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Spatial Variability of Soil pH, Electrical Conductivity, Moisture, and Temperature Across Three Land Use Zones in Barclayville, Liberia: An Exploratory Assessment using the ST03 Soil Tester

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Abstract

Background of the study: Liberia has no digital national soil map and, until recently, no functioning public soil laboratory, so farmers and planners in remote counties such as Grand Kru County lack site-level soil information.

Objective: The study measures the spatial variability of in-situ soil pH, electrical conductivity (EC), moisture and temperature across three land-use and landscape zones of Barclayville City (administrative, agricultural [lowland and upland] and undisturbed land) and to test whether zone or location explains more of the variation.

Methodology: the research measured purposively thirty-six (36) selected GPS-referenced locations (12 administrative zone, 12 agricultural zone [7 lowland, 5 upland], 12 undisturbed land) collected at 15–20 cm soil depth on 30 September–1 October 2026 with a handheld Intelligent Soil Tester (ST03) in Barclayville, Grand Kru County Liberia. A rank based was used to explore group differences and Spearman correlations to assess associations The zones were compared with Kruskal–Wallis and Holm-adjusted Mann–Whitney tests, associations with Spearman correlation, and spatial dependence with Moran's I and empirical semi variance and Spatial analyses were exploratory because the sample was small and purposively clustered.

The sampling was conducted on 30 September to 1 October 2026, near the end of the Liberia recognized rainy season; no site-specific rainfall series was available to quantify antecedent rainfall.

Results of the study: Soil pH averaged 6.10 ± 0.51 (range 4.5–6.6); 27 of 36 points lay between pH 6.0 and 6.6, and the three readings below 5.5 were all in the administrative zone. Zones did not differ significantly in pH ($p = 0.094$), the EC (median 36.5 µS/cm; $p = 0.466$) and moisture (66.0 ± 15.2%; $p = 0.165$), although upland plots were drier than lowland plots (61% vs 78%; $p = 0.018$). EC rose with moisture in every zone ($\rho = 0.61–0.73$). Zone explained only 15.5% of pH variance, 7.7% of log EC variance and 5.2% of moisture variance, and points less than 150 m apart were no more alike than random pairs; two points 21 m apart differed by 2.0 pH units. Soil temperature differed among zones (24.4–37.0 °C; $p < 0.001$), but undisturbed land was measured in the late afternoon and all other zones in the morning, so this contrast cannot be attributed to land use.

Conclusion: The main finding is the scale of variation. Zone explained 5–16% of the variance in pH, EC and moisture, points less than 150 m apart were no more alike than random pairs, and two points 21 m apart differed by 2.0 pH units. In this setting land-use zone is a poor predictor of soil condition, and a single reading describes a spot, not a zone.

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For agronomy and planning in Barclayville, the ST03 is suited to screening and to deciding where to sample for the laboratory, not to setting lime or fertilizer rates; those decisions need laboratory-validated pH and EC from composite samples taken at plot scale.

Keywords: *soil spatial variability; soil pH; electrical conductivity; handheld soil sensor; land use; Liberia; Grand Kru County; Barclayville.*

1. INTRODUCTION

1.1 A soil-information gap at the county level

A farmer in Grand Kru County who wants to know whether a plot needs lime, or whether a lowland patch is too wet to plant, has almost no local soil data to consult. Liberia's last national soil survey dates from the 1970s, there is still no digital soil map, and until recently the country lacked a functioning laboratory for routine soil analysis (CGIAR, 2025). Even the national fertilizer recommendation is a single general rate rather than a site-specific one (CGIAR, 2025). A World Bank diagnostic of the sector reported that fertilizer reaches less than 5% of cultivated land, that cereal yields fell from 1.5 to 0.7 t/ha between 2008 and 2019, and that the Ministry of Agriculture's extension service operates at roughly one officer per 33,000 farmers; it recommended soil testing and national soil maps as foundational investments (World Bank, 2022).

The gap is now being addressed, but not yet at the scale of a county seat. In 2023 FAO and the British Geological Survey trained 15 technicians from the Ministry of Agriculture, the Central Agriculture Research Institute and the University of Liberia in soil analysis, with 47 profiles from Nimba County feeding the first Liberia Soil Information System (FAO, 2023). In October 2025 the Ministry launched Soils4Liberia, an EU-funded effort to map and classify soils in all 15 counties (Deemie, 2025), and a further €5 million project on soil restoration and climate-smart farming was announced the following month (Liberian Investigator, 2025). Until those datasets reach Grand Kru, rapid field measurements are the only practical way to describe soil conditions around towns such as Barclayville.

1.2 Soil acidity and the Liberian baseline

Liberian soils are dominated by highly weathered, acidic Latosols, which a 2023 technician's manual on agricultural liming describes as covering about 75% of the country with a typical pH of 3–5 (Using Agricultural Lime, 2023). A recent synthesis of secondary sources reports mean pH of 4.8–5.3 in upland, 5.1–5.6 in lowland and 5.3–5.8 in inland-valley swamp soils, and links pH below 5.5 to reduced phosphorus availability and root growth (Bee, 2026); the same paper models rather than measures yield responses, so it is best read as a regional summary and not as field evidence. Comparable humid-tropical Ferralsols and Acrisols in western Ghana, sampled horizon by horizon, returned pH (H_2O) of 4.8–5.9 and EC of 81–121 µS/cm (El Mellouki et al., 2025). These values give a reference range against which any Barclayville measurement should be read.

1.3 Why Barclayville, and why three zones

Grand Kru County had 109,342 inhabitants at the 2022 census (LISGIS, 2024), and Barclayville is its administrative center. Within a few kilometres, the city combines three contrasting settings. The **administrative zone** is built-up land where compaction, drainage works, waste and burning may alter surface soil. The **agricultural zone** includes lowland plots, where water collects, and upland plots, where farming is rain-fed and slopes drain quickly. The **undisturbed land zone** is the least-managed ground in the study area and serves as an informal reference. A planner deciding where to site a market garden, a school farm or a

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drainage channel needs to know whether these zones differ in a way that matters, and how much a single reading can be trusted to represent its surroundings.

Evidence from comparable settings suggests why such zones might differ. In Ghana's forest–savannah transition zone, cropland topsoil was the most acidic (pH about 5.2) and forest the least (about 6.5), and forest soils also had the highest EC (Awoonor et al., 2025); in Ethiopia, cultivated land (pH 5.24) was more acidic than forest and grazing land (6.06 and 6.12) (Abile et al., 2025). Urban wetland soils in Bamenda, Cameroon, were more acidic than rural ones (5.35 vs 6.04) and had the highest EC (309 µS/cm) (Asongwe et al., 2022). Landscape position matters too: in equatorial Colombia, lower landscape positions were reported to have better soil quality than upper ones (Mahecha-Pulido et al., 2025). In humid-tropical Africa, clearing and cultivation can degrade soil quickly, with topsoil organic carbon, nitrogen and phosphorus falling by up to 69%, 72% and 92% on basalt-derived soils in Eastern Africa (Summerauer et al., 2026), and shifting cultivation, typically 2–4 years of cropping followed by 6–8 years of fallow, remains widespread in Sub-Saharan Africa (Kim, 2025). None of these studies is from Liberia, and they generally relied on laboratory analysis rather than in-situ sensors.

1.4 Handheld intelligent soil tester and spatial variability

Handheld intelligent soil tester is multi-parameter testers. A 2026 review of soil sensors reports that organic matter can shift electrode pH by about ±0.2–0.4 units, temperature swings of 0–40 °C add about ±0.1–0.3 pH of error, and salinity above 2 dS/m degrades resistive moisture sensors (Song et al., 2026). A field trial of a screen-printed pH sensor recorded diurnal oscillations of typically ±0.1 and up to ±0.25 pH units, partly attributed to temperature dependence of the reference electrode (Cisneros-Barba et al., 2026). Low-cost handheld moisture probes can approach commercial accuracy only after calibration against gravimetric samples (Mane et al., 2025), and the FAO reference method for EC uses a 1:5 soil–water extract at 25 °C rather than an in-situ reading (FAO, 2021). A tester that reports EC, pH, moisture and temperature in seconds is therefore a screening tool, and its readings are interpretable mainly as relative differences within a consistent protocol.

Spatial variability is the other half of the problem. In Brazilian cropland, apparent EC showed a stable spatial pattern linked to topography (Gonçalves et al., 2025), and in a Mississippi Delta field, location explained most of the variation in pH (Fletcher, 2025). We are not aware of comparable point-scale datasets for any coastal Liberian town, which is the gap this study addresses.

1.5 Objectives and hypotheses

This paper analyses 36 georeferenced sampling points measured at 15–20 cm depth. Its objectives are to:

(i) Describe the distribution of in-situ pH, EC, moisture and temperature in Barclayville;

(ii) Test whether these properties differ among the administrative, agricultural (lowland and upland) and undisturbed zones;

(iii) Explore relationships among the four properties;

(iv) Quantify spatial dependence and identify constraints on interpretation. We examine four working hypotheses:

H1. Soil pH differs among zones, with managed land (agricultural and administrative) departing from the undisturbed reference.

H2. Lowland soils are wetter than upland soils.

H3. EC increases with soil moisture, as dissolved ions are more mobile and more conductive in wetter soil.

H4. Soil under undisturbed cover is cooler than soil in managed zones, although the sampling schedule limits how far this can be tested .

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Vol. 15 Issue 10 , October - 2026

2. MATERIALS AND METHODS

2.1 Study area

Barclayville is the capital of Grand Kru County on the Atlantic coast of south-eastern Liberia. The 36 sampling points reported here lie between 4.666°–4.720° N and 8.217°–8.241° W, an area whose farthest points are 6.6 km apart. The climate is humid tropical with a pronounced rainy season, and sampling fell at the end of that. No local soil profile description exists; regional soils are mapped as highly weathered, acidic Latosols (Using Agricultural Lime, 2023).

2.2 Zones and sampling design

Field teams assigned each point to one of three land-use and landscape zones, with the agricultural zone subdivided by landscape position. Points were placed purposively along walking routes within each zone, in clusters 20–150 m apart, rather than on a random or regular grid. Inference therefore applies to the sampled locations and not to the whole city.

Zone	Code	n	Mean position (°N, °E)	Measurement window (local time)	Description
Administrative	ADZ	12	4.6762, −8.2359	07:39–11:11	Built-up central town area, including public and government grounds
Agriculture, lowland	ALL	7	4.7129, −8.2391	08:07–08:58	Low-lying, water-collecting cultivated plots
Agriculture, upland	AUL	5	4.7115, −8.2392	07:48–09:29	Elevated, rain-fed cultivated plots
Undisturbed land	UDL	12	4.6691, −8.2198	17:07–17:58	Least-managed ground, used as the informal reference

Table 1. Sampling zones, sample sizes, mean GPS position and measurement time window. The agricultural zone is analysed both as one group (n = 12) and as lowland and upland sub-zones. Centroid distances: administrative–undisturbed 1.95 km, administrative–agriculture about 4.0 km, undisturbed–agriculture about 5.2 km.

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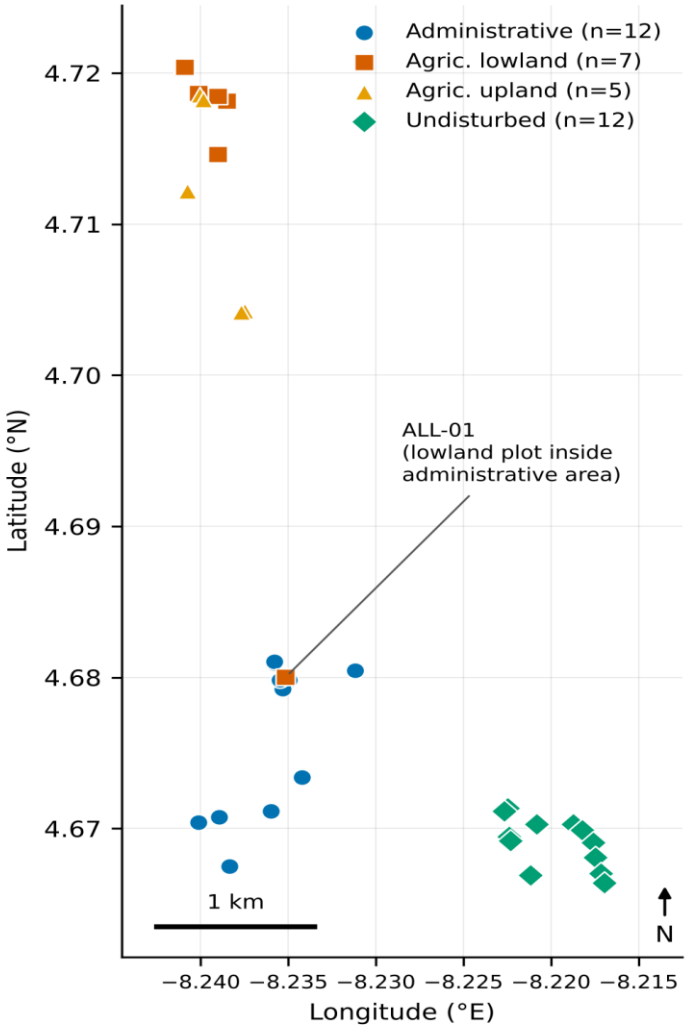


Figure 1. GPS locations of the 36 sampling points by zone. ALL-01, recorded in the field as a lowland agricultural plot, lies 24 m from administrative point ADZ-06; it is kept in the agricultural group and tested in a sensitivity analysis (Section 3.9).

2.3 Instrument and measurement protocol

All measurements used a handheld six-parameter Intelligent Soil Tester (ST03). The device reports four soil variables, which are the subject of this paper: soil EC, displayed on the unit as “Fertility” in µS/cm; moisture (%); pH; and soil temperature (°C). It also records ambient light (lux) and air humidity (%), which were noted in the field but are not analysed here. Throughout, “EC” refers to the unit's fertility reading, an in-situ bulk-soil conductivity proxy and not the 1:5 extract EC prescribed by FAO (2021).

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Figure 2. Display of the ST03 showing its output fields (Soil: Fertility in µS/cm, Moisture %, pH, Temp °C; Environment: Sunlight in lux, Humidity %). The values on this frame do not correspond to a record in the dataset.

At each point the probe was inserted into the soil at 15–20 cm depth, readings were allowed to stabilize at zero (o), and three value were recorded and the mean of replicate readings is reported. Position was recorded with a geotagging camera application on a smartphone; coordinates are taken as decimal degrees on the WGS84.

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Figure 3: a geo camera photograph showing students collecting sample at a agriculture land.

2.4 Sampling schedule and a time-of-day confound

Data were collected over two consecutive days, 30 September and 1 October 2026. Administrative, agricultural and undisturbed points were not measured at the same time of day: all administrative and agricultural readings were taken between 07:39 and 11:11, whereas all 12 undisturbed readings were taken between 17:07 and 17:58 (Table 1). Soil temperature is the property most exposed to this design, because time of day and zone are almost perfectly aligned for the undisturbed group. Temperature comparisons are therefore reported, but interpreted as confounded.

2.5 Data preparation and quality control

GPS strings were parsed into numeric latitude and longitude. Sample numbering is not strictly chronological (AUL-08 precedes AUL-04), so time stamps, not IDs, were used for sequence. Using Tukey fences (1.5 × interquartile range), we flagged pH outliers ADZ-06 (4.5) and ADZ-07 (5.0); EC outliers ADZ-07, ADZ-11, ALL-03 and ALL-04 (734 µS/cm, more than three times the next highest value); and two identical temperature readings of 37.0 °C (ADZ-09 and ADZ-10), 7–8 °C above neighbouring points measured within 15 minutes.

2.6 Statistical analysis

We summarized each property by zone as mean, standard deviation (SD), median, range and coefficient of variation (CV). Shapiro–Wilk tests showed non-normal distributions in most zone–variable combinations, and Levene's test indicated unequal pH

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Vol. 15 Issue 10 , October - 2026

variances ($p = 0.012$), so rank-based methods were used. Zone differences were tested with the Kruskal–Wallis test (three groups; and four groups with lowland and upland separated), reported with the epsilon-squared effect size, followed by pairwise Mann–Whitney tests with Holm adjustment. Lowland and upland plots were compared with a Mann–Whitney test and are treated as exploratory because $n = 7$ and 5. Monotonic associations were measured with Spearman's ρ. Spatial dependence was assessed with global Moran's I using inverse-distance weights from great-circle distances and 9,999 permutations. The significance level was 0.05; because the study is exploratory, p-values are not adjusted across the four soil properties. The scale of variation was examined further with empirical semivariance, $\gamma(h) = \frac{1}{2}\,\text{mean}[(z_i - z_j)^2]$, computed over all 630 point pairs in five distance classes (< 50 m, 50–150 m, 150–500 m, 0.5–2 km and > 2 km), with EC log-transformed ($\log_{10}$). A pure nugget effect, in which nearby points are no more alike than distant ones, was tested by permuting values among locations (9,999 permutations) and asking whether pairs closer than 150 m had lower mean semivariance than expected by chance. The share of total variance attributable to zone was expressed as η^2 (between-zone sum of squares divided by total). Analyses and figures were produced in Python (pandas, SciPy, matplotlib).

3. RESULTS

3.1 Overview of the dataset

Across the 36 points, soil pH averaged 6.10 ± 0.51, EC 69.6 ± 121.4 µS/cm (median 36.5), moisture 66.0 ± 15.2% and temperature 28.3 ± 2.6 °C (Table 2). EC was by far the most variable property (CV 174% overall, driven by a few high readings), followed by moisture (23%), temperature (9%) and pH (8%). The sampled soils were wet: 8 of 36 points read above 80% moisture, and the lowest reading was 37%.

Zone	n	pH	EC (µS/cm)	Moisture (%)	Soil temperature (°C)
Administrative	12	5.92 ± 0.69 (4.5–6.6)	52.8 ± 53.9 (6–157)	67.3 ± 14.1 (48–87)	30.4 ± 3.2 (27.2–37.0)
Agriculture, lowland	7	6.36 ± 0.24 (6.0–6.5)	165.3 ± 255.9 (34–734)	77.7 ± 12.8 (62–99)	28.7 ± 0.7 (27.7–29.6)
Agriculture, upland	5	6.40 ± 0.22 (6.0–6.5)	38.8 ± 25.9 (22–82)	57.8 ± 12.3 (37–69)	28.7 ± 0.3 (28.2–29.0)
Agriculture, combined	12	6.38 ± 0.23 (6.0–6.5)	112.6 ± 200.5 (22–734)	69.4 ± 15.8 (37–99)	28.7 ± 0.6 (27.7–29.6)
Undisturbed	12	6.00 ± 0.43 (5.5–6.5)	43.5 ± 27.1 (18–110)	61.3 ± 15.7 (49–96)	26.0 ± 0.8 (24.4–26.8)
All points	36	6.10 ± 0.51 (4.5–6.6)	69.6 ± 121.4 (6–734)	66.0 ± 15.2 (37–99)	28.3 ± 2.6 (24.4–37.0)

Table 2. Mean ± SD (minimum–maximum) of in-situ soil properties by zone, ST03, 30 September–1 October 2026. Median EC: administrative 38.5, lowland 65, upland 24, agriculture combined 42.5, undisturbed 34 µS/cm.

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Vol. 15 Issue 10 , October - 2026

Zone	pH	EC	Moisture	Temperature
Administrative	11.7	102.1	21.0	10.6
Agriculture, lowland	3.8	154.8	16.5	2.4
Agriculture, upland	3.5	66.7	21.3	1.2
Undisturbed	7.1	62.4	25.5	3.2

Table 3. Coefficient of variation (%) within each zone.

3.2 Soil pH

Soil pH was moderately acidic to near-neutral at nearly every point (Figure 3a). Twenty-seven of 36 readings were between 6.0 and 6.6, and the three readings below 5.5, at ADZ-06 (4.5), ADZ-07 (5.0) and ADZ-11 (5.3), were all in the administrative zone (Figure 4). All 12 agricultural points were 6.0–6.5, and undisturbed land spanned 5.5–6.5, with four points in the 5.5–5.9 class. Variability was greatest in the administrative zone (CV 11.7%) and least on agricultural land (CV 3.6%). Zone differences were not significant at the 5% level (Kruskal–Wallis H = 4.74, p = 0.094, ε^2 = 0.083; Table 4). The largest contrast was agriculture vs undisturbed land (6.38 vs 6.00; raw p = 0.023, Holm-adjusted p = 0.069). Lowland and upland pH were indistinguishable (median 6.5 in both; p = 0.83).

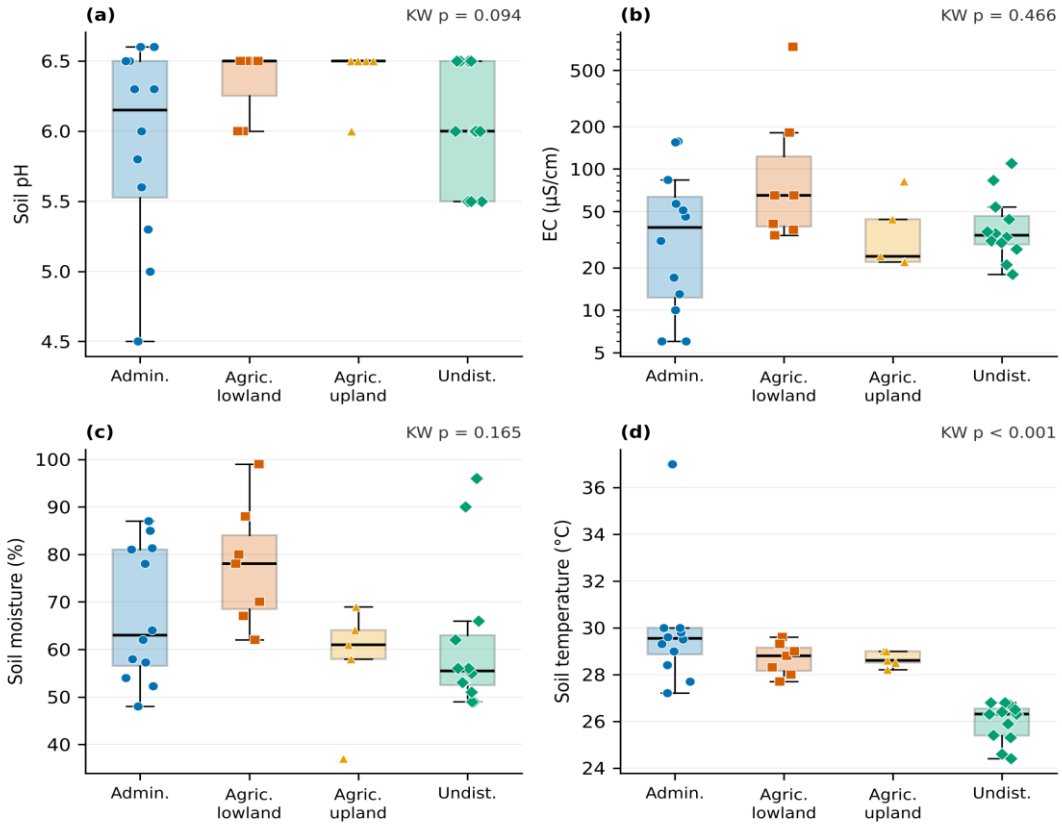


Figure 3. Distribution of (a) pH, (b) EC (log scale), (c) moisture and (d) temperature by zone. Boxes show the interquartile range, the line the median, and points the individual samples. KW = Kruskal–Wallis, three zones with agriculture combined.

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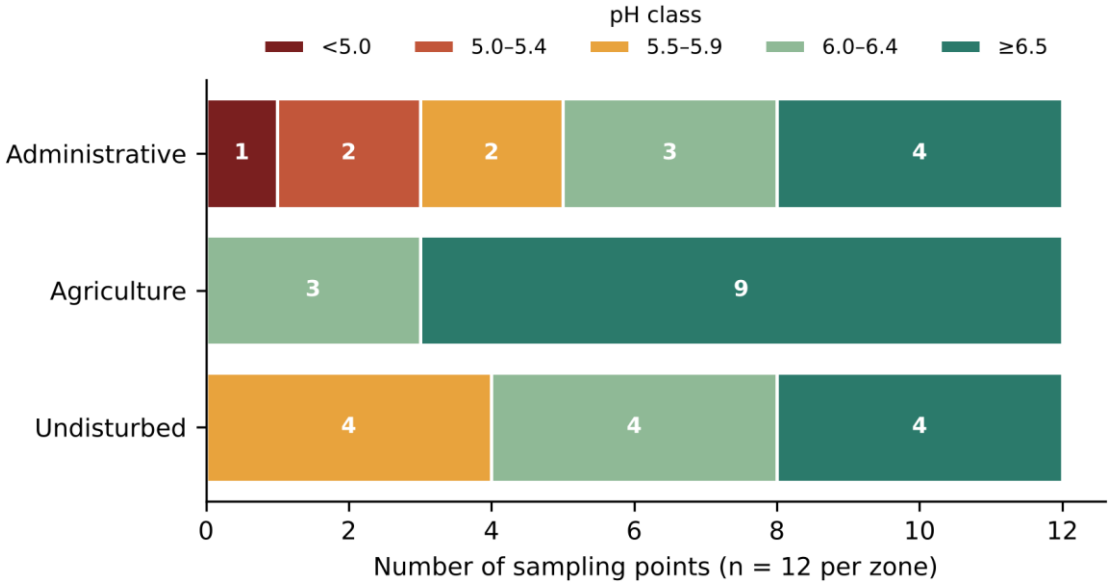


Figure 4. Number of sampling points in each pH class by zone.

Property	Kruskal–Wallis H (df = 2)	p	ε²	Administrative vs agriculture	Administrative vs undisturbed	Agriculture vs undisturbed
pH	4.74	0.094	0.083	0.256	0.930	0.069
EC	1.53	0.466	≈ 0	0.895	0.895	0.895
Moisture	3.60	0.165	0.049	0.583	0.545	0.170
Temperature	25.14	< 0.001	0.701	0.052	< 0.001	< 0.001

Table 4. Omnibus Kruskal–Wallis tests across the three zones and Holm-adjusted pairwise Mann–Whitney p-values. With lowland and upland separated (four groups), H = 4.78 (pH, p = 0.189), 4.35 (EC, p = 0.226), 7.31 (moisture, p = 0.063) and 25.15 (temperature, p < 0.001).

3.3 Electrical conductivity

EC was right-skewed in every zone (Figure 3b). Medians were 24–65 µS/cm, but five points exceeded 100 µS/cm: ADZ-07 (157), ADZ-11 (155), ALL-03 (181), UDL-09 (110) and ALL-04, which read 734 µS/cm in a lowland plot. That single value lifts the lowland mean to 165 µS/cm against a median of 65. No zone difference was detected (H = 1.53, p = 0.466), and upland and lowland EC did not differ significantly (median 24 vs 65 µS/cm, p = 0.14).

3.4 Soil moisture

Moisture did not differ significantly among the three zones (p = 0.165; Table 4), although the four-group test came closer (p = 0.063). The clearest contrast was within the agricultural zone: lowland plots had a median moisture of 78% and upland plots 61%

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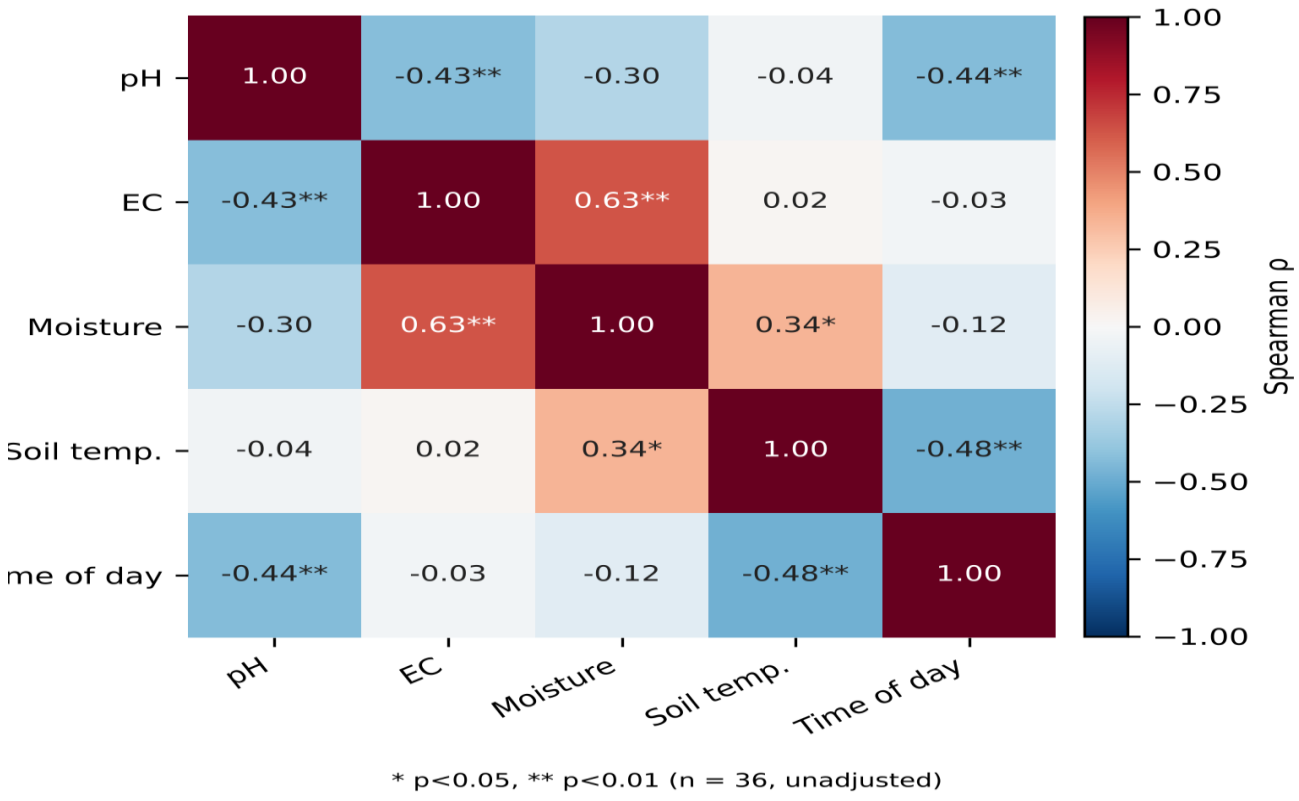
(Mann–Whitney U = 3, p = 0.018), which is consistent with H2 but rests on 7 and 5 points. Moisture ranged most widely in undisturbed land (49–96%), where UDL-06 and UDL-09 (90% and 96%) sat beside points near 50%.

3.5 Soil temperature and the time-of-day confound

Temperature was the only property that differed strongly among zones ($H = 25.14$, $p < 0.001$, $\varepsilon^2 = 0.70$). Undisturbed land averaged 26.0 ± 0.8 °C, against 28.7 ± 0.6 °C on agricultural land and 30.4 ± 3.2 °C in the administrative zone (Figure 3d). The administrative mean includes the two 37.0 °C readings (ADZ-09, ADZ-10); without them it is 29.1 ± 1.0 °C. However, Figure 6b shows that zone and time of day cannot be separated: the 12 undisturbed readings, the coolest of the dataset, are the only ones taken between 17:00 and 18:00, and temperature fell with later time of day across the dataset ($\rho = -0.48$, $p = 0.003$). The pattern is therefore compatible with canopy shade (H4) and with simple late-afternoon cooling, and the current data cannot tell them apart.

3.6 Relationships among properties

The strongest association was between EC and moisture ($\rho = 0.63$, $p < 0.001$; Figure 6a and Figure 5). It held within each group: $\rho = 0.73$ in the administrative zone, 0.61 on agricultural land and 0.68 in undisturbed land ($p = 0.007$, 0.034 and 0.015), supporting H3. EC was negatively related to pH overall ($\rho = -0.43$, $p = 0.009$), with similar within-zone coefficients of −0.44, −0.56 and −0.56 that individually fall just short of significance given 12 points each. Moisture and pH were only weakly related across the dataset ($\rho = -0.30$, $p = 0.080$); inside undisturbed land the link was strong ($\rho = -0.80$, $p = 0.002$) but it was absent in the administrative zone (−0.38, $p = 0.22$) and on agricultural land (−0.25, $p = 0.43$). Temperature correlated weakly with moisture ($\rho = 0.34$, $p = 0.045$) and not at all with pH or EC. pH also correlated with time of day ($\rho = -0.44$, $p = 0.008$), which mirrors the lower pH of the late-sampled undisturbed group and should not be read as a diurnal effect.



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*Figure 5. Spearman rank correlations among the four soil properties and time of measurement (n = 36; * p < 0.05, ** p < 0.01, unadjusted).*

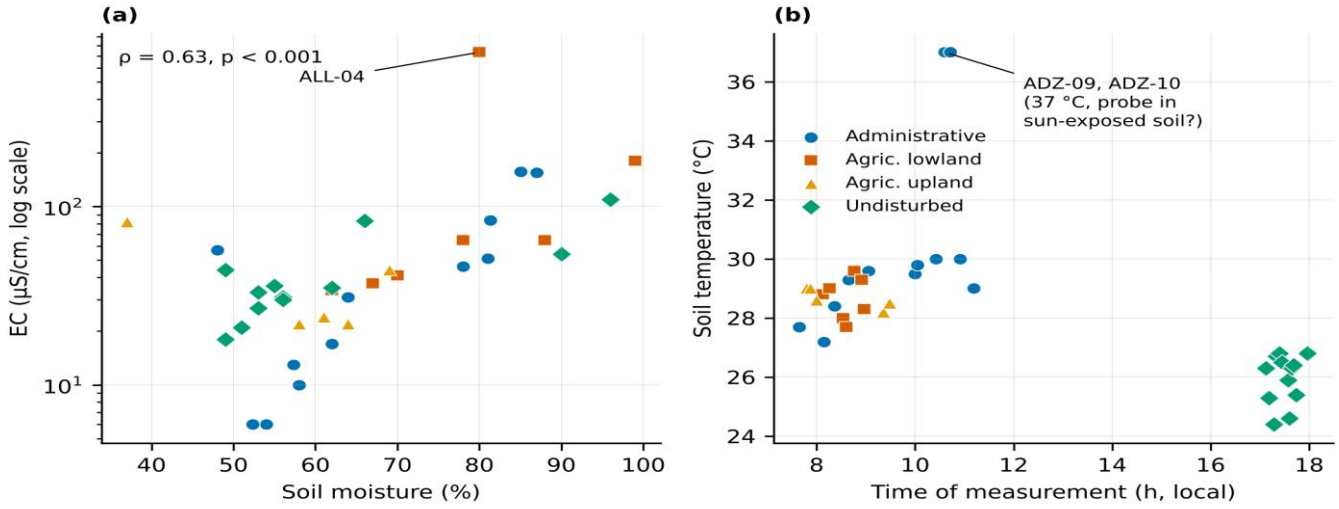


Figure 6. (a) EC (log scale) against soil moisture. (b) Soil temperature against time of measurement, showing that undisturbed land was sampled in the late afternoon and all other zones in the morning.

3.7 Spatial structure

Global Moran's I indicated no spatial autocorrelation for pH (I = 0.10, p = 0.42), EC (I = 0.00, p = 0.99) or moisture (I = 0.01, p = 0.93), so neighbouring points were not more alike than distant ones (Figure 7). Temperature was autocorrelated (I = 0.50, p = 0.004), which follows from zone and measurement time and not from any spatial gradient. Variation occurred over very short distances. ADZ-06 and ADZ-10, 21 m apart, differ by 2.0 pH units (4.5 vs 6.5). ADZ-06 and ADZ-07, 33 m apart, differ by 0.5 pH units, 151 µS/cm in EC and 33 percentage points in moisture. The two pH readings of 5.3 or lower that came with high EC (ADZ-07 and ADZ-11, 148 m apart) both coincided with the wettest administrative points (85% and 87%), whereas the most acidic point, ADZ-06 (pH 4.5), was dry by comparison (52%) and had the lowest EC in the dataset (6 µS/cm).

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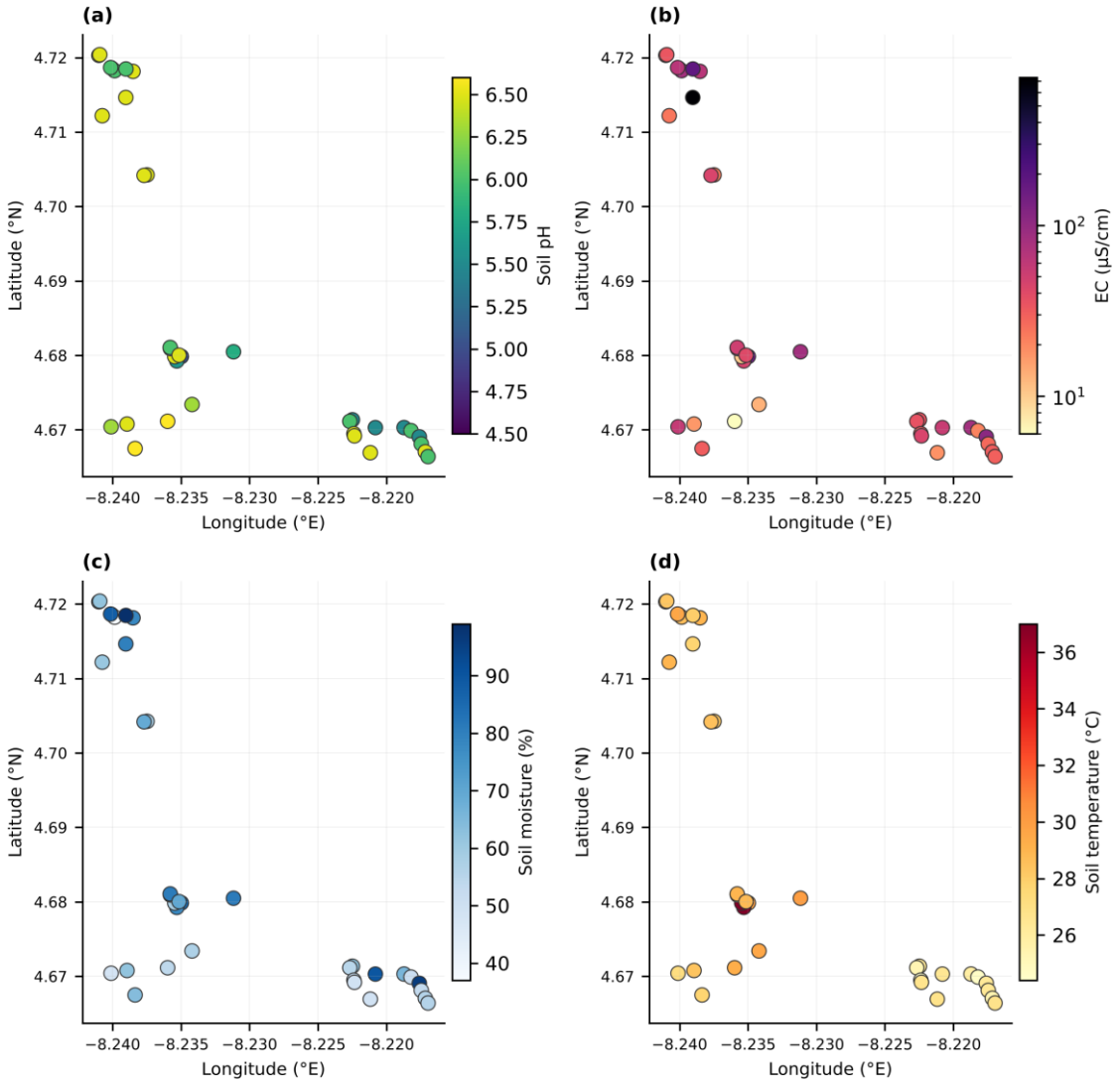


Figure 7. Spatial distribution of (a) pH, (b) EC (log colour scale), (c) moisture and (d) temperature at the 36 sampling points.

3.8 Scale of variation and variance partition

Empirical semivariance showed no spatial structure at any distance (Figure 8, Table 5). For pH, the semivariance of pairs under 50 m apart (0.49) exceeded the sample variance (0.26). Across all pairs closer than 150 m, semivariance was 1.34 times the sample variance for pH, 1.25 times for log EC and 1.40 times for moisture, and permutation tests found no evidence that these close pairs were more alike than random pairs (p = 0.84, 0.79 and 0.95 for lower semivariance). In practical terms, a point's nearest neighbour predicted its value no better than a randomly chosen point from anywhere in the study area. Pairs less than 50 m apart differed on average by 0.68 pH units, about threefold in EC and 13.9 percentage points in moisture, which is comparable to pairs more than 2 km apart (0.54 pH units, 2.9-fold, 17.8 points).

Zone accounted for little of the total variance: $\eta^2 = 0.155$ for pH, 0.077 for log EC and 0.052 for moisture, so more than 84% of the variance in each property lies within zones. Temperature is left out of this partition because of the time-of-day confound.

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

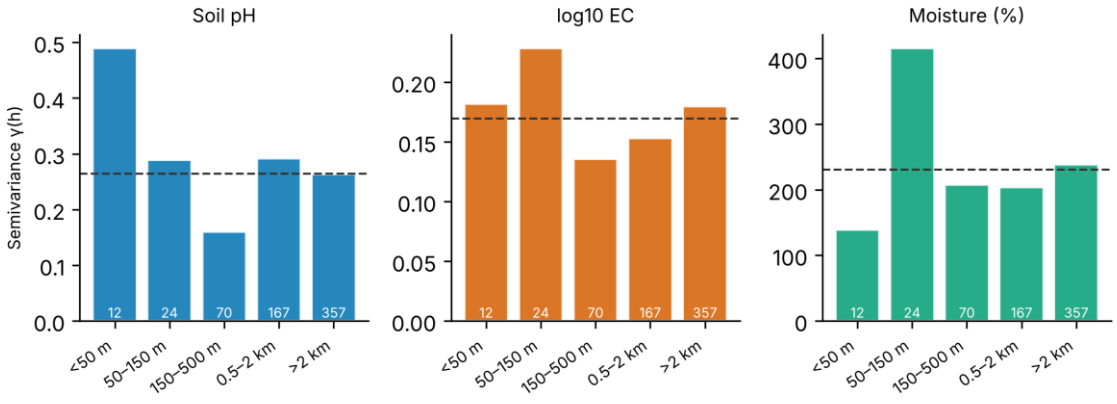


Figure 8. Empirical semivariance of soil pH (left), log₁₀ EC (centre) and moisture (right) by distance class. Numbers inside the bars are pair counts and dashed lines mark the sample variance; bars at or above the dashed line at short distances indicate no spatial structure (pure nugget).

Distance class	Pairs	Mean |ΔpH|	γ pH	Mean |Δlog₁₀ EC| (fold)	γ log₁₀ EC	Mean |Δmoisture| (points)	γ moisture
< 50 m	12	0.68	0.49	0.47 (3.0×)	0.18	13.9	139
50–150 m	24	0.63	0.29	0.55 (3.5×)	0.23	23.9	415
150–500 m	70	0.44	0.16	0.41 (2.6×)	0.14	15.5	208
0.5–2 km	167	0.56	0.29	0.44 (2.7×)	0.15	16.2	204
> 2 km	357	0.54	0.26	0.46 (2.9×)	0.18	17.8	238
Sample variance	630		0.26		0.17		230

Table 5. Mean absolute differences and empirical semivariance (γ) among point pairs by distance class. Pair counts sum to 630; the < 50 m and 50–150 m classes contain few pairs and are imprecise.

3.9 Sensitivity analyses

The main patterns were stable under the checks planned in Section 2.5. Removing ALL-04, ADZ-09 and ADZ-10 left EC unchanged in practice ($p = 0.74$) and temperature strongly different among zones ($H = 22.99$, $p < 0.001$). Restricting the temperature comparison to morning readings (administrative vs agriculture) gave $p = 0.049$ with all points and $p = 0.145$ once the two 37.0 °C readings were removed, so the administrative–agriculture difference rests on those two values. Rounding all pH values to the nearest 0.5 changed the zone test only slightly ($H = 5.05$, $p = 0.080$) and left agriculture vs undisturbed unchanged (raw $p = 0.023$).

Treating ALL-01, the lowland plot inside the administrative cluster, as administrative (13 vs 11 agricultural points), or excluding it, left the conclusions unchanged: the zone tests gave $p = 0.145$ and 0.126 for pH, 0.483 and 0.461 for EC, 0.182 and 0.194 for

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

moisture (reassigned and excluded, respectively) and $p < 0.001$ for temperature in both cases, and the agriculture vs undisturbed pH contrast was $p = 0.033$ in both.

4. DISCUSSION

4.1 pH: higher than the regional baseline, and why that needs checking

The Barclayville readings sit well above what the Liberian literature leads one to expect. Mean pH was 6.10, and every agricultural point read 6.0–6.5, whereas regional summaries put upland soils at about 4.8–5.3 and lowland soils at 5.1–5.6 (Bee, 2026) and describe Latosols as pH 3–5 (Using Agricultural Lime, 2023); Ferralsols and Acrisols in western Ghana, sampled by horizon, were 4.8–5.9 (El Mellouki et al., 2025). Three explanations, not mutually exclusive, deserve testing in follow-up work.

The first is real soil chemistry. Cultivated plots near the town may have received wood ash from clearing and burning, and lowland plots may receive base-rich sediment and runoff; both are plausible but untested here. The second is measurement. The ST03 reads pH in situ in soil that was often very wet (mean 66% moisture), and electrode pH is sensitive to organic matter (about ±0.2–0.4 units), to temperature (about ±0.1–0.3 units over 0–40 °C) and to drift (Song et al., 2026); field sensors can also oscillate by ±0.1 to ±0.25 pH units within a day (Cisneros-Barba et al., 2026). A constant offset would leave the contrasts between zones intact but would shift absolute classification. The third is sampling depth and method: readings were taken at 15–20 cm, below the 0–20 or 0–30 cm layers used in many laboratory surveys, and an in-situ probe reading and a laboratory suspension of a composite sample are not the same quantity. The 0.5-unit recording steps in 29 of 36 values add a further constraint: they cap the resolution at which small differences, such as agriculture vs undisturbed land (0.38 units), can be detected, although rounding did not alter the tests (Section 3.9).

The distinction matters in practice. Liming guidance for Liberia treats pH below 6 as the point at which cocoa soils should be limed and re-tested every three years, with recovery and maintenance decisions built around a 5.8–6.5 band (Using Agricultural Lime, 2023). On the ST03 readings, 9 of 36 points fall below 6.0 (five administrative, four undisturbed) and none of the agricultural points do. Whether that last statement survives laboratory confirmation is precisely what an in-situ screening instrument cannot settle alone.

The direction of the land-use contrast also differs from comparable studies. Cropland topsoil was more acidic than forest in Ghana's forest–savannah transition zone (about 5.2 vs 6.5; Awoonor et al., 2025) and in Ethiopia (5.24 vs 6.06; Abile et al., 2025), whereas in Barclayville agricultural land had the highest pH (6.38) and undisturbed land a lower one (6.00). Several explanations are open. Cropping in shifting-cultivation systems is typically short, 2–4 years before 6–8 years of fallow (Kim, 2025), so bases may not yet have been depleted; ash from clearing may have raised pH; and the in-situ measurement issues above may apply. Those studies analysed laboratory suspensions of composite samples, so differences in method may contribute to the contrast. Where degradation after clearing is severe, it has been documented as low pH with high aluminium mobility and large losses of carbon, nitrogen and phosphorus (Summerauer et al., 2026); nothing in the ST03 readings suggests that stage has been reached in Barclayville, but they cannot rule it out.

4.2 Variation is local, not zonal

The central pattern is that the differences between zones are small relative to the differences within them. The zone effect on pH is modest ($\varepsilon^2 = 0.083$, $p = 0.094$), no property except temperature separates the zones, and Moran's I finds no spatial dependence at the scale of the study area. Meanwhile ADZ-06 and ADZ-10, 21 m apart, differ by 2.0 pH units. The administrative zone shows

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

this most clearly (pH CV 11.7%, EC CV 102%), and its three acidic points fall into two types: a dry, low-EC point (ADZ-06) and two wet, high-EC points 148 m apart (ADZ-07, ADZ-11). In a town, such pockets could reflect buried or burnt waste, building material, drainage lines or garden beds, but no information on site history was collected, so these remain hypotheses for the follow-up work.

The semivariance analysis sharpens the point. Pairs less than 150 m apart were no more alike than random pairs (semivariance 1.25–1.40 times the sample variance; permutation $p \geq 0.79$ for lower semivariance), the signature of a pure nugget effect at the scale sampled, and zone explained only 15.5% of pH variance, 7.7% of log EC variance and 5.2% of moisture variance (Section 3.8). Chemical properties were likewise reported to be more variable than physical ones across land-use classes of a peri-urban landscape in India (Chaurasia et al., 2024). Heterogeneity cannot, however, be assumed for urban soils in general: a 1,000 m² plot near Paris with a heavily modified construction history proved more homogeneous than expected (Ribler et al., 2026). In Barclayville the heterogeneity appears real, with the caveat that the ST03 adds measurement noise of its own.

This contrasts with agricultural fields elsewhere, where location explained most pH variation in a Mississippi Delta field (Fletcher, 2025) and apparent EC held a stable pattern linked to topography in Brazil (Gonçalves et al., 2025). Those studies used dense, continuous sensor data on single fields; our 36 purposively placed points across a 6.6 km extent are far sparser and cannot resolve gradients at that scale, so the absence of spatial autocorrelation here is a statement about this design as much as about the soil. It does imply that a single reading at a plot should not be taken to represent its zone, and that replicate or composite sampling around each location is needed.

4.3 EC and moisture move together

The positive EC–moisture association ($\rho = 0.61$–0.73 within each group) is the most consistent signal in the data. Wetter soil carries more dissolved ions in a continuous water film, so higher conductivity is physically expected. It may also be partly instrumental, because a resistive or capacitive probe's EC response depends on how much water is in contact with it, and the review evidence is that such sensors need soil-specific calibration (Song et al., 2026; Mane et al., 2025). Our EC values (maximum 734 µS/cm, or 0.73 dS/m) are well below the 2 dS/m salinity level at which resistive moisture sensing is reported to degrade (Song et al., 2026), but the instrument's EC is also not the 1:5 extract measurement on which agronomic EC thresholds are built (FAO, 2021). The median EC of 36.5 µS/cm should therefore be read as an index, not compared directly with laboratory values such as the 81–121 µS/cm reported for Ghanaian Ferralsols and Acrisols (El Mellouki et al., 2025). ALL-04 (734 µS/cm in a lowland plot) is the clearest candidate for re-measurement, since poor probe contact, fresh manure or fertilizer, and a genuine salt pocket would all produce a high reading.

The lowland–upland moisture contrast (78% vs 61%) matches what landscape position would predict, and lowland EC was also higher (median 65 vs 24 µS/cm) although not significantly. With 7 and 5 points, both contrasts are indications rather than findings.

Landscape position is known to organise soil acidity and quality in equatorial settings, with lower positions reported to have better soil quality than upper ones in Colombia's Orinoquia (Mahecha-Pulido et al., 2025). In Barclayville, lowland and upland plots share the same median pH (6.5), so landscape position shows up in moisture and, weakly, in EC, but not in pH.

4.4 Temperature cannot yet be attributed to land use

The 2.7 °C gap between undisturbed land (26.0 °C) and agricultural land (28.7 °C) is the largest effect in the dataset, but the undisturbed points were measured 6–10 hours later in the day than every other point (Section 2.4), and temperature fell with time

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

of day across the dataset. Canopy shade is a plausible contributor, yet an afternoon–morning difference of this size cannot be excluded. Low-frequency probes may also be sensitive to temperature itself, although this was not tested in the one study that raises it (Mane et al., 2025), so temperature readings and temperature-dependent EC and pH readings are linked in ways the present data cannot untangle. The two 37.0 °C administrative readings, identical and 7–8 °C above their neighbours, are more consistent with a sun-exposed surface or a sensor artefact than with a real soil difference.

4.5 Agronomic and planning implications

The results arrive as national soil work expands. FAO and its partners have trained Ministry of Agriculture technicians in laboratory analysis and fed 47 Nimba County profiles into the first national soil information system (FAO, 2023), the Ministry's Soils4Liberia project intends to extend mapping to all 15 counties (Deemie, 2025), and the sector's diagnostic has called for soil testing as the basis for fertilizer decisions (World Bank, 2022). In that setting, a point dataset like this one has a specific job: to show where laboratory sampling is most likely to be informative and how much local variability a county-scale map must absorb. For practitioners in Barclayville, four points follow from the data.

- **Sampling unit.** Because pairs less than 150 m apart were no more alike than random pairs, advice for a plot should rest on replicated or composite samples from that plot, not on a zone-level value.
- **Liming screen.** The nine points below pH 6.0 (five administrative, four undisturbed) are candidates for laboratory pH and, if confirmed, liming against the 5.8–6.5 band used in Liberian liming guidance (Using Agricultural Lime, 2023); no agricultural point fell below 6.0 on the ST03.
- **Lowland plots.** Lowland points were the wettest agricultural points and included the highest EC readings, ALL-04 (734 µS/cm) and ALL-03 (181 µS/cm); these deserve laboratory EC before fertilizer is applied, so that salts are not added to soil that already reads high.
- **Upland plots.** Upland plots were the driest agricultural points (median 61%) with the lowest EC (median 24 µS/cm); whether that reflects lower dissolved nutrient levels needs laboratory confirmation.

4.6 Limitations

The conclusions should be read with the following limits in mind.

- **Design.** Points were placed purposively in clusters, with unequal group sizes (12, 12, and 7 + 5 for lowland and upland), so inference applies to the sampled locations and the lowland–upland contrasts rest on 7 and 5 points. Pairs at the shortest distances are few (12 under 50 m).
- **Timing.** Undisturbed land was measured only in the late afternoon and all other zones only in the morning, over two days at the end of the rainy season. Temperature, and possibly moisture and pH readings through temperature effects, cannot be separated from zone, and the results describe a single season.
- **Instrument.** ST03 readings were not paired with laboratory analysis. EC is an in-situ index, not a 1:5 extract EC, and pH was recorded in 0.5-unit steps at 29 of 36 points. Manufacturer accuracy and calibration status are to be reported with the data.
- **Depth.** All readings were taken at 15–20 cm, so the surface layer, which is most exposed to litter, ash and trampling, was not sampled.
- **Covariates.** Texture, organic matter, elevation, slope, vegetation and land-use history were not recorded, so zone differences can be described but not explained.

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

- **Positional accuracy.** Coordinates came from a smartphone camera application and their accuracy was not quantified. ALL-01 lies inside the administrative cluster, although the sensitivity analysis shows that this does not change the conclusions.
- **Multiplicity.** Tests across the four properties are not adjusted for multiple comparisons.

5. CONCLUSIONS

Thirty-six in-situ ST03 measurements at 15–20 cm depth shows that soils in Barclayville are moderately acidic to near-neutral (pH 6.10 ± 0.51), wet at the end of the rainy season (moisture 66 ± 15%) and low in conductivity (median EC 36.5 µS/cm), with pH higher than the 4.8–5.8 range reported in regional summaries for Liberian soils. Zones did not differ significantly in pH, EC or moisture; the clearest contrasts were pH on agricultural vs undisturbed land (6.38 vs 6.00, adjusted $p = 0.069$) and moisture on lowland vs upland plots (78% vs 61%, $p = 0.018$). EC rose with moisture in every zone, and the only pH readings below 5.5 were in the administrative zone. The soil temperature gap among zones is confounded by measurement time and does not support a land-use effect.

The main finding is the scale of variation. Zone explained 5–16% of the variance in pH, EC and moisture, points less than 150 m apart were no more alike than random pairs, and two points 21 m apart differed by 2.0 pH units. In this setting land-use zone is a poor predictor of soil condition, and a single reading describes a spot, not a zone.

For agronomy and planning in Barclayville, the ST03 is suited to screening and to deciding where to sample for the laboratory, not to setting lime or fertilizer rates; those decisions need laboratory-validated pH and EC from composite samples taken at plot scale. Future work should:

- take replicated or composite samples within each plot (for example within 10 m) and report the within-point spread;
- measure all zones in the same morning window and repeat the survey in the dry season;
- pair a subset of points with laboratory pH (in water) and 1:5 EC following FAO procedures (FAO, 2021), for instance at the University of Liberia laboratory (FAO, 2023), and report instrument–laboratory agreement;
- record texture, organic matter, slope, elevation and land-use history so that local variation can be explained;
- re-check the unusual readings at ADZ-09, ADZ-10 and ALL-04 with repeated probe insertions.

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Appendix A: Sample-level dataset

Sample ID	Zone	Latitude (°N)	Longitude (°E)	pH	EC (µS/cm)	Moisture (%)	Soil temp. (°C)	Time (h:min)
ADZ-01	Administrative	4.667488	−8.238352	6.6	31	64	27.7	07:39
ADZ-02	Administrative	4.670407	−8.240105	6.3	57	48	27.2	08:09
ADZ-03	Administrative	4.670775	−8.238940	6.5	17	62	28.4	08:22
ADZ-04	Administrative	4.671142	−8.235976	6.6	6	54	29.3	08:39
ADZ-05	Administrative	4.673399	−8.234194	6.3	13	57.33	29.6	09:03
ADZ-06	Administrative	4.679844	−8.235270	4.5	6	52.3	29.5	10:00
ADZ-07	Administrative	4.679849	−8.234975	5	157	85	29.8	10:03

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

Sample ID	Zone	Latitude (°N)	Longitude (°E)	pH	EC (µS/cm)	Moisture (%)	Soil temp. (°C)	Time (h:min)
ADZ-08	Administrative	4.680481	−8.231166	5.8	84	81.3	30	10:25
ADZ-09	Administrative	4.679248	−8.235306	5.6	46	78	37	10:36
ADZ-10	Administrative	4.679833	−8.235460	6.5	10	58	37	10:43
ADZ-11	Administrative	4.680916	−8.235772	5.3	155	87	30	10:55
ADZ-12	Administrative	4.681062	−8.235789	6	51	81	29	11:11
ALL-01	Agriculture, lowland	4.680021	−8.235141	6.5	41	70	28.8	08:07
ALL-02	Agriculture, lowland	4.718145	−8.238504	6.5	65	78	29	08:16
ALL-03	Agriculture, lowland	4.718468	−8.239022	6	181	99	28	08:32
ALL-04	Agriculture, lowland	4.714640	−8.239030	6.5	734	80	27.7	08:36
ALL-05	Agriculture, lowland	4.718657	−8.240135	6	65	88	29.6	08:46
ALL-06	Agriculture, lowland	4.720299	−8.240999	6.5	37	67	29.3	08:55
ALL-07	Agriculture, lowland	4.720391	−8.240930	6.5	34	62	28.3	08:58

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

Sample ID	Zone	Latitude (°N)	Longitude (°E)	pH	EC (µS/cm)	Moisture (%)	Soil temp. (°C)	Time (h:min)
AUL-01	Agriculture, upland	4.712188	−8.240749	6.5	24	61	29	07:48
AUL-02	Agriculture, upland	4.718555	−8.240053	6.5	22	64	29	07:52
AUL-03	Agriculture, upland	4.718239	−8.239846	6	82	37	28.6	08:00
AUL-04	Agriculture, upland	4.704177	−8.237697	6.5	44	69	28.5	09:29
AUL-08	Agriculture, upland	4.704246	−8.237478	6.5	22	58	28.2	09:21
UDL-01	Undisturbed	4.671346	−8.222480	5.5	35	62	26.3	17:07
UDL-02	Undisturbed	4.671142	−8.222672	6	36	55	25.3	17:11
UDL-03	Undisturbed	4.669478	−8.222377	6.5	33	53	24.4	17:17
UDL-04	Undisturbed	4.669187	−8.222334	6.5	44	49	26.7	17:20
UDL-05	Undisturbed	4.666925	−8.221174	6.5	18	49	26.8	17:24
UDL-06	Undisturbed	4.670293	−8.220804	5.5	54	90	26.5	17:27
UDL-07	Undisturbed	4.670300	−8.218713	5.5	83	66	25.9	17:34
UDL-08	Undisturbed	4.669892	−8.218204	6	21	51	24.6	17:36
UDL-09	Undisturbed	4.669059	−8.217596	5.5	110	96	26.3	17:39
UDL-10	Undisturbed	4.668102	−8.217453	6	27	53	26.4	17:41

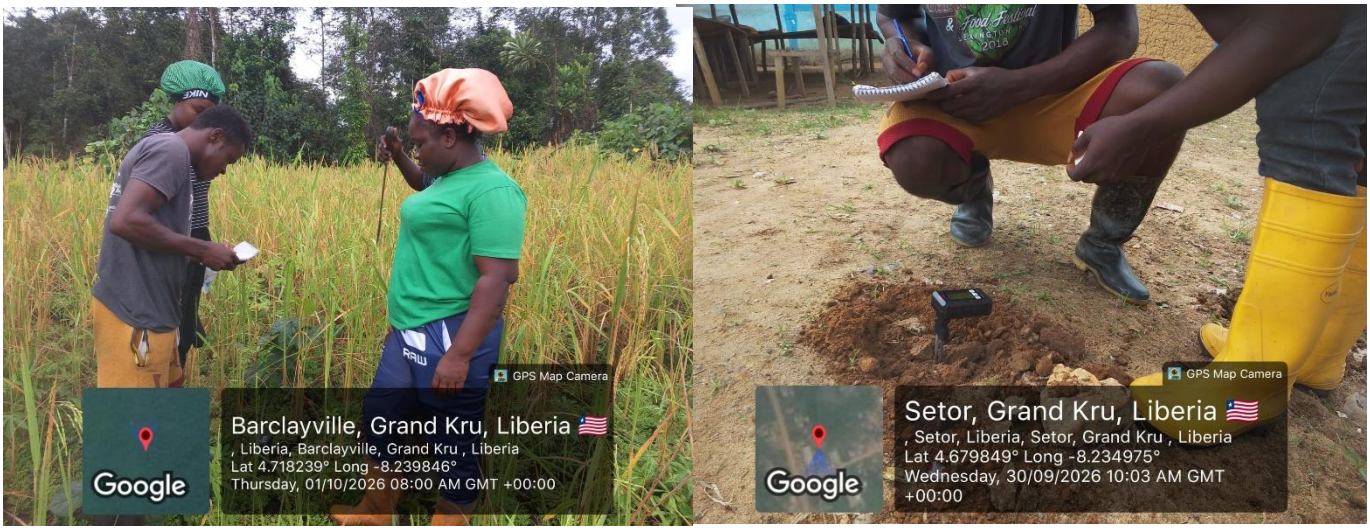
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Sample ID	Zone	Latitude (°N)	Longitude (°E)	pH	EC (µS/cm)	Moisture (%)	Soil temp. (°C)	Time (h:min)
UDL-11	Undisturbed	4.667044	−8.217157	6.5	31	56	25.4	17:44
UDL-12	Undisturbed	4.666401	−8.216958	6	30	56	26.8	17:58

Table 1: Sample-level data as recorded. Longitudes are decimal degrees west (negative). AUL-04 longitude was corrected from −8237697 (Section 2.5). Time is local time of measurement; sampling dates were 30 September and 1 October 2026.

Appendix B: Sample level photos using the geo camera



Appendix C: Sample level photos of students collecting soil sample data using soil intelligent tester.



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