

Studies on the Genesis of Soils in Jong River Basin in the Northern Province of Sierra Leone

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Abstract

The soil resources of Sierra Leone remain an integral part of sustainable agricultural development but knowledge of the suitability of soils and their management requirements for a variety of land uses is still lacking to a greater extent. In this view, a detailed soil survey of three chiefdoms in Northern Sierra Leone was undertaken to evaluate the genesis of soils and interpret soil-landscape properties and their relationships using the toposequence and free style approach of soil survey. Three major soil types, viz, gravelly, gravel-free over gravel and gravel-free soils, formed either directly or indirectly from weathered and disintegrated parent materials of two geologic origins namely Rokel River Series (comprising of sandstone, shale and mudstone), and Granite and Acid Gneiss were identified. The gravelly soils are formed from sandstone and sandy shales of the Rokel River Series, which upon weathering released iron and hydrated oxides that hardened into plinthite upon drying. The gravel-free over gravel soils are formed from acid gneiss containing acid and intermediate igneous and metamorphic rocks, which upon weathering produced sandy clay textured soils whereas the gravel-free soils are derived from sedimentary rocks (shales and mudstones) of Rokel River Series, which upon weathering and action of organisms produced sandy clay loam and sandy clay textured soils. The gravel-free over gravel soils are mostly located in the summit and back slopes and show dark brown to dark yellowish-brown hue and moderate chroma, weak to moderate structure and absence of coarse fragments in the 0 - 40 cm layer, and a strong brown hue and high chroma, very weak fine angular blocky structure having abundance of coarse fragments from 40 cm and above. In these soils, the compactness of ironstone and sandstone gravels increases with depth. The gravel-free soils are found on three landscape positions, viz, back slopes, foot slopes and toe slopes. On the back and foot slopes, the soils are characterized by very dark brown to dark yellowish-brown hue and high chroma, sandy loam to sandy clay texture, coarse angular to moderate sub-angular blocky structure and absence of coarse fragments throughout the horizon. In these soils, the clay content and sand grain sizes were observed to increase with depth. On the toe slopes, the soils show black to greyish-brown hue and low chroma, silty loam to sandy loam, structureless and high water holding capacity.

Keywords

Physiography, Genesis, Soil, Land Suitability, Climate, Oxisols, Landform, Land Use, Sierra Leone

1. Introduction

Five soil orders namely, Oxisols, Inceptisols, Entisols, Spodosols and Ultisols, have been discovered in Sierra Leone [1]. Depending on the physiography, factors and processes of soil formation, these were further subdivided into sixteen natural regions called "soil provinces" to guide land use planning. Within these subdivisions, three widely distributed soil types are gravelly soils, gravel-free over gravel soils and gravel-free soils. The occurrence of these soils was first reported in the Njala area of Southern Sierra Leone by Dijkerman and Breteler (1969) and van Vuure et al. (1973) [2] [3], and in the Jagbwema area of Eastern Sierra Leone by Sutton et al. (1980) [4]. In Northern Sierra Leone, earlier studies by van Vuure and Miedema (1973) [5] reported the presence of these soils in the Makeni area. This was further confirmed by Blokhuis (1979) [6] in the Robis Polder area of Mambolo Chiefdom along the coastal plains between the estuaries of the Great Scarcies and Little Scarcies rivers. The origin of these soils is attributed to the integrated effect of soil-forming factors, of which climate (*i.e.* rainfall and temperature) is most influential. These soils are formed from primary minerals, which undergo rapid weathering due to instability in environmental conditions such as high rainfall and temperature during the rainy and dry seasons respectively [1]. This seasonal variability in rainfall and temperature is a recipe for the formation of iron-rich reddish materials commonly known as "plinthite" in soils of Sierra Leone, especially in gravelly soils and sub-surface layers of gravel-free over gravel soils.

In the upland gravelly and gravel-free over gravel soils, iron-rich reddish ma-

terials from overlying horizons or higher adjacent areas are added to sub-surface horizons, which harden irreversibly when exposed to recurrent wetting and drying thereby forming "*plinthite glaebules*". About 80% of the total soil mass of these well-drained gravelly upland soils contain hardened plinthite glaebules of variable gravel sizes [7], which develop from gravelly colluvium parent materials usually overlying residual materials over weathered bedrock (or *saprolite*) of about 122 cm thick. In colluvial foot slopes and stream terraces, gravel-free over gravel soils contain very high gravel content in the subsoil, but gravel-free surface layers. In some uplands, gravelly soils that develop from sedimentary rocks such as sandstone, siltstone, and mudstone, a gravel-free layer of about 25 cm thick may overlay a gravelly layer as a result of termite activities.

Conceptually, the physiography of Sierra Leone influences several landscape position-related factors such as runoff, drainage and soil erosion, and hence soil genesis. Depending on the soil-forming factors such as relief/topographic factors, different soils have developed over time under different ecological conditions. According to Miller *et al.* (1988) [8], the spatial variability of soil properties along the various landscapes needs to be well correlated with the pattern of crop production based on thorough understanding of the genesis of the soils. Hence, the present study was undertaken to interpret soils-landscape relationships and evaluate the genesis of soils in the study area.

2. Materials and Methods

2.1. Study Area

The study area is located in the Jong river basin, and lies in the domain of 8.4°N - 8.4667°N and 11.8833°W - 11.8167°W covering a total area of 1810.8 ha (Figure 1). This area comprises patches of land situated in the Upper Massakong, Petifu Mayawa A and Yele Manowo chiefdoms in Tonkolili District, Northern Province of Sierra Leone. The mean annual rainfall for the district is about 1979 mm [9]. The physiography is interior plains with very gentle undulating plains, and a geology that has developed on the resistant sediments of the Rokel River Group [10]. The vegetation is a mosaic of elephant grasses (Pennisetum purpureum) and shrubs with some areas having thicket and patches of cultivation. According to the United Nations Development Programme/Food and Agriculture Organization (UNDP/FAO) Land System classification [11], the area belongs to the Blama Land system. This land system consists of dissected plains of extremely low relief with scattered small hills and common terraces, located on Precambrian granite complex and local granulities. The soils are moderately deep and very gravelly reddish clay loam to clays. In this land region, the slopes are more subdued given rise to the development of extensive localized terraces and swamps that normally broaden into featureless depressions commonly referred to as Bolis. The major livelihood for about 80% of the population is agriculture, with fallow shifting cultivation being the major agricultural land



Figure 1. Map of the study area showing surveyed sites.

use system.

2.2. Soil Survey and Mapping

A detailed soil survey was carried out using LANDSAT ETM+ imageries, digital elevation model (DEM) and land system map [11] as base maps for field work. The imageries, DEM and digitized land system map were geocoded, and subsets were created in ArcMap 10.5 on a 1:12,500 scale. After processing the LANDSAT imageries, standard False Colour Composites (FCC) were produced by a combination of bands 4, 3 and 2, and these were used for on-screen visual interpretation of landforms. The isolated landforms were intensively traversed and the different land facets were identified and studied to establish soil-landscape relationships.

A digital soil mapping model using a high resolution DEM of 12.5 m, which assigns the same colour attributes to soils located at same elevation was used to speed up the survey process. Ground truth observations were conducted in order to verify map predictions and eliminate any possible errors. Within each land facet in the established toposequences, soil profiles were excavated from which five representative modal pedons were selected and their morphological characteristics were described using the guidelines for soil survey [12] [13]. Around each pedon, four mini-pits of 60 cm depth at 200 m distance in a square range were also dug and their morphological features were examined to enhance finalization of soil boundaries.

2.3. Soil Analysis and Classification

From each pedon, horizon-wise soil samples were collected, processed and analyzed at the Njala University Quality Control Laboratory (NUQCL) following standard analytical procedures. Based on the morphological, physico-chemical and chemical properties, the soils were classified using the "Keys to Soil Taxonomy" [14]. The taxonomic classes of soils were correlated with the UNDP/FAO Land System classification [11] and soils were mapped as gravelly, gravel-free over gravel and gravel-free soils.

3. Results and Discussion

3.1. Landscape Characteristics and Physiography-Soil Relationship

The relationship between physiography and landscape elements (land facets) of an area and soils has been widely recognized as the factors involved in the physiographic processes corresponding close to that of soil formation. This relationship between landscape features and soil conditions makes it possible for predicting the nature and distribution pattern of different soils in a landscape. In the present study, three major physiographic units, namely upland, undulating midlands and lowlands, with land facets comprising of crests, side slopes (shoulder and back slopes), terraces (foot slopes and toe slopes) and adjacent inland valley swamps were identified using on-screen visual interpretation of satellite images and in-situ terrain feature characterization. The landscape characteristics and physiography-soil relationship attributes are presented in Table 1. The lowlands were situated at 0% - 2% slopes having grayish-green tones with red patches, undulating midlands at 2% - 6% slopes having checker board pattern with light grayish tones and medium to coarse textures, whereas uplands were situated at 6% - 10% slopes having checker board pattern and gravish green tones with slight pinkish spots. Geomorphological studies revealed that the landform was characterized by gently to very gently undulating plains with interconnecting interfluves. Interfluves were undulating uplands that occur between adjacent inland valley swamps (IVS). These interfluves were mainly gently undulating, consisting of variable slopes of 1% - 5%. The elevation ranged from 63 - 94 meters.

The results of landscape characterization studies (**Table 1**) show that there have been changes in the morphological characteristics, as well as in the physical and chemical properties of soils due to changes in slope and landform. It is

Table 1. Landscape characteristics of pedoli locations	Table 1.	Landscape	characteristics	of pedon	locations.
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Characteristic	Soil Profile N°									
features	1	2	3	4	5					
GPS Coordinates (UTM)	184,787/931,248	185,215/932,039	184,930/93,0902	185,101/932,644	183,744/932,075					
Physiography/ landscape position/Land facet	Upland/ summit	Undulating midland/ side slope (back slope)	Undulating midland/ interfluve side slope	Undulating midland/ side slope	Lowland/Interfluve— Inland Valley Swamp					
Elevation (m)	85	85	63	79	80					
Parent material	Weathered Residium	Weathered colluvium over Residium	Gravel-free colluvium	Gravel-free colluvium/alluvium	Gravel-free colluvium					
Soil type	Gravelly soil (Plinthic paleudult)	Gravel-free over gravel soil (Inceptisol over plinthic paleudult)	Gravel-free soil (Inceptisol)	Gravel-free soil (Inceptisol)	Hydromorphic gravel-free soil (Psammaquent)					
Surface condition	Gravels mixed with dried leaves	Surface covered with dried leaves	Surface covered with dried leaves	Surface covered with dried leaves	Marshy surface covered with young grasses					
Degree of slope	1% - 3%	3% - 5% 1% - 3%		3% - 5%	1% - 2%					
Slope class	Very gently sloping	Gently sloping	Very gently sloping	Gently sloping	Very gently sloping					
Effective depth of soil (cm)	100+	115+	150+	100+	37					
Natural vegetation	Bush regrowth	Bush regrowth	Bush regrowth	Bush regrowth	Wet grass species, Raphia palm and shrubs					
Land use	Agriculture	Fallow land	Fallow land just cleared for cultivation	Fallow land	Fallow land					
Human influence	Agriculture (patches of cultivation)	re Agriculture Agriculture ((currently under orchar of fallow) intercroppe n) cereals		Agriculture (Mango orchard intercropped with cereals)	Agriculture (rice cultivation)					
Moisture condition in profile	Surface layer is dry but profile is moist throughout	Slightly moist throughout the profile	Moist throughout the profile	Moist throughout the profile	Wet throughout the profile					
Drainage	Well drained	Well drained	Well drained (rapid)	Moderately well to well drained	Imperfect to poorly drained					
Erosion class	No or slight	Moderate	Moderate	Slight	Nil					

evident that the undulating nature of the landform and gentleness of the slopes (in addition to climate, parent material, vegetation, land use, water erosion and other environmental conditions) have played a major role in influencing these properties. The crests are level to nearly level, having slopes not exceeding 2%. The side slopes are gently to very gently sloping from the upper to the lowest parts along the topo-sequence of the interfluves, comprising of slopes ranging from 2% - 5%. In some areas, the lower side slopes of the interfluves are very gentle, with a level to nearly level topography that is shaped by a trough of undulation having slopes of not more than 2%. Adjacent to the Taia River, is a long and narrow stretch of nearly level terrace soils (**Figure 2**) of about 1% slope that is believed to have been formed by the deposition of colluvial materials. Within these areas, IVS are also evident. These are generally narrow, elongated and nearly level valley bottoms, drained by seasonal streams, which are largely waterlogged for much of the year. At some points, these IVS occur as narrow and elongated





patches within the valleys of the second and third order tributaries of the main stream, with slopes not greater than 1%.

Generally, the soils in the lowlands are deep, sandy clay to sandy clay loam, and show slight or no sign of erosion. Due to the recurrent deposition of eroded materials from the uplands on this landscape position, the soils exhibit better chemical properties and fertility status than soils in other landforms. The soils in undulating midlands are moderately deep to deep, sandy loam to clay loam and sandy clay loam, weak to moderate and granular to sub-angular blocky. These soils are moderately eroded and show moderate to high chemical and fertility status, whereas the soils in uplands are moderately deep, sandy loam to sandy clay, weak granular to crumbly structure, non-sticky and non-plastic. These soils are moderately deep, having poor to fairly good chemical and fertility status.

Among the sand, silt and clay fractions, the sand content decreases with depth while silt and clay distributions follow an irregular pattern. However, the clay content is higher in the second horizons of almost all the soil profiles. This might be due to the translocation of clay fractions from the surface to subsurface layers, which according to Satyavathi and Reddy (2003) and Reddy et al. (2013) [15] [16], is a characteristic pedogenic process in soils of humid and sub-humid tropical climates that are under high rainfall conditions. In the gravelly pedons, gradual decrease in sand content with depth and accumulation of clay in subsurface horizons was observed. This is as a result of eluviation of clay fractions from surface layers and their accumulation in subsurface layers under the influence of high rainfall [17]. In the gravel-free pedons, especially those located in interfluves, the finer fractions of soil separates increase from the surface to subsurface. The surface enrichment of sand fractions in surface horizons followed by removal of finer particles due to clay eluviation and surface runoff could possibly have played a significant role in influencing the lateral eluviation of soil particles, and hence the formation of these soils.

Gravelly soils in upland areas, due to their location in the sloping uplands are more eroded compared to other soils. These eroded soil fractions might have accumulated over time to form deep soils in midlands and lowlands. As a result, the soils at these landscape positions are moderately deep to deep and very deep with finer texture due to presence of high silt- and clay-sized particles. In addition, it is also evident from the nature of surface features that the land use might have influenced the erosion of these soils in the order of agriculture > open scrub > plantation > IVS. According to Odell *et al.* (1974) [7], sediment yield and total runoff water are directly proportional to slope percent. In conformity with this proposition, soils found on gentle slopes, having thick vegetation cover were less eroded than soils without vegetation.

3.2. Soil Morphological Features

Morphological studies were conducted on five representative pedons and the results (Table 2) revealed that soils are moderately deep to very deep. Soil depth

is moderate to deep in uplands and undulating midlands and deep to very deep at lower elevations. This confirmed the findings of Odell *et al.* (1974) [7] that upland soils of Sierra Leone are generally well-drained and are influenced by topography-related factors such as water holding capacity and material deposition.

Table 2. Morphological features of pedons.

Depth		Colour		н.	Structure			Consistence			Root		Boundary	
Horizon	(cm)	Dry	Moist	- Texture	Size	Grade	Туре	Dry	Moist	Wet	Size	Quantity	Distinctness	Topography
Pedon 1	(Gravelly s	oil)												
Ар	0 - 15	10YR4/4	10YR3/4	gsl	f	1	cr	s	fr	so po	vf, f	p, f	а	S
Bs1	15 - 45	10YR4/6	10YR3/6	gsc	с	2	cr	sh	fr	ss sp	vf, f	a, f	g	w
Bs2	45 - 65	10YR5/6	10YR4/6	gsc	с	2	cr	sh	vfr	so po	vf, f	f; f	g	s
BCx	65 - 100+	7.5YR6/8	7.5YR5/8	gsc	m	2	abk	sh	vfr	ss sp	vf	f	g	s
Pedon 2	(Gravel-fre	e over gra	vel soil)											
Ар	0 - 20	10YR4/3	10YR3/3	scl	f	3	sbk	h	vfi	so po	vf, f	p, p	а	w
Bt	20 - 60	10YR4/4	10YR3/4	gsc	m	2	cr/abk	sh	vfi	ss sp	vf	р	c	i
Bw	60 - 85	10YR5/6	10YR4/6	gsc	с	2	cr	sh	fi	ss sp	vf	f	g	s
С	85 - 115+	10YR6/8	10YR5/8	gsc	с	2	cr	sh	fi	so po	f, m	f	g	s
Pedon 3	(Colluvium	/ Interflux	ve gravel-i	free soil)										
Ар	0 - 15	10YR4/2	10YR3/2	sl	f	2	cr	sh	fi	so po	vf, f	p, p	с	w
A1	15 - 40	10YR4/3	10YR3/3	scl	m	2	cr	h	fi	ss sp	vf, f	p, f	а	w
Bt1	40 - 75	10YR5/4	10YR4/4	sc	f	3	sbk	vh	vfi	ss sp	vf, m	f, f	g	S
Bt2	75 - 120	10YR5/4	10YR4/4	sc	f	3	sbk	vh	vfi	ss sp	m	f	g	S
Cr	120 - 150+	10YR5/6	10YR4/6	sc	f	3	abk	vh	vfi	ss sp	f	f	с	S
Pedon 4	(Alluvium	gravel-free	e soil)											
Ар	0 - 10	10YR4/2	10YR3/2	sl	f	2	cr	h	fi	so so	vf, f	p, p	с	W
Bw1	10 - 40	10YR4/3	10YR3/3	scl	f	3	sbk	vh	vfi	ss sp	f, m, c	p, f, f	g	S
Bw2	40 - 80	2.5YR4/2	2.5YR3/2	SC	f	3	sbk	vh	vfi	ss sp	f, m	f, f	с	i
С	50 - 100+	2.5YR4/4	2.5YR4/3	SC	f	3	sbk	h	fi	ss sp	f, m	f, f	с	i
Pedon 5	(Hydromoi	phic grave	el-free soi	1)										
А	0 - 18	2.5Y3/0	2.5Y2/0	siL	vf	1	cr	s	vfr	so so	vf, f	p, f	c	s
Bg1	18 - 37	2.5Y3/0	2.5Y3/2	sc	vf	1	cr	s	vfr	so so	f	f	c	w
Bg2	37 - Δ	2.5Y5/0	2.5Y4/0	s	m	1	gr	1	1	so so	vf	f	с	w

Note: Texture: sc—sandy clay, gsc—gravelly sandy clay, scl—sandy clay loam, gsc—gravelly sandy clay, sl—sandy loam, gsl—gravelly sandy loam, siL—silty loam, s—sand. Structure: Size: vf—very fine, f—fine, m—medium, c—coarse; Grade: 1—weak, 2—moderate, 3—strong; Type: cr—crumb, sg—single grain, g—granular, abk—angular blocky, sbk—sub-angular blocky. Consistence: Dry: s—soft, 1—loose, sh—slightly hard, h—hard, vh—very hard. Moist: 1—loose, sfr—slightly friable, fr—friable, vfr—very friable, fi—firm, vfi—very firm. Wet: so—non-sticky, ss—slightly sticky, s—sticky, vs—very sticky, po—non-plastic, ps—slightly plastic, p—plastic, vp—very plastic. Roots: Size: vf—very fine, f—fine, m—medium, c—coarse; Quantity: f—few, c—common, m—many, p—plenty. Boundary: Distinctness: a—abrupt, c—clear, g—gradual, d—diffuse; Topography: s—smooth, w—wavy, i—irregular, b—broken; Δ—discontinuity.

This variability in depth in relation to landform and slope is attributed to the physiographic effect of landscape positions and the removal of finer soil particles, mainly silts and organic materials by runoff water and their subsequent deposition in the lowlands.

The gravelly soil pedons are characterized by dark brown to red hue and high chroma whereas pedons representing gravel-free over gravel soils show dark brown to dark yellowish-brown hue and moderate to high chroma. In the gravel-free soils, pedons located on back and foot slopes are characterized by very dark brown to dark yellowish-brown hue and high chroma, whereas those on toe slopes show black to greyish-brown hue and low chroma. The texture of the gravelly soil pedons varied from sandy loam to sandy clay with high gravel content throughout the profile. However, the size of gravels increases with depth indicating the influence of lateral eluviation of coarse fragments.

Pedons of gravel-free over gravel soils are characterized by sandy clay loam to sandy clay texture with gravel content increasing with depth from 35 cm and above. In the gravel-free soils, surface horizons exhibit a sandy loam to silty loam texture while subsurface horizons are sandy clay loam to sandy clay. In general, the morphogenesis of these soils show considerable homogeneity with the exception of the hydromorphic gravel-free soils. In addition, prominent slickensides and pressure faces were observed at 40 cm and above in some of the gravel-free pedons, which is an indication of clay eluviation in subsurface layers. However, hydromorphic gravel-free soils show lesser mobilization and translocation of finer fractions, which could be attributed to the deposition of finer fractions and differences in physiography under waterlogged conditions.

The structure of gravelly as well as gravel-free over gravel soils is fine to medium, granular to sub-angular blocky but weak to moderate ped for gravelly soils and moderate to strong ped for gravel-free over gravel soils. In colluvium interfluve and alluvium gravel-free soils, the structure is angular to sub-angular blocky with fine and moderate to strong ped while hydromorphic gravel-free soils are structureless. The angular and sub-angular blocky structure is an indication of slickensides formation in these soils. In either soils, with the exception of hydromorphic gravel-free soils, the structure of the subsurface horizons of all pedons irrespective of physiography is more developed compared to surface horizons. This is an indication of how the factors of soil formation had influenced soil development over time in the study area.

With reference to resistance of soil material to rupture, gravelly soils exhibit a slightly hard to hard (dry), very friable to friable (moist) and non-sticky and non-plastic to slightly sticky and slightly plastic (wet) consistence whereas gravel-free over gravel soils are slightly hard to hard (dry), firm to very firm (moist) and non-sticky and non-plastic to slightly sticky and slightly plastic (wet). In gravel-free soils, consistence vary with depth from hard to very hard (dry), firm to very firm (moist) and non-sticky and non-sticky and non-plastic to moderately sticky and moderately plastic (wet). The increase in stickiness and plasticity could be re-

lated to clay illuviation in the subsurface horizons [18] [19]. Surface horizons exhibited lower class consistency while sub-surface horizons exhibit higher class consistency, which is possibly due to clay eluviation from surface layers and illuviation into subsurface layers [20]. According to Rudramurthy and Dasog (2001) [21], this physical behaviour of soils as influenced by dry, moist and wet conditions could be attributed to the textural make-up and clay mineral composition.

The horizon boundaries are abrupt to gradual and smooth to wavy in gravelly soils, abrupt to clear and wavy to irregular in gravel-free over gravel soils, and abrupt to gradual and smooth to irregular in gravel-free soils. In hydromorphic gravel-free soils, horizon boundaries are more distinct but with wavy and irregular topography, which is an indication of Gleization due to the persistent waterlogged condition to which these soils were subjected.

3.3. Soil Physical Properties

The physical properties of the pedons are presented in **Table 3**. The textural properties of soils revealed that the soils contain high sand content compared to silt and clay fractions, which may permit high infiltration rate, thus making them fairly good for the cultivation of most arable crops. The soil depth vary from deep to very deep. In gravelly soils, the content of coarse fragments increases with depth, whereas in gravel-free over gravel soils, an irregular trend ranging from non-gravelly in surface horizons to very gravelly in subsurface horizons was observed. The gravel-free soils are non-gravelly except in some areas, the surface is covered with patches of partially decomposed plant residues. The content of coarse fragments in the Bt and AC horizons is less than the Ap and Cr horizons due to Argilli pedoturbation in these horizons.

The clay content in the gravel-free over gravel and gravel-free soils is higher compared to their gravelly soils counterpart. In general, increase in finer materials and clay content with depth is observed in gravel-free soils. This could be attributed to the illuviation of finer fractions as well as the vertical migration and translocation of clay fractions from surface to subsurface horizons. In gravelly soils, the clay content increases with depth but became more stabilized in the B, Cr and transition AC and BC horizons. These subsurface horizons exhibit higher clay content compared to the surface horizons due to illuviation and change in structure from a granular to angular and sub-angular blocky structure in surface and sub-surface horizons respectively. In gravel-free over gravel and gravel-free soils, profile development indicated surface enrichment of sand fraction in surface horizons due to the removal of finer particles by clay eluviation and surface runoff. In addition, illuviation processes might have affected the vertical distribution of silt and sand fractions in these soils. Most transition horizons show higher clay content than the A and B horizons as a result of the accumulation of clay fractions following eluviation from the upper layers.

All the pedons exhibit an irregular trend in silt content with depth, which might be due to the variation in weathering of parent material [22]. The Ap

		Sand	Silt	Clay	Bulk Density			
Horizon	Depth (cm)		%		g/cm ³			
Pedon 1 (Gra	avelly soil)							
Ар	0 - 15	83.6	5.4	11.0	1.08			
Bs1	15 - 45	63.9	1.1	35.0	1.12			
Bs2	45 - 65	63.4	23.6	13.0	1.12			
BCx	65 - 100+	63.3	3.7	33.0	1.20			
Pedon 2 (Gra	avel-free over grav	vel soil)						
Ар	0 - 20	76.2	4.8	19.0	1.13			
Bt	20 - 60	63.9	1.1	35.0	1.14			
Bw	60 - 85	68.0	5.0	27.0	1.16			
С	85 - 115	64.0	1.0	35.0	1.12			
Pedon 3 (Colluvium/ Interfluve gravel-free soil)								
Ар	0 - 15	83.5	1.5	15.0	1.14			
A1	15 - 40	79.4	3.6	17.0	1.19			
Bt1	40 - 75	82.1	2.9	15.0	1.27			
Bt2	75 - 120	88.0	1.0	11.0	1.40			
Cr	120 - 150	81.2	1.8	17.0	1.28			
Pedon 4 (All	uvium gravel-free	soil)						
Ap	0 - 10	77.3	5.7	17.0	0.73			
Bw1	10 - 40	84.5	2.5	13.0	1.20			
Bw2	40 - 80	86.6	0.4	13.0	1.23			
С	50 - 100	86.2	0.8	13.0	1.25			
Pedon 5 (Hy	dromorphic grave	el-free soil)						
А	0 - 20	74.9	8.1	17.0	1.17			
Bg1	20 - 42	63.4	1.6	35.0	1.16			
Bg2	42 - 110	65.5	1.5	33.0	1.24			

Table 3. Physical properties of soils.

horizon of pedon 4 has the lowest bulk density $(0.73 \text{ g}\cdot\text{cm}^{-3})$ while the Cr horizon of pedon 3 has the highest bulk density $(1.4 \text{ g}\cdot\text{cm}^{-3})$. In general, the bulk density increases with depth in majority of the pedons, thus indicating the positive impacts of tillage.

3.4. Soil Chemical Properties

The chemical properties of the pedons are presented in **Table 4**. The soil pH measured in 1*:*2*.*5 *soil:water extract* was strongly acidic (5*.*05 - 5*.*64) but very strongly acidic to extremely acidic (4*.*25 - 4*.*65) when measured in 1*:*1 *soil:KCl extract*.

Horizon	Depth (cm)	pH E		EC	CEC	OC %	$N-NH_4$	N-NO3	Bray P1	К	S	Ca	Mg	Na	H⁺
		H ₂ O	H ₂ O KCl cmol(+)/kg		- 70				mg/	kg					
Pedon 1 (G	ravelly soil)														
Ap	0 - 15	5.45	4.65	2.96	9.62	2.07	246.7	4.51	9.0	91.0	8.8	395.0	85.0	12.0	0.23
Bs1	15 - 45	5.10	4.30	0.51	3.72	0.67	56.3	2.51	1.0	17.0	15.6	63.0	13.0	11.0	0.85
Bs2	45 - 65	5.17	4.37	0.54	1.13	0.36	34.3	1.52	1.0	15.0	19.6	65.0	14.0	14.0	0.59
BCx	65 - 100+	5.21	4.41	1.51	8.96	0.10	26.3	0.58	1.0	29.0	30.1	198.0	42.0	24.0	0.38
Pedon 2 (G	ravel-free over	gravel	soil)												
Ap	0 - 20	5.12	4.32	1.17	6.83	1.76	120.0	1.67	6.0	84.0	11.2	122.0	34.0	15.0	0.51
Bt	20 - 60	5.17	4.37	0.36	1.09	0.31	24.7	2.25	1.0	14.0	16.1	41.0	9.0	9.0	0.73
Bw	60 - 85	5.10	4.30	2.71	3.43	0.36	23.2	1.16	1.0	38.0	14.1	369.0	84.0	18.0	0.63
С	85 - 115	5.06	4.26	0.59	1.81	0.07	462.5	0.93	1.0	12.0	24.8	77.0	14.0	14.0	0.58
Pedon 3 (C	olluvium/Inter	fluve g	ravel-	free soi	1)										
Ap	0 - 15	5.05	4.25	0.46	1.81	1.25	4.1	0.22	5.0	29.0	9.6	46.0	14.0	9.0	0.72
A1	15 - 40	5.18	4.38	0.22	7.47	0.20	2.9	2.31	1.0	10.0	8.0	21.0	7.0	7.0	0.48
Bt1	40 - 75	5.22	4.42	0.25	6.13	0.28	2.3	1.13	1.0	7.0	13.1	29.0	7.0	7.0	0.34
Bt2	75 - 120	5.64	4.84	0.17	1.78	0.10	2.3	0.11	2.0	4.0	5.8	20.0	5.0	5.0	0.17
Cr	120 - 150	5.18	4.38	0.24	5.54	0.15	2.3	0.23	1.0	8.0	25.8	27.0	7.0	8.0	0.32
Pedon 4 (A	lluvium gravel	-free so	oil)												
Ap	0 - 10	5.14	4.34	1.04	9.71	1.04	25.2	1.51	24.0	81.0	17.1	108.0	26.0	20.0	0.92
Bw1	10 - 40	5.14	4.34	0.27	7.68	0.51	5.2	0.31	2.0	11.0	5.8	30.0	7.0	7.0	0.49
Bw2	40 - 80	5.21	4.41	0.25	6.32	0.42	4.3	0.07	1.0	9.0	5.5	28.0	7.0	8.0	0.37
С	50 - 100	5.10	4.30	0.27	5.73	0.25	4.3	0.04	1.0	8.0	4.4	31.0	7.0	7.0	0.31
Pedon 5 (H	lydromorphic g	gravel-f	free so	il)											
А	0 - 20	5.11	4.31	0.98	4.21	0.08	4.5	1.31	1.0	27.0	10.2	124.0	30.0	9.0	0.45
Bg1	20 - 42	5.07	4.27	0.42	3.17	0.77	3.0	3.12	1.0	13.0	25.8	49.0	12.0	9.0	0.61
Bg2	42 - 110	5.21	4.41	0.32	5.36	0.06	2.8	0.75	1.0	9.0	30.5	39.0	9.0	7.0	0.21

Table 4. Chemical properties of soils.

Note: pH—soil reaction; EC—electrical conductivity; CEC—cation exchange capacity; OC—organic carbon; K—potassium; S—sulphur; Ca—calcium; Mg—magnesium, Na—sodium; H⁺—hydrogen ion concentration.

The low pH (*i.e.* strong acidity) could be ascribed to the well-drained condition and the leaching out of large amount of bases from the solum as a result of high proportion of macro pores, leaving behind sesquioxides. According to Sitanggang *et al.* (2006) [23], such increase in soil reaction with depth is due to leaching of bases from higher to lower elevations.

All the pedons exhibit an irregular trend in electrical conductivity, which

ranged from 0.17 to 2.96 dS·m⁻¹, thus indicating non-salinity condition. However, the surface horizons show higher EC values than subsurface horizons, which is probably due to the removal of released bases by percolating water as favoured by the prevailing high rainfall and free drainage conditions.

The organic carbon ranges from very low to high (0.06% - 2.07%) and is observed to either increase or decrease with depth or follow an irregular trend, which might be associated with the physiographic-soil relationships and land use patterns. In addition, the organic carbon content of the surface soils is higher than the subsurface soils in most of the pedons. This could be attributed to the high amount of litter and crop residues and the rapid mineralization at the surface layers. However, most pedons exhibit low organic carbon content, resulting from the induced rapid rate of organic matter oxidation due to the high temperature, with resulting decreasing trend tending towards accumulation of crop residues every year, without substantial downward movement [24].

Nutrients have a profound effect on soil fertility and crop yield. Nitrogen, for example, contributes to an increase yield and after-harvest residue, thus preventing the loss of soil organic matter [25]. In this study, the $N-NH_4^+$ concentration ranges from 2.3 to 462.5 mg·N·kg⁻¹ and that for N-NO₃⁻ was from 0.07 to 4.51 mg·N·kg⁻¹. This level of N-NH⁺₄ and N-NO⁻₃ is an indication of high rate of ammonification and nitrification taking place in these soils under the mediation of soil microorganisms. These two processes are however affected by several environmental variables, including soil moisture, temperature, pH, C:N ratio and the type of organic materials in the organic residue. The Bray P1 (level of phosphorus) content vary from 1 to 24 mg·P·kg⁻¹, which is observed to be critically low in some cases, thus confirming the findings of Rhodes (1977) [26]. The Bray-Kurtz P1 test (often referred to as the Bray-P1 test) was developed in 1945 at the University of Illinois [27] and is recommended for neutral and acid soils (pH < 7.0), but not for alkaline soils (pH > 7.0). The test's extractant is a dilute hydrochloric acid and ammonium fluoride solution. The correlation between P uptake by the plant and the P concentration in the extractant ranges from 0.74 to 0.94 for soils of the North Central Region of the United States, with a detection limit of 1.0 part per million (dry soil basis) and reproducibility of 10% [28]. In African soils such soils of Sierra Leone are highly weathered soils [7], and thus pH is usually low [26]. Under such conditions, phosphorus levels less than 15 ppm Bray P1 puts crops at the greatest risk of yield loss from a deficiency of phosphorus. Potassium is moderate, ranging from 4 to 91 mg·kg⁻¹.

The exchangeable bases are in the order of $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ on the exchange complex, ranging from 20 - 395, 5 - 85 and 5 - 24 mg·kg⁻¹, for Ca, Mg and Na respectively. The trend shows that the exchange complex is saturated with Ca^{2+} followed by Mg^{2+} , Na^+ and K^+ . This order of abundance is in accordance with Jenny's proposition that leaching caused preferential losses of Na⁺ and K⁺ [29]. The high content of exchangeable Ca/Mg is an indication of decreasing extractable magnesium content in these soils. From the distribution of

 Ca^{2+} and Mg^{2+} , it is obvious that Ca^{2+} forms the strongest relationship with all the ionic species in these soils. In comparison with other ions (Ca^{2+} , Mg^{2+} , K^+ and Na^+), it is noted that Mg^{2+} content is lower than Ca^{2+} in these soils due to the high mobility of Mg^{2+} . The low value of exchangeable monovalents compared to divalent cations is as a result of the preferential leaching of monovalents than divalents in these soils. The exchangeable acidity (H^+) content is also high varying from 0.17 to 0.92 mg·kg⁻¹, and this is probably due to the weathering of acidic parent material originating from acid rocks and granitic magnetite complexes [11].

The CEC is low, ranging from 1.13 to 9.71 cmol·(p+)·kg⁻¹. These values are critically low to medium, which might have serious implications on the overall productivity of these soils because soils with CEC less than 5 cmol(+)/kg generally have a low clay and organic matter content, low water holding capacity, requires more frequent lime and fertilizer additions, and are subject to leaching of NO₃, B, NH₄, K and most probably Mg [30].

3.5. Pedogenesis

Jenny (1941) [29] stated that soil formation is a function of five factors, *viz.*, climate (cl), vegetation (v), relief (r), parent material (p) and time (t), which he expressed mathematically as S = f(cl, o, r, p, t). The pedogenic studies reveal that two passive factors including topography (relief) and parent material, and one active factor, climate are the dominant factors of soil genesis in the study area. The active pedogenic processes involved in the genesis of gravelly and gravel-free over gravel soils are rubification, ferrugination and braunification, whereas in gravel-free soils, pedoturbation is the most active pedogenic process. These pedogenic processes together with climate, topography and parent material had played a greater role in the formation of soils, as explained below.

3.5.1. Influence of Topography and Relief on Genesis of Soils

The influence of topography and relief on soil formation in the study area exhibits a topo-sequence and soil catena character, which vary with slope steepness and severity of surface water runoff and erosion. Gravel-free soils are located in lowlands at the footslopes and valleys, gravel-free over gravel soils in the undulating midlands within the back slopes and gravelly soils in the crest and pediments regions of the uplands. Gravelly and gravel-free over gravel soils, due to their position in the landscape, show well developed soil profiles having coarse-textured, deep to very deep and brown to dark-brown soils with eroded surfaces. The A horizon of these soils is slightly shallow due to constant surface disturbance resulting from cultivation and erosion. In addition, the external and internal drainage conditions as well as the differential transport of eroded materials, leaching and translocation of mobile constituents have also been influenced by relief, resulting in the development of severe to very severely eroded soils having thinner A horizon, low organic matter content, lighter colour, shallow to moderately deep and well-drained soils with rapid and moderate permeability

for gravely and gravel-free over gravel soils respectively.

Gravel-free soils are slightly eroded, having thicker A horizon, high organic matter content, dark colour, deep to very deep and moderately drained soils with slow to moderate permeability. This is related to the frequent transport and enrichment of finer materials that are eroded from the uplands and undulating midlands into the lowlands. The moderate to poor drainage conditions and differential deposition of eroded materials in the toe slopes is a measure of the effect of topo-function on the genesis of these soils, which over time might have resulted in the formation of associated gravel-free over gravel soils in substantial amount (Table 5).

3.5.2. Influence of Parent Material on Genesis of Soils

Many difficulties arise when recognising the material from which a soil originates. Jenny (1941) [29] defined parent material as the initial state of the soil system, which consist of consolidated rocks as well as unconsolidated deposits such as river alluvium, lake or marine sediments, glacial tills, loess (silt-sized, wind-deposited particles), volcanic ash and organic matter (such as accumulations in swamps or bogs). According to Aide (2022) [31], he influence of parent material is integral to the discerning soil profile differences. Depending on the mineralogical composition, texture and stratification, soil formation in any area can be influenced by the kind of parent materials. Dark-coloured ferromagnesian (iron- and magnesium-containing) rocks, for example, can produce soils with a high content of iron compounds and of clay minerals in the kaolin or smectite groups, whereas light-coloured siliceous (silica-containing) rocks tend to produce soils that are low in iron compounds but contain clay minerals in the illite or vermiculite groups. The pedogenesis of soils in the study area revealed that these soils have developed over time from weathered schist and acid rock and granitic magnetite complexes under prevailing humid tropical climate and topography, as exhibited by toposequence variability [1].

Under favourable climatic conditions, the coarse-textured granitic rocks have undergone weathering to form coarse and loamy-textured gravelly soils with well-developed E horizons while the fine-textured rocks have weathered to form

		D 4 4 6		<u>\1</u>	••						
Soil types	Extent of soil types (ha) by community										
Son types	Mile 40	Maramneh	Markoya	Matopi	Rosint	Mamaiti					
Colluvial hydromorphic	-	-	-	-	36.9	-					
Gravelly soils	82.0	188.0	334.3	67.4	19.6	16.3					
Gravel-free to gravelly soils	32.2	135.3	161.1	52.8	14.3	55.5					
Gravel-free soils	20.3	95.2	41.1	45.8	13.2	280.2					
River terrace soils	28.1	30.7	-	11.9	48.5	-					
Total	162.6	449.1	536.5	177.9	132.6	352.0					

Table 5. Extent of soil types and their suitability in the study area.

clay loam and sandy clay loam textured soils having minimal presence of E horizons. Due to the coarse textured parent materials from which these soils are formed, the clearly defined E horizons tend to develop more fully in gravelly soils, which accord them their characteristic well-drained nature due to percolation of water to greater depths. The presence of high content of plinthite materials (i.e. iron-rich reddish materials) in the gravelly soils is an indication that their genesis is associated with the dark-coloured ferromagnesian (iron- and magnesium-containing) rocks of sedimentary origin, which upon weathering might have produced soils with a high content of iron materials. The distribution of iron gravels is also observed to be high throughout the profiles of gravelly soils with the size and content of gravels increasing with depth, which further reveals that these soils have undergone higher degree of weathering and laterization. The occurrence of gravel-free over gravel soils is due to the variation in mineralogical composition of the parent rock, which is an indication of soil development from a transported parent material over weathered residual parent material. The finer texture of gravel-free soils denotes their formation from transported parent materials, which become deposited at lower elevations, thus forming deep to very deep gravel-free soils over time.

3.5.3. Influence of Climate on Genesis of Soils

According to Amara *et al.* (2020) [9], rainfall pattern of Sierra Leone shows high variability, ranging from 1400.7 mm in Koinadugu district in the northern region to 3027 mm in Kailahun district in the eastern region with an average of 2213.9 mm. This variability in rainfall pattern together with variation in the mineralogical composition of parent materials might have resulted to the formation of gravelly, gravel-free over gravel and gravel-free soils in close association in the study area.

Due to the pronounced effect of relief in the study area, it is evident that the influence of climate on soil formation is responsible for the chain of geochemical phenomena over time, which differed in nature. The renewal and dilution of soil solution containing cations like magnesium, hydroxides, salts and silica on the one hand and evapouration and cementation of soil minerals on the other hand, might have directly influenced the intensity of rainfall and temperature and their combined influence on major pedogenic processes in the study area.

As noted by Jenny (1941) [29], the climate of a place has a greater impact on the type and rate of soil formation. Percolation and leaching are the direct effect of precipitation on soil formation. As percolation water comes in contact with the parent material, some constituents go into solution and become translocated while others are transported from one point to another, which may be either downward, upward or horizontal. The high rainfall and adequate temperature is a recipe for weathering of primary to secondary clay minerals and leaching of soluble minerals from upper to lower parts, which could have resulted to the formation of different soils along the different toposequence units. Under such conditions, the organic acids released from the weathering of acid rocks and granitic magnetite complexes might have increased the dissolving properties of soil water, and hence hasten soil profile development in the area.

3.6. Soil Classification and Mapping

After laboratory analysis, soil correlation was done based on the morphological, physical and chemical properties and soils of the study area were classified into four taxonomic classes and mapped as follows: gravelly soils are classified as Plinthic Paleudult, gravel-free over gravel soils as Eutropept over plinthic paleudult, colluvium/alluvium gravel-free soils as Inceptisol, and hydromorphic gravel-free soils as Psammaquents. The five major soil types which are representative of the study area have been mapped and named after the communities where their occurrence is greater (**Table 5**). Colluvial hydromorphic soils cover 36.9 ha, gravelly soils account for 640.2 ha, gravel-free over gravel soils cover 451.2 ha, gravel-free soils cover 495.8 ha and river terrace soils account for 119.2 ha of the study area (**Table 5**; Figure 2).

4. Conclusion

Gravelly soils with dark brown to red hue, having high chroma and abundance of coarse fragments; gravel-free over gravel soils with dark brown to dark yellowish-brown hue and moderate chroma, having weak to moderate structure and absence of coarse fragments in the 0 - 40 cm layer, and a strong brown hue and high chroma, very weak fine angular blocky structure and abundance of coarse fragments from 40 cm and above; and gravel-free soils characterized by very dark brown to dark yellowish-brown hue and high chroma, having silty and sandy loam to sandy clay texture, coarse angular to moderate sub-angular blocky structure and absence of coarse fragments throughout the horizon and structureless conditions in some cases with high water holding capacity. These soils were formed either directly or indirectly from weathered and disintegrated parent materials of two geologic origins: 1) Rokel River Series (comprising of sandstone, shale and mudstone) and 2) Granite and Acid Gneiss. The gravelly soils were formed from sandstone and sandy shales of the Rokel River Series, which upon weathering released iron oxides and hydrated oxides that harden into plinthite upon drying. The gravel-free over gravel soils were formed from the acid gneiss series containing acid and intermediate igneous and metamorphic rocks, which upon weather gave rise to the sandy clay texture nature of these soils. The amount of coarse fragments found in gravel-free over gravel soils was less when compared to gravelly soils. The gravel-free soils were derived from the sedimentary rocks of the Rokel River Series such as shales and mudstones, which upon weathering and action of organisms gave these soils their characteristic sandy clay loam to sandy clay texture. The active pedogenic processes involved in the formation of the gravelly and gravel-free over gravel soils were rubification, ferrugination and braunification, whereas, in gravel-free soils, pedoturbation was the most active pedogenic process. The results of present study are informative that the genesis of soils has been greatly affected by pedogenic processes together with the prevailing soil-forming factors including parent material, climate and relief, which was reflected in the formation of the three different types of soils in the study area.

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Conflicts of Interest

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

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