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Pedogenic Controls of Deep Soil Organic Carbon Storage Along a Tropical Highland Toposequence

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Research Article

Keywords: Deep soil carbon, Pedogenesis, Toposequence, Luvisols, Vertisols, Ethiopia

Posted Date: June 26th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9913449/v1

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Additional Declarations: No competing interests reported.

Abstract

Deep soil organic carbon (SOC; >30 cm) represents a major but still poorly constrained component of terrestrial carbon stocks, particularly in tropical highland environments. This exploratory pedon-scale study quantified SOC stocks to 200 cm depth along a representative toposequence in the Kersa sub-watershed, eastern Ethiopian highlands, and evaluated pedogenic controls on SOC distribution with depth.

Eight pedons representing upper-, middle-, and lower-slope positions were described, classified using the World Reference Base (WRB) system, and sampled by genetic horizons. SOC stocks were calculated from bulk density, SOC concentration, horizon thickness, and coarse fragment content. Soil depth increased downslope (25–200 cm), reflecting combined effects of pedogenesis and colluvial deposition.

Five Reference Soil Groups were identified: Leptosols and Regosols (upper slope), Cambisols (middle slope), and Luvisols and Vertisols (lower slope). Total SOC stocks ranged from 43 to 347 Mg ha^{-1} (0–200 cm), with substantially greater storage in lower slope positions.

In a representative Luvisol, 75% of total SOC was stored below 30 cm, while subsurface horizons contributed 68% of total SOC. SOC concentration showed a strong positive correlation with clay content at depth ($r = 0.60–0.89$), indicating increasing importance of organo-mineral stabilization in subsurface horizons.

These patterns reflect pedogenic processes including clay translocation, argic horizon formation, vertic structure development, and colluvial deposition, which jointly regulate soil depth, texture redistribution, and SOC stabilization along slope gradients.

Given the limited replication (eight pedons), results are interpreted as hypothesis-generating and intended to support future regional-scale studies incorporating SOC fractionation and isotopic analyses.

1. INTRODUCTION

Soil organic carbon (SOC) is the largest terrestrial carbon reservoir, storing approximately 1500–2400 Pg C in the upper meter globally (Batjes, 1996; Lal, 2004). Nearly half of this pool occurs below 30 cm depth (Jobbágy and Jackson, 2000; Batjes, 2014), where carbon is typically older and stabilized through mineral associations and reduced microbial activity (Rumpel and Kögel-Knabner, 2011; Schmidt et al., 2011).

Despite its importance, deep SOC is often excluded from inventories and ecosystem models due to limited sampling depth, leading to systematic underestimation of total soil carbon stocks, particularly in clay-rich tropical landscapes.

In Ethiopia, SOC studies have largely focused on surface soils, with limited investigations beyond 100 cm depth (Okolo et al., 2019). The eastern Ethiopian highlands remain underrepresented despite strong

topographic gradients and intensive land use.

Previous work in the Kersa sub-watershed quantified SOC to 60 cm depth (Tefera et al., 2018) and documented strong soil variability along toposequences (Tefera et al., 2026). However, deep SOC distribution and its pedogenic controls remain insufficiently understood.

This study addresses this gap by quantifying SOC stocks to 200 cm depth along a tropical highland toposequence and evaluating pedogenic controls on SOC redistribution. The objectives were to: (i) quantify SOC stocks to 200 cm, (ii) evaluate pedogenic controls on SOC distribution, and (iii) assess SOC–clay relationships with depth.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in the Kersa sub-watershed, eastern Ethiopian highlands (9°26'–9°27' N; 41°52'–41°53' E), at elevations of 1968–2127 m a.s.l. The climate is sub-humid with mean annual rainfall of 665 mm and mean annual temperature of 18°C. Land use includes cultivated fields, grazing land, and fallow systems.

2.2 Toposequence Design

Three slope positions were defined:

Position	Elevation (m a.s.l.)	Slope (%)	Land use
Upper	> 2100	19–26	Cultivated, fallow
Middle	2000–2100	7–19	Cultivated
Lower	1968–2000	3–5	Grazing, cultivated

Eight representative pedons (1.5 m × 2 m) were described following FAO (2006).

2.3 Soil Description and Classification

Soil morphological description included horizon designation, color, structure, texture, and diagnostic features. Classification followed WRB (2014) (detailed in Tefera et al., 2026).

2.4 Laboratory Analysis

Standard procedures were applied:

Parameter	Method	Reference
Particle size	Bouyoucos hydrometer	Bouyoucos (1962)
Bulk density	Core method	Black and Hartge (1986)
SOC	Walkley–Black wet oxidation	Walkley and Black (1934)
pH	1:2.5 soil–water ratio	van Reeuwijk (1993)
CEC	1 M NH_4OAc (pH 7)	van Reeuwijk (1993)

SOC values were not corrected for incomplete oxidation and may underestimate true SOC by 10–30%.

2.5 SOC Stock Calculation

SOC stocks (Mg ha⁻¹) were computed for each genetic horizon as:

$$SOCS_i = (L_i \times SOC_i \times BD_i \times (1 - CF_i/100)) / 10$$

where L_i is horizon thickness (cm), SOC_i is SOC concentration (g kg⁻¹), BD_i is bulk density (Mg m⁻³), and CF_i is coarse fragment content (%).

2.6 Statistical Analysis

General Linear Model (SAS 9.2) tested slope differences. Pearson correlation assessed SOC–clay relationships. All analyses are exploratory due to limited replication (n = 5–8 per depth interval).

3. RESULTS

3.1 Soil Development Along the Toposequence

Soil depth increased downslope from 25 cm to 200 cm (Table 1). Upper slopes were dominated by Leptosols and Regosols, middle slopes by Cambisols, and lower slopes by Luvisols and Vertisols.

Table 1
Reference Soil Groups by slope position.

Slope position	Reference Soil Groups	Depth range (cm)
Upper	Leptosols, Regosols	25–80
Middle	Cambisols	110–150
Lower	Luvisols, Vertisols	200

3.2 SOC Stocks by Slope Position

SOC stocks increased markedly downslope. Upper slope soils stored 43–66 Mg ha⁻¹, middle slope approximately 156 Mg ha⁻¹, and lower slope 290–347 Mg ha⁻¹. Lower slopes stored 4.4–8.1 times more

SOC than upper slopes.

3.3 Vertical SOC Distribution

In a representative Luvisol (Pedon 1), SOC distribution is shown in Table 2. Overall, 75% of total SOC was stored below 30 cm depth, with the 100–200 cm layer alone containing 33% of total SOC.

Table 2
Depth-interval SOC distribution (representative Luvisol).

Depth (cm)	SOC stock (Mg ha^{-1})	Proportion (%)
0–30	87	25
30–60	68	20
60–100	78	22
100–200	113	33
Total	**346**	**100**

3.4 SOC–Clay Relationships

SOC concentration was positively correlated with clay content, with correlations strengthening with depth (Table 3), indicating increased mineral-associated stabilization in subsurface horizons.

Table 3
SOC–clay correlations by depth.

Depth (cm)	n	r
0–20	8	0.60
20–40	7	0.68
40–60	6	0.89
60–100	5	0.85
Note: Correlations are exploratory due to limited sample size.		

4. DISCUSSION

4.1 Topographic Controls

SOC accumulation increased downslope due to reduced erosion and enhanced colluvial deposition, consistent with catena-based redistribution models (Van Oost et al., 2007; Doetterl et al., 2012).

4.2 Pedogenic Controls

Key processes include:

- **Clay translocation**: Bt horizons in Luvisols concentrate SOC through organo-mineral associations (Wiesmeier et al., 2015; Baldock and Skjemstad, 2000).
- **Vertic processes**: Shrink–swell dynamics in Vertisols enhance SOC stabilization (Bhattacharyya et al., 2006; Dalal et al., 2011).
- **Colluvial deposition**: Lower slopes accumulate deeper, SOC-rich profiles (Van Oost et al., 2007; Doetterl et al., 2012).

4.3 Depth-Dependent Stabilization

Increasing SOC–clay correlations with depth suggest a shift from plant-input-driven SOC near the surface to mineral-stabilized SOC at depth (Rumpel and Kögel-Knabner, 2011; Schmidt et al., 2011). However, absence of SOC fractionation limits mechanistic confirmation.

4.4 Carbon Accounting Implications

Standard 0–30 cm sampling captures only 25% of total SOC in deep Luvisols, resulting in major underestimation. Sampling to at least 100 cm is recommended in tropical highland systems.

4.5 Limitations

This study is limited by small sample size (eight pedons), single-watershed design, and lack of SOC fractionation and radiocarbon dating. Walkley–Black SOC may underestimate true values by 10–30%.

5. CONCLUSIONS

Pedogenic processes strongly control deep SOC distribution along tropical highland toposequences. Lower slope positions store substantially more SOC due to greater soil depth, clay translocation, and colluvial deposition.

In Luvisols, most SOC is stored below 30 cm, demonstrating that shallow sampling severely underestimates total SOC stocks.

These findings are hypothesis-generating and highlight the need for larger-scale, process-based studies integrating SOC fractionation and isotopic analysis.

ABBREVIATION

SOC, soil organic carbon; WRB, World Reference Base; MAOC, mineral-associated organic carbon; POM, particulate organic matter; BD, bulk density.

DECLARATIONS

Conflict of Interest:

The authors declare no conflict of interest.

Funding:

No external funding was received (Haramaya University provided internal support).

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

Author Contribution

Y.M.T. conceptualized the study, conducted field work and laboratory analysis, performed data analysis, and wrote the original manuscript. K.K., B.B., and M.M. supervised the research, provided methodological guidance, and reviewed and edited the manuscript. All authors approved the final version.

Acknowledgement

The authors acknowledge Hawassa University, Wondo Genet College of Forestry and Natural Resources, and Haramaya University for institutional and laboratory support. The Ministry of Education of Ethiopia provided PhD scholarship support to Y.M. Tefera. The Kersa dataset was collected during doctoral research .

Data Availability

The data supporting this study are presented in full within the manuscript. Additional information is available from the corresponding author upon reasonable request.

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