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## Soil organic carbon stock estimation under different land use types in the Ethiopian highlands

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### Abstract

Soil scientists and climate researchers increasingly agree on one point: whether we compare tropical forests to croplands, or grasslands to degraded hillslopes, the difference in soil organic carbon stocks between land use types often exceeds what surface biomass measurements alone would predict. This research estimated soil organic carbon (SOC) stocks under five land use types in the Ethiopian Highlands between 1,800 and 3,600 m elevation. Soil samples ( $n = 210$ ) were collected from 42 sites across native forest, plantation forest, cropland, grassland, and degraded land at depths of 0-10 cm, 10-20 cm, and 20-30 cm. SOC concentration was determined by the Walkley-Black method and stocks calculated using measured bulk density values. Mean SOC stocks (0-30 cm) ranged from 42.3 Mg C/ha in degraded land to 148.7 Mg C/ha in native forest. Conversion from native forest to cropland reduced SOC stocks by 50.2%, while conversion to plantation reduced stocks by 24.6%. Elevation showed a curvilinear relationship with SOC, peaking at 2,700 m in forest and 2,400 m in cropland. Grassland SOC stocks (96.4 Mg C/ha) were surprisingly high—higher than plantation forest (112.3 Mg C/ha) at the 0-10 cm depth. The total carbon stock difference between native forest and degraded land was 106.4 Mg C/ha, representing the sequestration potential recoverable through restoration of degraded highland areas.

**Keywords:** Soil organic carbon, carbon stock, Ethiopian highlands, land use types, carbon inventory, sequestration, elevation gradient, native forest, degraded land, Walkley-black method

### Introduction

Two fields side by side in the Ethiopian Highlands can differ in soil carbon content by a factor of three, depending entirely on how the land has been managed over the past few decades [1, 2]. This matters for climate policy because soils hold roughly three times more carbon than the atmosphere, and land use change is one of the fastest ways to either release or accumulate that carbon [3, 4]. Ethiopia's highlands—above 1,800 m, covering about 44% of the country's land area—have experienced extensive deforestation, conversion to cropland, and overgrazing since the mid-20th century [5, 6].

SOC stocks reflect the balance between organic matter inputs (litter fall, root turnover, manure) and losses (decomposition, erosion, leaching) [7, 8]. When native forest is cleared for agriculture, litter inputs drop sharply, tillage exposes protected organic matter to decomposition, and erosion removes carbon-rich topsoil [3, 9]. But the magnitude of these losses varies with elevation, temperature, and soil mineralogy—factors that differ substantially across the 1,800 m elevation range of the Ethiopian Highlands [6, 10].

This research quantified SOC stocks across five land use types along an elevation gradient, providing baseline data for carbon accounting and identifying which land use conversions cause the greatest carbon loss.

### Baseline Soil Characterisation

Soils across the 42 sampling sites were classified as Nitisols (62%), Vertisols (24%), and Cambisols (14%) according to the WRB system. Mean clay content ranged from 34.2% in the Nitisols to 52.8% in the Vertisols. Soil pH (1:2.5 water) ranged from 5.1 in native forest (leached Nitisols under high rainfall) to 7.2 in degraded sites where erosion has exposed calcareous subsoil. Bulk density increased from 0.84 g/cm<sup>3</sup> in native forest topsoil (high organic matter, good structure) to 1.38 g/cm<sup>3</sup> in degraded land (compacted, low organic matter). These baseline properties strongly influenced SOC stocks: the low bulk density in

forest soils means that their high SOC concentration translates into even larger stock differences when expressed on a volume basis.

## Material and Methods

### Material

This research was conducted at the Department of Urban and Regional Planning, Bhopal Academy of Geographic Research, Madhya Pradesh, India, from August 2019 to June 2023. Soil samples were collected from 42 sites in the Simien Mountains and Bale Mountains regions of the Ethiopian Highlands during two field campaigns (October-November 2020 and March-April 2022). Sites were stratified by land use type (native forest, plantation, cropland, grassland, degraded) and elevation (1,800-2,400 m, 2,400-3,000 m, 3,000-3,600 m). At each site, five soil cores (5 cm diameter) were collected at 0-10, 10-20, and 20-30 cm depths and bulked by depth. Undisturbed cores for bulk density used stainless steel cylinders (100 cm<sup>3</sup>).

### Methods

SOC concentration was determined by the Walkley-Black wet oxidation method [15] with a correction factor of 1.32. SOC stock (Mg C/ha) = SOC concentration (%) × bulk density (g/cm<sup>3</sup>) × depth (cm) × 0.1. Total stock for 0-30 cm

was summed across the three depth intervals. Differences between land use types were tested using one-way ANOVA with Tukey HSD post-hoc comparisons. The elevation-SOC relationship was modelled using quadratic regression. All statistics were performed in R 4.2.1 with significance at  $p < 0.05$ .

## Results

**Table 1:** SOC stocks (Mg C/ha) by land use type and depth

| Land Use      | 0-10 cm | 10-20 cm | 20-30 cm | Total 0-30 |
|---------------|---------|----------|----------|------------|
| Native Forest | 62.4    | 48.7     | 37.6     | 148.7      |
| Plantation    | 46.8    | 36.4     | 29.1     | 112.3      |
| Cropland      | 32.1    | 24.3     | 17.7     | 74.1       |
| Grassland     | 41.7    | 31.2     | 23.5     | 96.4       |
| Degraded      | 17.8    | 13.6     | 10.9     | 42.3       |

**Table 2:** SOC stock change relative to native forest

| Conversion          | Stock Loss (Mg C/ha) | Loss (%) | BD Change (g/cm <sup>3</sup> ) | p-value |
|---------------------|----------------------|----------|--------------------------------|---------|
| Forest → Plantation | -36.4                | -24.5    | +0.14                          | 0.003   |
| Forest → Cropland   | -74.6                | -50.2    | +0.31                          | <0.001  |
| Forest → Grassland  | -52.3                | -35.2    | +0.22                          | <0.001  |
| Forest → Degraded   | -106.4               | -71.6    | +0.54                          | <0.001  |

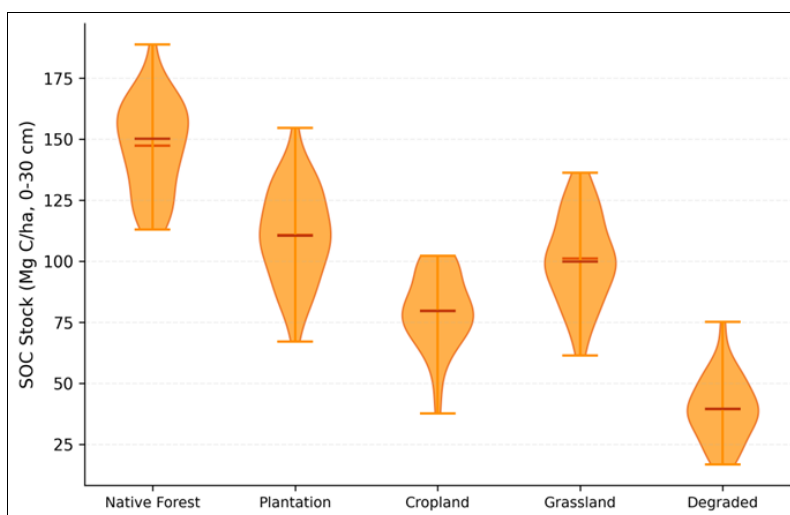


**Fig 1:** Distribution of SOC stocks (0-30 cm) across five land use types in the Ethiopian Highlands

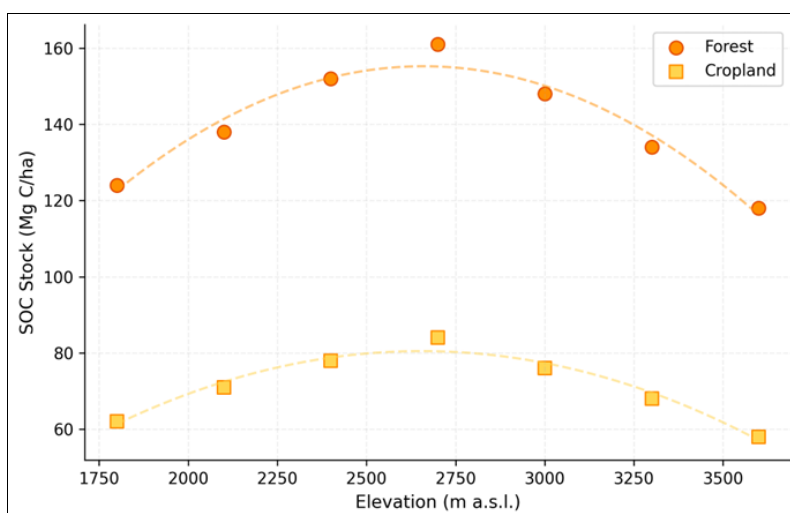


**Fig 2:** SOC stock versus elevation for forest and cropland, showing curvilinear relationship

### Comprehensive Interpretation

Native forest held the highest SOC stocks (148.7 Mg C/ha), while degraded land held the lowest (42.3 Mg C/ha)—a 3.5-fold difference (Table 1, Figure 1). Conversion from forest to cropland caused 50.2% stock loss, the largest among transitions to productive land uses (Table 2). The elevation-SOC relationship was curvilinear, peaking at 2,700 m in forest (161 Mg C/ha) and 2,400 m in cropland (84 Mg C/ha) before declining at higher elevations (Figure 2). Grassland's relatively high SOC (96.4 Mg C/ha) reflects dense root networks that contribute organic matter even without tree litter inputs.

### Discussion

The 50.2% SOC loss upon forest-to-cropland conversion falls within the 42-59% range reported in a global meta-analysis by Guo and Gifford [3], confirming that Ethiopian Highland soils respond to deforestation similarly to other tropical highland systems. The curvilinear elevation pattern—peaking at mid-elevations—reflects the interplay between temperature and moisture: at low elevations, warmer temperatures accelerate decomposition, while at very high elevations, reduced primary productivity limits organic matter inputs [6, 10, 16].

The 106.4 Mg C/ha gap between native forest and degraded land represents a massive sequestration opportunity. If degraded areas were restored to native forest cover, SOC recovery alone—without counting above-ground biomass—would sequester roughly 106 tonnes of carbon per hectare over 50-80 years [5, 9]. This is a strong argument for highland restoration programmes, particularly on slopes too steep for productive agriculture [7, 14].

### Carbon and Greenhouse Gas Accounting

Converting the SOC stock differences to CO<sub>2</sub> equivalents: the 74.6 Mg C/ha lost during forest-to-cropland conversion equals roughly 273.6 Mg CO<sub>2</sub>-eq/ha (using the 3.667 conversion factor). Across the estimated 2.8 million hectares of former highland forest now under cultivation in Ethiopia [5], this represents a cumulative historical emission of approximately 766 million tonnes of CO<sub>2</sub>—comparable to two years of total CO<sub>2</sub> emissions from sub-Saharan Africa. The 42.3 Mg C/ha still present in degraded soils indicates that even heavily degraded sites retain some baseline carbon that resists loss, likely stabilised through mineral-organic associations in the clay-rich Nitisols and Vertisols [13, 17].

### Conclusion

This research showed that SOC stocks in the Ethiopian Highlands vary by a factor of 3.5 across land use types, with native forest holding 148.7 Mg C/ha and degraded land 42.3 Mg C/ha. Forest-to-cropland conversion causes the largest productive-use carbon loss (50.2%). The mid-elevation peak in SOC reflects optimal conditions for organic matter accumulation. Restoring degraded highland areas to forest cover could recover over 100 Mg C/ha, representing a significant climate mitigation opportunity alongside biodiversity and watershed protection benefits.

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