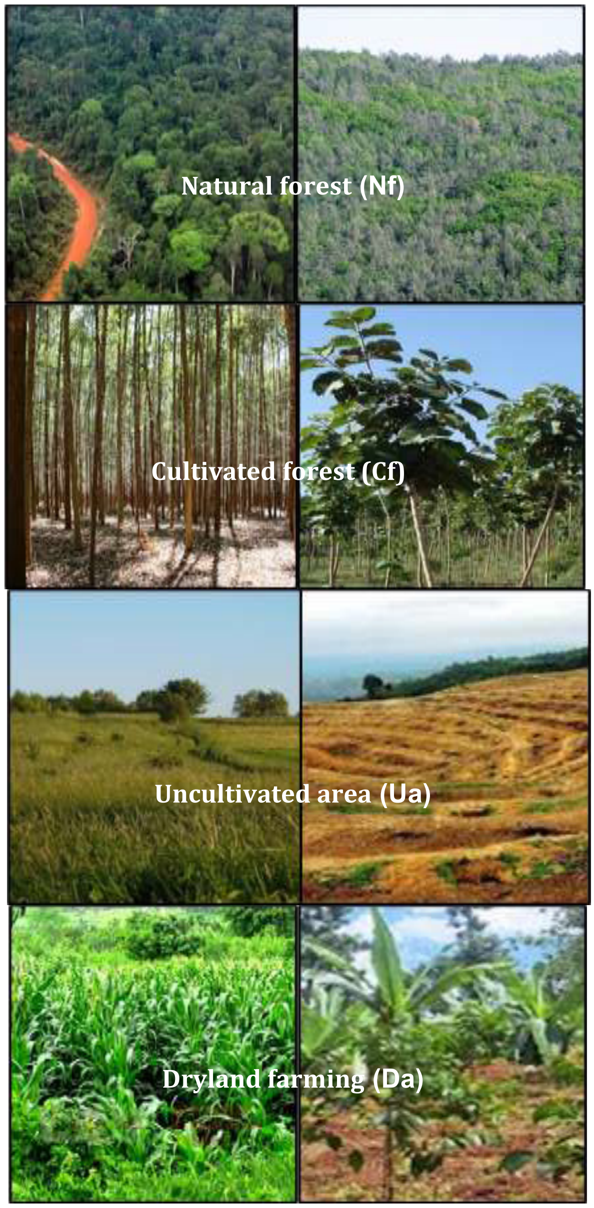

Fig. 2. Several types of land use in the suboptimal dryland area of Aceh Besar District

3.2 The Influence of Land Use Type (LUT) on Soil Physical Properties

3.2.1 Primary particle distribution (texture)

The distribution of primary soil particles (texture) is a very important indicator of soil physics, especially in agricultural cultivation areas. In mineral soils, the soil texture desired by many cultivated plants, especially food crops, is medium texture, namely a texture with a balanced proportion of sand, silt, and clay. Included in medium texture are loam, clayey loam, sandy clay loam, and sandy loam. The results of statistical analysis (F test) show that there is a very significant variation in the distribution of fraction sizes (texture) between land use types (LUT).

Table 3. Average distribution of primary particles and soil texture in various suboptimal dryland use units in Aceh Besar District

Land Use Type (LUT)	Sand (%)	Silt (%)	Clay (%)	Texture	Class of texture
Natural forests (Nf)	28 ± 0.5 a	40.4±1.5 b	31.7±2.2 b	Loamy	Medium
Cultivated forests (Cf)	27.5±0.3 a	39.2±0.3 b	33.3±2.4 b	Loamy	Medium
Uncultivated areas (Ua)	48.6±3.9 b	31.6±2.2 a	19.9±0.9 a	Sandy loam	Slightly coarse
Dryland farming (Da)	21.5±2.3 a	37.0±2.12 b	41.6±3.0 c	Clay	Fine

Numbers followed by the same letter in the same column do not show significant differences according to the LSD test (0.05)

Table 3 shows that the soil texture under the LUT of natural forest (Nf) and cultivated forest (Cf) is included in the medium class. The average sand fraction content ranges from 27.5-28.0%, the silt fraction ranges from 39.2-40.4%, while the clay fraction ranges from 31.7-33.3%. In the LUT of unmanaged areas or idle land (Ua), the soil texture is classified as rather coarse with an average sand content of 48.6%, silt 31.6%, and clay 19.9%. Furthermore, the dryland area used for agriculture (Da) has a fine-texture class, with an average sand content of 21.5%, silt 37.0%, and clay 41.6%. The research data show that the soil texture beneath forest vegetation, in primary, secondary, and cultivated forests (pine, teak, and eucalyptus), is superior to that beneath unmanaged and cultivated areas.

The improved soil texture beneath forest vegetation occurs because these areas have a balanced proportion of sand, silt, and clay. This medium texture provides better soil physical properties because it forms a crumbly soil structure, loose consistency, and good porosity, thus providing better aeration conditions for plant growth, including those found on the forest floor [1,12]. In uncultivated areas (Ua), the soil texture is somewhat coarser because the sand fraction is more dominant than the silt and clay fractions. This texture class is less favorable as a plant growth medium because the higher sand content and lower clay content reduce the soil's capacity to retain water and nutrients and limit aggregate formation [3,12].

The poor soil texture characteristics observed in this land-use type are likely associated with land degradation caused by erosion, which removes fine particles and organic matter from the surface layer, leaving a coarser-textured soil with lower organic matter content [7,8]. Based on field observations, this land-use type includes grasslands, shrublands, and open or severely eroded areas. These sites are characterized by sparse vegetation cover, and some areas remain completely bare, leaving the soil surface vulnerable to erosion.

In dryland areas managed for agricultural cultivation, such as dry fields and mixed gardens (Da), the predominance of a fine (clayey) soil texture is considered less favorable. Although clay-rich soils have a high water-holding capacity, inadequate soil management can increase their susceptibility to compaction and surface crust formation, thereby restricting root growth and reducing water infiltration [12]. The high clay content in this land-use type is primarily determined by the original soil-forming materials; however, long-term cultivation and intensive soil management may further deteriorate soil physical conditions by increasing compaction and weakening soil structure [4,9,12].

3.2.2 Bulk density (BD)

The results of statistical analysis (F test) indicate that land use type (LUT) influences soil bulk density. Table 4 shows that soil bulk density varies between LUTs.

Table 4. Physical properties of soil in various land use types of suboptimal dryland in Aceh Besar District

Land Use Type (LUT)	Bulk density (Mg m^{-3})	Porosity (%)	Permeability (cm h^{-1})	Aggregate stability index
Natural forests (Nf)	1.19±01 a	66.3±2.7 c	11.3 ± 1.3 b	0.97±0.01 c
	Medium	Porous	Medium	Very stable
Cultivated forests (Cf)	1.25±0.1 b	60.3±4.2 b	8.74±0.7 a	0.73±0.01 b
	High	Good	Medium	Stable
Uncultivated areas (Ua)	1.51±01 c	49.1±5.2 a	21.5±3.12 c	0.43±0.02 a
	Very high	Not good	Slightly quick	Not stable
Dryland farming (Da)	1.19±0.1 a	60.4±2.9 a	6.12±0.3 a	0.68±0.01 b
	Medium	Good	Slightly slow	Stable

The BD value in natural forests (Nf) and agricultural cultivation areas (Da) falls within the medium category, with an average value of 1.10 ± 0.01 Mg m^{-3}. This bulk density is generally favorable for plant root development because it provides adequate pore space for water movement and soil aeration [11,12]. In cultivated forests (Cf), the average BD was 1.25 ± 0.02 Mg m^{-3}, which is classified as high, whereas unmanaged areas (Ua) exhibited the highest BD (1.51 ± 0.01 Mg m^{-3}), indicating severe soil compaction. The relatively high BD observed in cultivated forests suggests that these sites may have experienced previous land degradation before being reforested with conservation tree species, including *Pinus mercusii*, *Tectona grandis*, and *Eucalyptus* sp.

Based on field observations, pine stands have been established for more than 80 years, teak for more than 50 years, and eucalyptus for approximately 45 years. The results of this study indicate that land-use conversion from natural forest to other land uses can increase soil bulk density, thereby reducing soil physical quality [10]. Bulk density is defined as the oven-dry mass of soil per unit total soil volume, including solids and pore spaces, and is widely used as an indicator of soil compaction and porosity [12]. Because bulk density is inversely related to total pore space, it strongly influences root penetration, water infiltration, aeration, and nutrient availability [1,4,11]. Lower bulk density generally reflects greater pore space and more favorable conditions for plant growth, whereas higher bulk density indicates soil compaction that restricts root development and limits water and air movement through the soil [9,11,12].

3.2.3 Soil porosity

Table 4 also shows that the average soil porosity in suboptimal drylands in Aceh Besar varies from 49.1 ± 5.21% (poor) to 66.3 ± 2.65% (very good). The highest porosity values were observed under natural forest (Nf), whereas the lowest values occurred in unmanaged land (Ua). This indicates that soil under forest vegetation has better physical quality than soil in unmanaged or bare land.

The high porosity observed in forest land is likely associated with greater soil organic matter accumulation. Natural forests generally receive continuous inputs of plant residues that decompose into soil organic matter, thereby improving soil aggregation and increasing pore space [3,6]. Soil porosity in cultivated forest (Cf) and agricultural land (Da) also remained relatively high, suggesting that reforestation and appropriate land management can contribute to the recovery of soil physical quality [10]. In contrast, unmanaged land, including grassland, shrubland, and severely eroded areas, exhibited lower porosity because of soil compaction, coarser soil texture, and reduced organic matter resulting from erosion [7,8,9]. These findings highlight the importance of rehabilitating suboptimal drylands through reforestation, agroforestry, or sustainable agricultural management to maintain and improve soil physical quality [10,14].

Soil porosity is defined as the proportion of pore space within the total soil volume and is expressed as a percentage [12]. These pores are occupied by either air or water and play essential roles in water movement, gas exchange, nutrient transport, root penetration, and biological activity [1,11,12]. Higher porosity generally indicates greater pore space for air and water storage, whereas lower porosity reflects soil compaction and reduced soil functionality [9,11,12]. Soil porosity is therefore an important indicator of soil structural quality and strongly influences the capacity of soil to support plant growth [1,12]. In agricultural systems, pore-size distribution governs water storage, aeration, and root-zone water availability [5,11]. Moreover, greater porosity and water-holding capacity create favorable conditions for microbial activity and organic matter decomposition, thereby contributing to improved soil functioning [3,6].

3.2.4 Soil permeability

Table 4 also shows that soil permeability in suboptimal drylands in Aceh Besar varies among land-use types, ranging from 6.12 ± 0.34 cm h^{-1} to 21.5 ± 3.12 cm h^{-1} (moderately slow to moderately fast). The highest permeability values were observed in unmanaged land (Ua), whereas the lowest values occurred in agricultural land (Da). Natural forest (Nf) and cultivated forest (Cf) exhibited moderate permeability, indicating relatively favorable soil physical conditions. These results suggest that forest vegetation contributes to improved soil physical quality by increasing organic matter inputs and promoting root growth, which enhances pore formation and facilitates vertical and lateral water movement [3,6,10].

Soil permeability is the ability of soil to transmit water and air through interconnected pore spaces and is primarily controlled by soil texture, pore-size distribution, soil structure, and the continuity of macropores [11,12]. Permeability influences infiltration, drainage, soil water availability, and ultimately plant growth [5,11]. In general, coarse-textured soils contain larger pores that facilitate rapid water movement, whereas well-aggregated soils with stable pore networks also exhibit high permeability despite having finer textures [1,12]. Therefore, soil permeability is determined not only by particle-size distribution but also by soil structure, pore connectivity, and land management practices [1,4,12].

3.2.5 Aggregate index stability (ASI)

Table 4 shows that the soil aggregate stability index across various land-use types (LUTs) in the suboptimal drylands of Aceh Besar varied considerably, ranging from 0.43 to 0.97 (unstable to very stable). The highest aggregate stability was observed under natural forest (Nf), whereas the lowest stability occurred in unmanaged land (Ua). Agricultural land (Da) and cultivated forest (Cf) exhibited intermediate to stable aggregate stability. Aggregate stability is influenced by several factors, including soil texture, clay mineralogy, soil organic matter, microbial activity, soil moisture, and aggregate structure [1,3,6,12].

Forest soils generally exhibit greater aggregate stability because continuous inputs of litter and root biomass increase soil organic matter and stimulate biological activity, thereby promoting aggregate formation and stabilization [3,6]. Improved aggregate stability enhances soil porosity, water retention, and resistance to erosion, resulting in better soil physical quality than that of land converted to agricultural or unmanaged uses [1,6]. In contrast, bare or unmanaged land has weak aggregate stability because the absence of vegetation cover exposes the soil surface to raindrop impact, accelerates erosion, and reduces organic matter inputs [7,8]. Without sufficient organic matter and biological activity, soil aggregates become more susceptible to breakdown under rainfall, tillage, and repeated wetting–drying cycles [1,12]. Increasing soil organic matter through appropriate vegetation management is therefore essential for improving aggregate stability and maintaining soil physical quality [3,6,14].

3.2.6 Water holding capacity

The water holding capacity (WHC) of a soil is crucial for predicting plant water requirements. Water holding capacity is the ability of a material, particularly soil, to retain water in its pores against the force of gravity. This concept indicates the maximum amount of moisture a soil can hold, which is crucial for water availability to plants and for maintaining soil moisture over a longer period. The results of the analysis of water content and water holding capacity are shown in Table 5.

Table 5. The water holding capacity in various suboptimal dryland use types in Aceh Besar District

Land Use Type (LUT)	pF 2.5 (%)	pF 4.2 (%)	WHC (%)
Natural forests (Nf)	48.0 ±4.41 b	21.4±3.91 b	26.6±2.96 c
Cultivated forests (Cf)	41.1 ±2.35 a	18.1±3.13 a	22.9±5.04 b
Uncultivated areas (Ua)	37.3 ±2.22 a	19.3±2.41 a	18.1±2.15 a
Dryland farming areas (Da)	54.5 ±5.15 c	24.0±3.86 b	30.6±4.78 d

Numbers followed by the same letter in the same column do not show significant differences according to the LSD test (0.05)

Table 5 shows that the soil water content at pF 2.5 and pF 4.2, and the soil water holding capacity in suboptimal dryland in Aceh Besar vary and differ between land use types (LUT). The highest soil water content and water holding capacity are found in agricultural cultivation areas (Da) with a WHC of 30.6±4.78%, followed by the natural forest land use type (Nf) at 26.6±2.96%. The lowest WHC is found in soil below the LUT of unmanaged areas (Ua), at 18.1±2.15%, and in cultivated forest LUT at 22.9±5.04%.

The water content at pF 2.5 represents the soil water retained after gravitational drainage and is commonly used to estimate field capacity. It is an important component of plant-available water because it reflects the upper limit of water retained in the soil that is readily available for plant uptake. Lower pF values indicate wetter soil conditions, whereas higher pF values, such as pF 4.2, represent the permanent wilting point, at which soil water is held too tightly to be extracted by most plants [11,12].

The high water-holding capacity (WHC) observed in agricultural land (Da) is associated with its relatively high clay content. Conversely, the low WHC in unmanaged land (Ua) is mainly attributable to its coarser soil texture, which reduces the soil's ability to retain water. Soil water-holding capacity is determined primarily by soil texture, organic matter content, soil structure, and pore-size distribution [3,5,11,12]. Soils with higher water-holding capacity can retain more water for plant use, thereby reducing drought stress and irrigation requirements [3,11]. Water-holding capacity is commonly evaluated using the difference between water content at field capacity and the permanent wilting point [11,12]. The low WHC observed in unmanaged land (Ua) is also associated with soil erosion, sparse vegetation cover, and low organic matter content [3,7,8,14]. Field observations further indicated that these sites had shallow soil profiles and were dominated by coarse sand fractions. Reduced vegetation cover accelerates erosion and further degrades soil physical quality [7,8]. Based on these findings, it can be concluded that the physical quality of soils under forest vegetation and agricultural land remains relatively favorable and should be maintained through appropriate land management to prevent further degradation [10,14].

3.3 Correlation between Soil Physical Properties

The results of the Spearman correlation analysis to see the level of closeness of the relationship between the soil physical parameters studied are presented in Table 6.

Table 6 shows that the relationship between soil physical parameters, including primary fraction content (sand, silt, clay), bulk density, porosity, permeability, aggregate stability index, and soil WHC, is strongly to very strongly correlated, with correlation coefficients (r) ranging from 0.50 to 0.97. This indicates that the physical properties of soil in suboptimal dryland in Aceh Besar are strongly correlated with one another. The only weak relationship is found in the correlation between water content at pH 4.2 (permanent wilting point) with sand content, porosity, permeability, and aggregate stability index (ASI).

Table 6. Spearman correlation coefficient values between various soil physics parameters in the suboptimal dryland in Aceh Besar

Soil Physical Parameters	Sand (%)	Silt (%)	Clay (%)	Bulk density	Poro-sity	Permea-bility	ASI	pF 2.5	pF 4.2
Silt (%)	-0.82	1.00							
Clay (%)	-0.97	0.64	1.00						
Bulk density	0.97	-0.91	-0.89	1.00					
Porosity	-0.84	0.97	0.69	-0.94	1.00				
Permeability	0.99	-0.77	-0.97	0.93	-0.77	1.00			
ASI	-0.67	0.94	0.51	-0.84	0.98	-0.61	1.00		
pF 2.5	-0.82	0.49	0.88	-0.80	0.65	-0.77	0.51	1.00	
pF 4.2	-0.53	0.14†	0.65	-0.51	0.36†	0.47†	0.25†	0.92	1.00
WHC	-0.91	0.61	0.93	-0.89	0.74	-0.86	0.60	0.99	0.89

ASI = aggregate stability index; Critical level (P<0.01 = 0.476); Number of samples: 24. Correlation coefficients that are underlined and have a [†] sign are not significantly correlated.

Soil texture (sand, silt, and clay) is strongly correlated with bulk density, porosity, permeability, aggregate stability index (ASI), and water-holding capacity (WHC). A positive correlation occurs between the sand fraction and bulk density as well as permeability. This indicates that soils with higher sand content generally have higher bulk density and greater permeability, which reduce their capacity to retain water because coarse-textured soils contain fewer water-retaining micropores [11,12]. Conversely, the sand fraction is negatively correlated with silt and clay contents, soil porosity, water content at pF 2.5 (field capacity), pF 4.2 (permanent wilting point), and WHC. This indicates that increasing sand content generally decreases total porosity and reduces the soil's water-retention capacity [3,5,11,12]. Good soil porosity is achieved through an appropriate balance between macropores, which facilitate aeration and drainage, and micropores, which retain plant-available water [11,12].

Table 6 also shows that soil bulk density is strongly correlated with porosity, permeability, water content at pF 2.5 and pF 4.2, ASI, and WHC. Bulk density was positively correlated with permeability but negatively correlated with porosity, aggregate stability, soil water content, and WHC. These results indicate that increasing bulk density, particularly in coarse-textured soils, is associated with increased permeability but reduced porosity and water retention [4,9,11,12]. High bulk density accompanied by low porosity and low water-holding capacity is characteristic of compacted soils with low organic matter content [3,9,12]. Such conditions reduce pore space, restrict root penetration, limit gas exchange, and decrease the soil's capacity to retain and store water [1,9,11,12]. Bulk density is influenced by soil texture, soil structure, organic matter content, and land management practices, including tillage and cultivation [4,10,12].

Soil porosity was negatively correlated with permeability but positively correlated with ASI, soil water content, and WHC. These relationships indicate that decreasing porosity accompanied by increasing permeability is associated with lower aggregate stability and reduced soil water storage. Likewise, permeability was negatively correlated with ASI, soil water content, and WHC, whereas WHC was positively correlated with soil water content at both pF 2.5 and pF 4.2. These findings suggest that excessively rapid water movement through the soil reduces the residence time of water within the root zone, thereby lowering water availability to plants. In addition, unstable soil aggregates increase the susceptibility of soil to erosion, whereas low WHC limits the soil's ability to maintain adequate moisture for plant growth [1,7,8,11,12].

3.4 Soil Physics Improvement Recommendations

Improving the physical properties of suboptimal dryland soils, particularly to increase water retention, can be achieved through several approaches, including: (i) applying organic amendments, (ii) minimizing soil disturbance, (iii) utilizing beneficial microorganisms, (iv) improving water management, (v) diversifying crop rotations, (vi) implementing agroforestry, and (vii) integrating crop and livestock production.

One of the simplest and most cost-effective approaches is the application of organic amendments such as compost, biochar, and animal manure. Soil organic matter is a key factor controlling soil physical quality because it increases water-holding capacity, promotes aggregate formation, and improves soil structure [3,6]. Organic amendments also increase soil carbon content and stimulate microbial activity, thereby enhancing aggregate stability and pore development [3,6]. Crop residues and other organic materials further contribute to maintaining soil moisture and reducing soil degradation [3,14]. Biochar produced from agricultural residues, such as rice straw, rice husks, and woody biomass, may also serve as a stable carbon source for improving soil quality.

Green manure crops, particularly legumes and other high-biomass species, can provide additional organic inputs and nutrients to the soil. These practices improve soil aggregation, increase porosity, enhance water infiltration, and reduce bulk density, thereby improving soil resilience and productivity [3,4,6]. Priority for soil rehabilitation should be given to physically degraded lands, particularly unmanaged areas dominated by *Imperata cylindrica*, barren land, and shrubland.

Minimizing soil disturbance through conservation tillage or reduced tillage is another important strategy because excessive tillage disrupts soil aggregates, accelerates organic matter decomposition, and degrades soil structure. Conservation tillage helps preserve soil structure, maintain soil organic matter, reduce erosion, and improve soil physical quality [4,5]. Efficient rainfall management through water conservation practices is also essential for dryland agriculture to maximize water availability and reduce runoff.

The use of beneficial microorganisms, such as mycorrhizal fungi, *Trichoderma*, and plant growth-promoting rhizobacteria (PGPR), together with crop diversification, crop rotation, and agroforestry systems, can further improve soil quality by enhancing root development, maintaining soil cover, and increasing organic matter inputs [14]. Integrating crop production with livestock also contributes additional organic matter through manure, thereby improving nutrient cycling and long-term soil quality [3,14]. Based on these land management strategies, appropriate management recommendations for each land-use type (LUT) in the suboptimal drylands of Aceh Besar are presented in Table 7.

Table 7. Recommendations for land management and soil physics improvement in each LUT in the suboptimal Dryland in Aceh Besar Regency

Land Use Type (LUT)	Directions and alternatives for soil physics management /improvement
Natural forests (Nf)	Protect from deforestation; no physical soil improvement needed.
Cultivated forests (Cf)	Prevent logging and fires; maintain forest cover and apply organic amendments.
Uncultivated areas (Ua)	Restore through reforestation, agroforestry, or livestock integration with soil conservation and organic amendments.
Dryland farming (Da)	Improve soil quality using organic farming: amendments, biofertilizers, biopesticides, and soil-water conservation.

4 Conclusions

Soil physical properties such as primary particle distribution (texture), bulk density, porosity, permeability, aggregate stability index (ASI), and water holding capacity (WHC) in suboptimal drylands of the Aceh Besar Regency vary across land use types (LUT). In general, the physical properties of the soil in natural forest vegetation types (primary forest and secondary forest) are relatively better compared to other land use types (such as cultivated forests, uncultivated land, and dryland agriculture). Poor soil physical properties are characteristics of uncultivated (abandoned) areas, such as shrublands, *Cilindrica* sp. fields, and degraded land, and become obstacles to plant growth. In these areas, a number of soil physical constraints were found, such as rather heavy bulk density, low porosity, slightly quick soil permeability, unstable ASI, and low WHC. Providing organic amendments in the form of compost, biochar, green manure, biofertilizer, and the application of agricultural conservation systems need to be implemented to improve the physical quality of the soils.

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