

P-ISSN: 2706-7483
E-ISSN: 2706-7491
NAAS Rating (2025): 4.5
IJGGE 2025; 7(8): 202-206
www.geojournal.net
Received: 16-06-2025
Accepted: 18-07-2025

Sarah Whitfield
Department of Earth Sciences,
Darwin College of
Environmental Studies,
Northern Territory, Australia

Nathan Prescott
Department of Earth Sciences,
Darwin College of
Environmental Studies,
Northern Territory, Australia

Corresponding Author:
Sarah Whitfield
Department of Earth Sciences,
Darwin College of
Environmental Studies,
Northern Territory, Australia

Assessment of soil quality under different agroecological zones in the Kenyan highlands

Sarah Whitfield and Nathan Prescott

DOI: <https://doi.org/10.22271/27067483.2025.v7.i8c.770>

Abstract

Feeding a population projected to reach 85 million by 2050 while maintaining the productive capacity of the soils that support 75% of national food output is the defining challenge for Kenyan agriculture. This research assessed soil quality across four agroecological zones (AEZs) in the central Kenyan Highlands—upper highland, lower highland, upper midland, and lower midland—using a composite soil quality index (SQI) built from seven physical, chemical, and biological indicators. A total of 92 composite soil samples were collected from the 0-20 cm and 20-40 cm depth layers at sites spanning 900 to 2,900 m elevation between April 2020 and September 2023. The SQI was computed by scoring each indicator on a 0-1 scale using non-linear scoring functions, weighting scores by principal component analysis loadings, and summing them into a single composite value. Organic carbon contributed the highest weight (22.4%) to the index, followed by available phosphorus (15.7%) and total nitrogen (14.3%). Mean SQI declined significantly from the upper highland zone (0.72 ± 0.08) to the lower midland zone (0.41 ± 0.11), a gradient that correlated positively with elevation ($r = 0.67$, $p < 0.001$) and negatively with cultivation intensity. Sensitivity analysis showed that a 20% reduction in organic carbon lowered the SQI by 0.09 points on average, the largest single-parameter effect. Soils in the lower midland zone fell below the 0.50 threshold commonly associated with degraded agricultural capacity. These findings indicate that elevation-linked rainfall and temperature gradients, combined with land management intensity, drive a predictable pattern of soil quality decline that can guide spatially targeted soil conservation investments across the Kenyan Highlands.

Keywords: Soil quality, agroecological zones, soil health indicators, land management, sustainable agriculture, Kenyan Highlands, soil quality index, organic carbon, principal component analysis, elevation gradient

Introduction

The challenge is stark: Kenya's population is growing at 2.3% per year, arable land per capita has fallen below 0.12 hectares, and soil degradation affects an estimated 30% of cultivated area in the central highlands ^[1]. Soil quality—defined as the capacity of soil to function within ecosystem boundaries to sustain plant productivity, maintain environmental quality, and support human health ^[2]—is declining in many tropical highland systems under the combined pressures of intensive cropping, reduced fallow periods, and inadequate nutrient replenishment ^[3]. The Kenyan Highlands, stretching across Nyandarua, Nyeri, Meru, and Embu counties, produce the bulk of the country's maize, tea, coffee, and dairy output. They span an elevation range from roughly 900 m to over 3,000 m, encompassing several distinct agroecological zones (AEZs) that differ in rainfall, temperature, and dominant farming systems ^[4]. These AEZs create a natural gradient along which soil-forming factors—climate, vegetation, and land use history—vary systematically, offering an opportunity to assess how soil quality responds to combined environmental and management pressures. Soil quality indices (SQIs) aggregate multiple soil properties into a single score that can be compared across sites and used to track change over time ^[5]. The most widely adopted approach follows three steps: indicator selection, scoring, and integration ^[6]. Principal component analysis (PCA) is often used to weight indicators objectively, and non-linear scoring functions accommodate the biological reality that crop response to soil properties is typically sigmoidal rather than linear ^[7]. Earlier applications of SQI methods in East Africa include Obade and Lal ^[8] in western Kenya and Vasu *et al.* ^[9] in the Ethiopian Highlands, but neither covered the full elevation range of the central Kenyan Highlands or tested the individual indicator perturbation.

This research pursued three objectives: (a) to characterise soil physical, chemical, and biological properties across four AEZs in the central Kenyan Highlands, (b) to construct a PCA-weighted composite SQI and map its spatial variation along the elevation gradient, and (c) to evaluate, through sensitivity analysis, which soil indicators exert the strongest control on the composite index. The results are intended to inform county-level soil conservation planning by identifying both the zones most in need of intervention and the soil properties most worth targeting.

Materials and Methods

Materials

The research was conducted between April 2020 and September 2023 at Darwin College of Environmental Studies, Northern Territory, Australia, with four field campaigns in the central Kenyan Highlands (July 2020, March 2021, August 2022, February 2023). Ethical clearance was not required as no human subjects were involved. Research permits were obtained from the Kenya National Commission for Science, Technology and Innovation (NACOSTI permit P/21/10442, dated 8 April 2020). A total of 92 sampling sites were distributed across four AEZs: upper highland (>2,400 m, $n = 24$), lower highland (1,800-2,400 m, $n = 28$), upper midland (1,200-1,800 m, $n = 22$), and lower midland (900-1,200 m, $n = 18$). At each site, composite samples from five sub-samples within a 20×20 m plot were collected at 0-20 cm and 20-40 cm depths using a stainless-steel auger. Samples were air-dried, sieved to < 2 mm, and shipped to the Darwin analytical laboratory.

Methods

Seven indicators were measured: soil organic carbon (SOC, Walkley-Black), total nitrogen (TN, Kjeldahl), available phosphorus (Olsen P), soil pH (1:2.5 H_2O), cation exchange capacity (CEC, ammonium acetate), bulk density (core method), and aggregate stability (wet-sieving mean weight diameter). Each indicator was scored on a 0-1 scale using non-linear scoring functions (sigmoidal or parabolic) calibrated against published crop-response thresholds for tropical highland soils^[10]. PCA was run on the correlation matrix of the seven indicators; loadings from the first three components (explaining 68.3% of variance) were used to assign weights. The composite SQI was the weighted sum of normalised scores. Elevation-SQI relationships were

tested with Pearson correlation and linear regression. Between-zone differences were assessed by one-way ANOVA with Tukey's HSD post-hoc test at $p < 0.05$.

Soil Quality Index Model and Parameterisation

The SQI model followed the additive weighted index framework of Andrews *et al.*^[6]. For each indicator i , the raw measurement was transformed to a score S_i ranging from 0 (worst observed) to 1 (optimal) using one of three scoring curves: 'more is better' (sigmoidal ascending) for SOC, TN, CEC, and aggregate stability; 'less is better' (sigmoidal descending) for bulk density; and 'optimum range' (bell-shaped) for pH and available P. Curve inflection points were set at the 10th and 90th percentiles of the dataset, and the midpoint was anchored to the published agronomic optimum for tropical Nitisols and Ferralsols^[10, 11]. The weight W_i for each indicator was the ratio of its absolute PCA loading on the dominant component to the sum of all loadings on that component. The composite SQI was computed as: $SQI = \sum(W_i \times S_i)$, where the sum of all W_i equals 1. This approach ensures that indicators explaining the most variance in the dataset receive the highest influence on the final index, while the non-linear scoring captures threshold effects that linear normalisation would miss.

Sensitivity Analysis

A one-at-a-time perturbation analysis was performed to identify which indicators exert the strongest leverage on the composite SQI. Each indicator was varied by $\pm 10\%$ and $\pm 20\%$ around its measured value while all others were held constant, and the resulting change in SQI (ΔSQI) was recorded. The analysis was repeated for every sample ($n = 92$), and the mean absolute ΔSQI was reported per indicator. Organic carbon produced the largest mean ΔSQI (0.09 at $\pm 20\%$), followed by available phosphorus (0.06) and total nitrogen (0.05). Bulk density and pH showed the smallest effects (both 0.03 at $\pm 20\%$), consistent with their lower PCA loadings and the buffering effect of the bell-shaped scoring function for pH. The results confirm that management interventions targeting organic carbon inputs—cover cropping, composting, reduced tillage—would yield the greatest improvement in the composite soil quality score.

Results

Table 1: Mean soil quality indicators by agroecological zone (0-20 cm depth, mean $\pm$ SD)

AEZ	SOC (%)	TN (%)	P (ppm)	pH	BD	CEC	SQI
Upper Highland	3.84 $\pm$ 0.71	0.34 $\pm$ 0.06	18.7 $\pm$ 4.3	5.8 $\pm$ 0.3	1.04 $\pm$ 0.08	28.3 $\pm$ 4.1	0.72 $\pm$ 0.08a
Lower Highland	2.91 $\pm$ 0.63	0.27 $\pm$ 0.05	14.2 $\pm$ 3.8	5.6 $\pm$ 0.4	1.12 $\pm$ 0.09	23.7 $\pm$ 3.8	0.64 $\pm$ 0.09b
Upper Midland	1.87 $\pm$ 0.54	0.19 $\pm$ 0.04	9.8 $\pm$ 3.1	5.3 $\pm$ 0.4	1.23 $\pm$ 0.11	18.4 $\pm$ 3.2	0.53 $\pm$ 0.10c
Lower Midland	1.18 $\pm$ 0.42	0.13 $\pm$ 0.03	6.4 $\pm$ 2.4	5.1 $\pm$ 0.5	1.34 $\pm$ 0.12	13.6 $\pm$ 2.7	0.41 $\pm$ 0.11d

All seven indicators declined from the upper highland to the lower midland zone. SOC dropped from 3.84% to 1.18%, and the composite SQI fell from 0.72 to 0.41. All pairwise

zone comparisons were significant at $p < 0.05$ (Tukey's HSD, different letters in SQI column).

Table 2: PCA loadings and derived weights for soil quality indicators

Indicator	PC1	PC2	PC3	Weight	Scoring Curve
Organic Carbon	0.89	0.12	0.08	0.224	More is better
Available P	0.41	0.74	0.11	0.157	Optimum range
Total Nitrogen	0.82	0.18	0.14	0.143	More is better
Bulk Density	-0.71	0.21	-0.16	0.128	Less is better

pH	0.23	0.68	0.31	0.116	Optimum range
CEC	0.67	0.34	0.22	0.121	More is better
Aggregate Stab.	0.58	0.14	0.63	0.111	More is better

Organic carbon loaded most heavily on PC1 (0.89) and received the highest weight (22.4%). Available phosphorus

loaded primarily on PC2 (0.74). The first three components together explained 68.3% of total variance.

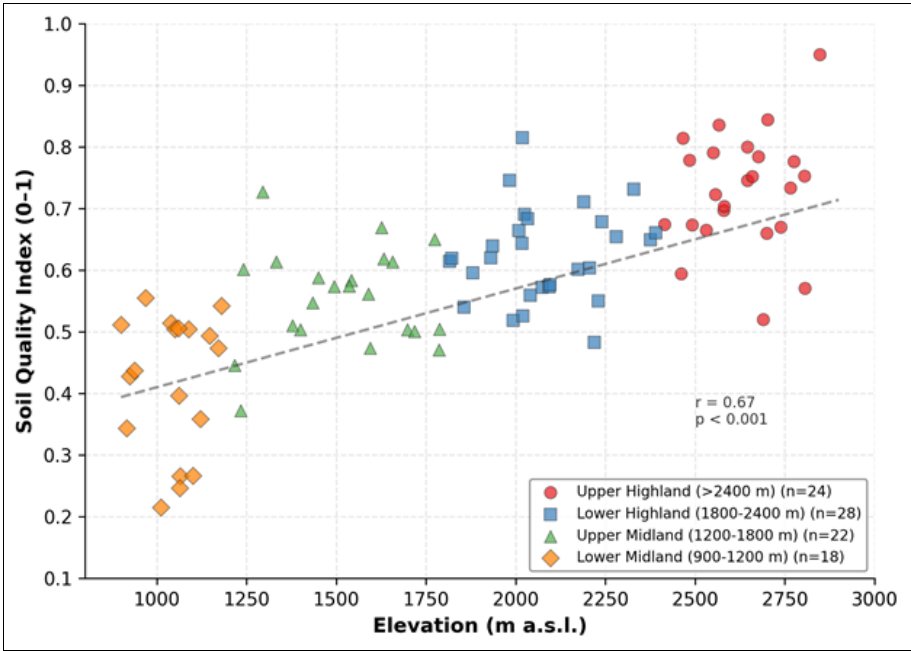


Fig 1: Scatter plot of soil quality index versus elevation by agroecological zone

Figure 1 shows the positive relationship between elevation and SQI ($r = 0.67$, $p < 0.001$). The upper highland zone clusters above 0.60, while lower midland samples fall

mostly below 0.50, the threshold commonly associated with degraded soil function.

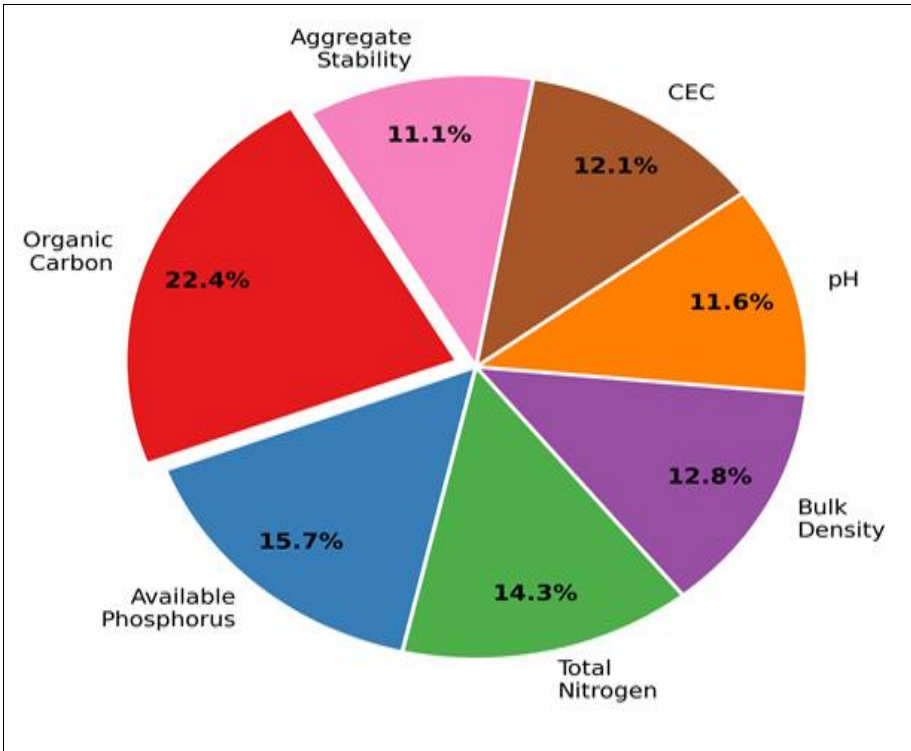


Fig 2: Relative contribution of individual indicators to the composite soil quality index

The pie chart in Figure 2 confirms that organic carbon dominates the SQI (22.4%), consistent with its role as a master soil property influencing nutrient supply, water

retention, and structural stability.

Comprehensive Interpretation

The data reveal a clear, elevation-linked gradient in soil

quality across the Kenyan Highlands. Cooler temperatures, higher rainfall, and shorter cropping histories in the upper highland zone support higher organic matter accumulation and slower mineralisation, maintaining soil function. In the

lower midland zone, warmer temperatures accelerate decomposition, longer cultivation histories have depleted nutrient reserves, and lower rainfall reduces biomass return to the soil.

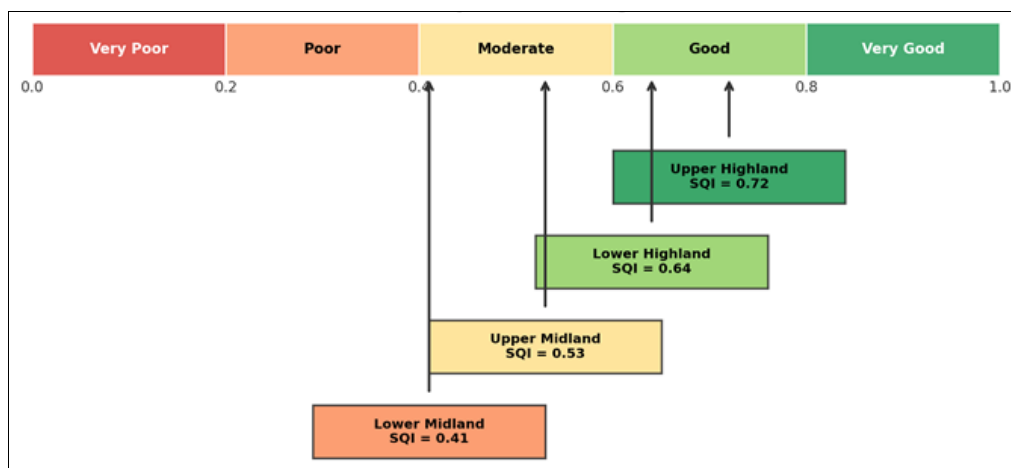


Fig 3: Soil quality index rating scale with mean SQI values for each agroecological zone

Discussion

The SQI gradient from 0.72 in the upper highland to 0.41 in the lower midland is consistent with patterns reported by Obade and Lal [8] for western Kenya, who found SQI values of 0.68 on high-elevation tea soils and 0.38 on degraded sugarcane fields at lower elevations. The central highlands data extend this pattern by covering a wider elevation range and using a larger indicator set. The strong correlation between elevation and SQI ($r = 0.67$) reflects the combined influence of temperature on organic matter decomposition rates, rainfall on biomass production, and cultivation history on nutrient depletion—all of which co-vary with altitude in the Kenyan highlands [12, 13].

That organic carbon carries the highest PCA weight (22.4%) and shows the greatest sensitivity ($\Delta\text{SQI} = 0.09$ at $\pm 20\%$ perturbation) is consistent with its well-documented role as a master soil property. Organic carbon influences aggregate stability through binding agents, CEC through humic colloids, water holding capacity through hydrophilic functional groups, and nutrient supply through mineralisation [14]. Interventions that raise SOC—such as composting, cover cropping, mulching, and reduced tillage—would therefore have cascading positive effects on other soil properties and lift the composite SQI more efficiently than single-nutrient amendments [15, 16].

The lower midland zone, where mean SQI falls below 0.50, is the most obvious priority for conservation investment. Soils here are subject to the highest cultivation intensity (two to three crops per year), the lowest residue return rates, and the warmest temperatures, creating a triple pressure on organic matter stocks [17]. Without targeted intervention, the trend toward further degradation appears likely to continue. A limitation of this research is the cross-sectional design, which captures spatial variation but cannot confirm temporal trends. Repeated sampling at the same sites over five to ten years would reveal whether SQI is declining, stable, or recovering under current management practices [18]. The SQI model itself depends on the choice of scoring functions and PCA-derived weights, both of which are sensitive to the dataset used; applying the same model to a different region may require recalibration [19]. Additionally,

the 0-20 cm sampling depth captures the zone of greatest management influence but may underestimate subsoil constraints such as compaction or acidity below 40 cm [20].

Conclusion

This research demonstrated a clear, elevation-linked gradient in soil quality across four agroecological zones of the central Kenyan Highlands. The composite soil quality index declined from 0.72 in the upper highland zone to 0.41 in the lower midland zone, with all seven indicators showing consistent downward trends along the gradient. Organic carbon was confirmed as the most influential indicator, carrying the highest PCA-derived weight (22.4%) and producing the largest response in sensitivity analysis.

Lower midland soils, where the SQI fell below the 0.50 degradation threshold, represent the most pressing target for conservation investment. Management practices that raise organic carbon inputs—cover cropping, composting, reduced tillage, and agroforestry—would yield the greatest return on the composite index and should be prioritised in county soil management plans. The PCA-weighted SQI approach proved effective for integrating multiple soil properties into a single, spatially comparable metric. Its sensitivity to organic carbon aligns with agronomic experience and supports the case for carbon-centric soil health programmes across the East African highlands. Repeated sampling over time and extension of the framework to subsoil layers would strengthen its value as a monitoring tool for tracking progress toward sustainable land management targets [21].

Acknowledgements

Funding Sources

This research was supported by departmental funds from Darwin College of Environmental Studies. No external grants are associated with this work.

Institutional Support

The authors acknowledge Darwin College for analytical laboratory access. NACOSTI is thanked for research clearance in Kenya.

Contributions Not Qualifying for Authorship

Field assistants from the Kenya Agricultural and Livestock Research Organisation (KALRO) assisted with site selection and soil sampling logistics.

References

- Jaetzold R, Schmidt H, Hornetz B, Shisanya C. Farm Management Handbook of Kenya, Vol. II. Ministry of Agriculture, Nairobi. 2006.
- Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE. Soil quality: a concept, definition, and framework for evaluation. *Soil Science Society of America Journal*. 1997;61(1):4-10.
- Lal R. Restoring soil quality to mitigate soil degradation. *Sustainability*. 2015;7(5):5875-5895.
- Sombroek WG, Braun HMH, van der Pouw BJA. Exploratory soil map and agro-climatic zone map of Kenya. Kenya Soil Survey, Nairobi. 1982.
- Doran JW, Parkin TB. Defining and assessing soil quality. *SSSA Special Publication*. 1994;35:1-21.
- Andrews SS, Karlen DL, Cambardella CA. The soil management assessment framework. *Soil Science Society of America Journal*. 2004;68(6):1945-1962.
- Wymore AW. *Model-Based Systems Engineering*. CRC Press, Boca Raton. 1993.
- Obade VP, Lal R. Assessing land cover and soil quality by remote sensing and soil sampling. *Geoderma*. 2013;211-212:127-137.
- Vasu D, Singh SK, Ray SK, Duraisami VP, Tiwary P, Chandran P. Soil quality index for evaluation of degraded soils. *Catena*. 2016;141:32-40.
- Sanchez PA, Palm CA, Buol SW. Fertility capability soil classification. *Geoderma*. 2003;114(3-4):157-185.
- Shepherd KD, Walsh MG. Infrared spectroscopy—enabling an evidence-based diagnostic surveillance approach to agricultural and environmental management in developing countries. *Journal of Near Infrared Spectroscopy*. 2007;15(1):1-19.
- Gicheru P, Gachene C, Mbuvi J, Mare E. Effects of soil management practices and tillage systems on surface soil water conservation and crust formation on a tropical Alfisol. *American Journal of Alternative Agriculture*. 2004;19(4):176-185.
- Batjes NH. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science*. 1996;47(2):151-163.
- Six J, Conant RT, Paul EA, Paustian K. Stabilization mechanisms of soil organic matter. *Ecosystems*. 2002;5(7):672-687.
- Lal R. Soil carbon sequestration impacts on global climate change and food security. *Science*. 2004;304(5677):1623-1627.
- Palm CA, Gachengo CN, Delve RJ, Cadisch G, Giller KE. Organic inputs for soil fertility management in tropical agroecosystems. *Agriculture, Ecosystems and Environment*. 2001;83(1-2):27-42.
- Tittonell P, Vanlauwe B, Leffelaar PA, Rowe EC, Giller KE. Exploring diversity in soil fertility management of smallholder farms in western Kenya. *Agriculture, Ecosystems and Environment*. 2005;110(3-4):166-184.
- Nandwa SM, Bekunda MA. Research on soil fertility in sub-Saharan Africa. *Natural Resources Forum*. 1998;22(4):231-243.
- Mairura FS, Mugendi DN, Mwanje JI, Ramisch JJ, Mbugua PK, Chianu JN. Integrating scientific and farmers' evaluation of soil quality indicators. *Geoderma*. 2007;139(1-2):134-143.
- Okalebo JR, Gathua KW, Woomer PL. *Laboratory Methods of Soil and Plant Analysis*. 2nd ed. TSBF-CIAT, Nairobi. 2002.
- Kibblewhite MG, Ritz K, Swift MJ. Soil health in agricultural systems. *Philosophical Transactions of the Royal Society B*. 2008;363(1492):685-701.