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RESEARCH ARTICLE

The effect of altitude and soil-adjusted vegetation index on soil organic carbon and other soil properties across the mountainous landscape in West Usambara, Tanzania

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ABSTRACT

This study was conducted in West Usambara to assess the effects of altitude and SAVI (Soil-Adjusted Vegetation Index) on soil organic carbon (SOC) and other soil properties within the plateaued mountainous landscape. Soil sampling, laboratory, and statistical analyses were undertaken. The correlation analysis results demonstrated an increase in SOC and Total Nitrogen (TN) with altitude. Altitude exhibited a negative correlation with available phosphorus, soil pH, exchangeable bases (Ca, K, and Na), and cation exchange capacity (CEC). The SOC and various soil properties, such as TN, exchangeable bases (Ca, K, and Na), and cation exchange capacity (CEC), exhibited an increase in correlation with the SAVI. Soil pH exhibited a decline as SAVI levels increased. The study's results are significant for land management practices, highlighting the importance of considering altitude and SAVI in optimizing SOC and nutrient content to enhance soil fertility and productivity in the study area.

Keywords: altitude; soil-adjusted vegetation index; soil organic carbon; plateaued mountainous landscape; West Usambara.

INTRODUCTION

Enhancing soil health, particularly through the rehabilitation of degraded soils, is crucial for advancing several of the 17 Sustainable Development Goals (SDGs) for 2030, including the eradication of hunger, poverty, and the preservation of terrestrial ecosystems (Lal et al., 2021). To do this, it is essential to enhance soil fertility and productivity through the management and monitoring of soil fertility strategies, including the augmentation and preservation of soil carbon storage and other nutrient components. Altitude, vegetation, and climate significantly influence soil carbon content, nutrient status, and other physical and chemical properties, particularly in soils with substantial canopy cover, such as forest soils (Sitaula et al., 2004). Vegetation, in the form of dead plant tissues, is the primary source of soil organic carbon (SOC), affecting numerous soil characteristics and nutrient availability (Fageria, 2012). The physicochemical properties of soils exhibit spatial and temporal fluctuations influenced by vegetation cover and factors such as climate, topography, soil microbial activity, weathering, and other biotic and abiotic elements (Saha et al., 2018). The West Usambara Mountains, characterized by intricate mountainous geography and vegetation predominantly consisting of Cedar Forests—montane dry forests with dense shrubs and cedar trees—and Camphor-Podo forests—montane rainforests featuring dispersed camphor and Podo trees-constitute one of Tanzania's most densely vegetated regions, crucial for the nation's soil carbon reservoir. The altitudinal gradient in mountainous regions significantly affects the microclimate, particularly annual precipitation and air temperature, hence influencing the physical, chemical, and biological processes of the soil (Schawe et al., 2007; Griffiths et al., 2009).

Vegetation indices such as the Soil-Adjusted Vegetation Index (SAVI) and the Normalized Difference Vegetation Index (NDVI), ascertainable using remote sensing methods, provide efficient assessments of vegetation cover (Gilabert et al., 2002). Elevated vegetation index values signify greater vegetation coverage, while diminished vegetation index values denote reduced vegetation coverage (Vani and Mandla, 2017). Various spectral vegetation indicators utilize red and near-infrared canopy radiances to assess vegetation health; however, their accuracy is constrained by atmospheric effects and soil variability. Variations in soil affect index values in regions with varying organic matter, wetness, and roughness (Gilabert et al., 2002). Consequently, soil brightness influences specific indices, leading to inflated estimates for darker soil substrates (Gao et al., 2000). In contrast to NDVI and various other vegetation indices, SAVI mitigates the impact of soil brightness, rendering it optimal for associating vegetation indices with SOC concentration (Huete, 1988).

The soil fertility quality in the Western Usambara Mountains of Tanzania has been evaluated, with the quantities of critical plant nutrients including N, P, K, and Ca reported by Ndakidemi and Semoka (2006). The vegetation and landscape of the Western Usambara Mountains have prompted numerous studies aimed at characterizing, mapping, and reporting its ecology and soil properties for various objectives, including soil classification, quantification of plant nutrients, and investigation of plague disease and its vectors (Massawe, 2011; Meliyo, 2014; Hieronimo et al., 2014; Kimaro et al., 2014; Ralaizafisoloarivony et al., 2014; Hieronimo, 2015). Nevertheless, there has been a lack of significant interest in examining the impact of vegetation and altitude gradients on the spatial distribution of SOC and other soil properties in this region, despite the ecological and topographical characteristics suggesting such an influence. The study was conducted to examine the following hypotheses: (i) whether SOC and other soil properties in the West Usambara Mountains vary with altitude, and (ii) whether SOC and other soil properties vary with vegetation cover as indicated by the SAVI, given the ecological significance of the region for food security and carbon sequestration, particularly in Northern and Eastern Tanzania.

MATERIALS AND METHODS

Description of the study site

The study area was conducted in the Western Usambara Mountains in Lushoto District, Tanzania, with an altitudinal range of 400–2270 m above sea level. The study location was situated between latitudes 4°36’26.65” S to 4°43’12.51” S and longitudes 38°19’15.54” E to 38°8’20.72” E. Gently undulating to steep slopes surrounding the plateau landscape intersected at their base by broad U-shaped and narrow flat valleys are predominant in the landscape of the Western Usambara Mountains. Pyroxene, gneiss (acid), hornblende granulites and bauxite deposits are the most common soil parent materials in the study area (Halperin, 2002; Mutakyahwa et al., 2003).

The main soil types identified in the study area include sandy clays, sandy clay loams, and clays (Massawe, 2011). The study area experiences a bimodal rainfall pattern, with short rains occurring from October to December and long rains from March to June. April exhibits maximum precipitation levels. The average annual precipitation varies between 600 and 2,000 mm annually. Temperature variations with altitude indicate that the mean annual temperature is 25-27°C at 900 m above sea level, whereas at altitudes of 1,400-1,800 m, the mean annual temperature ranges from 17 to 18°C. The area demonstrates an average annual relative humidity of 70%. The region is primarily composed of a plateau and escarpment situated in a humid cold agro-ecological zone, whereas the remaining area, characterized by a piedmont-plain landscape, is located in a dry-warm zone. The study area comprises two main vegetation types: the Cedar Forest type, a montane dry forest primarily composed of cedar trees (*Juniperus procera*) with dense undergrowth, and the Camphor-Podo type, a montane rainforest distinguished by scattered camphor (*Ocotea usambarensis)* and multiple Podo species (*Podocarpus usambarensis* and *Podocarpus pensiculy).*

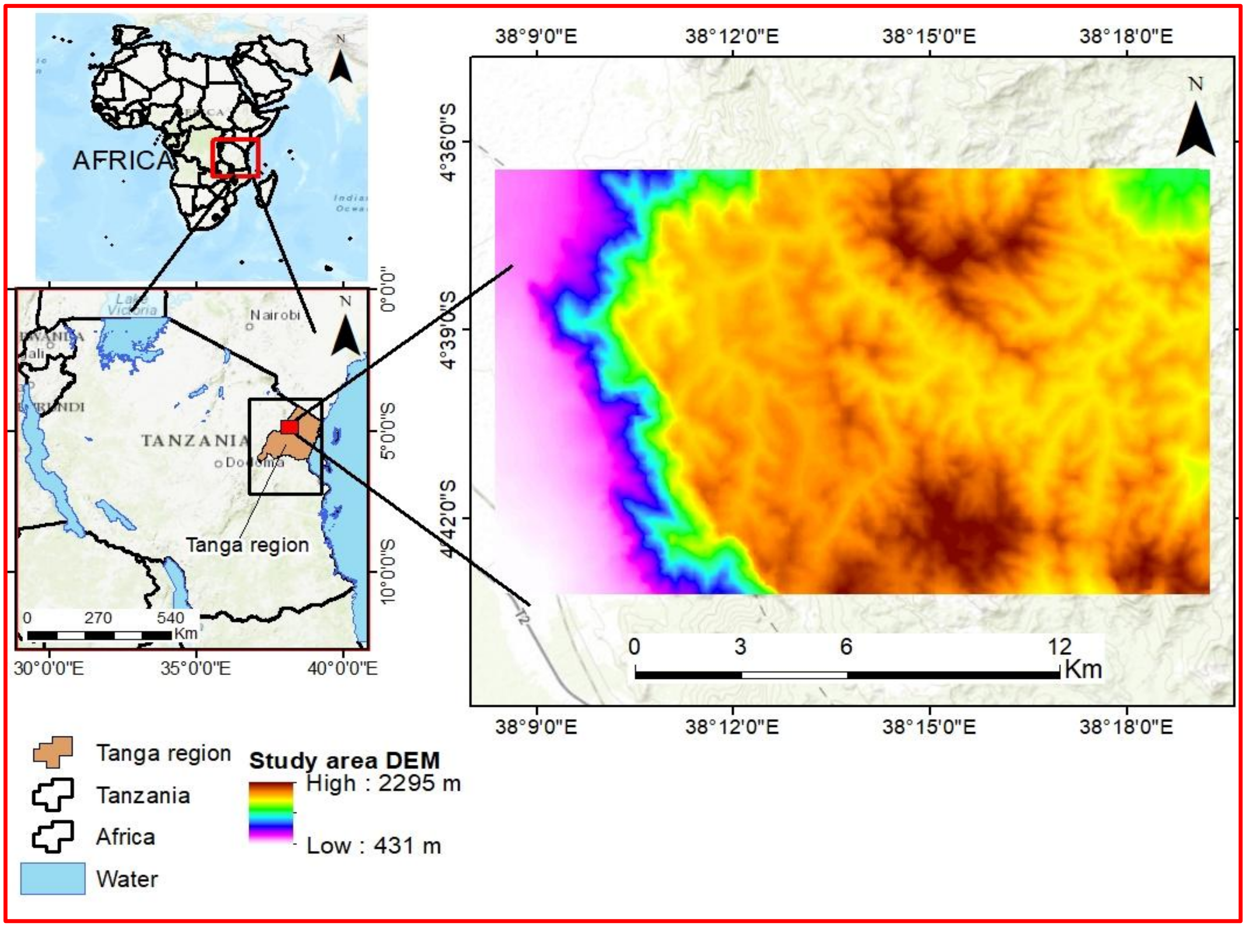

Figure 1. Map of the study area and its topography

Soil sampling and analysis

A total of 96 soil samples were collected from the study area employing a stratified sampling technique. Soil sampling involved excavating profiles to a depth of 0–40 cm. Samples were air-dried in the shade, ground using a wooden pestle, and subsequently passed through a 2 mm sieve for further laboratory analysis. This document outlines laboratory methods for soil analysis focusing on specific physical and chemical properties: soil pH is measured using the glass electrode method as described by Okalebo et al. (2002); soil electrical conductivity (EC) is determined via the potentiometric method according to Moberg (2001); total nitrogen (TN) percentage is assessed using the Micro-Kjeldahl method as per Moberg (2001); and available phosphorus (P) in mg/kg is evaluated using either the Bray and Kurtz-1 method or the Olsen method, following the guidelines of Okalebo et al. (2002). Exchangeable calcium, sodium, and potassium (cmol(+)/kg) were extracted using the ammonium acetate method and quantified via atomic absorption spectrophotometry (AAS) or flame emission spectrophotometry (FES) as per Moberg (2001). Soil organic carbon (%) was determined using the Walkley and Black method while cation exchange capacity (cmol(+)/kg) was assessed using the NH4-acetate saturation method (Okalebo et al., 2002).

Acquisition of remote sensing data

Altitude data were obtained from the Digital Elevation Model (DEM) downloaded from the USGS website. Landsat 8 band 5 (NIR band) and band 4 (red band) were obtained from the USGS website with the specific purpose of utilizing them in the calculation of the SAVI. This index, developed to mitigate soil brightness influences on traditional vegetation indices, was computed using the NIR band, red band and Adjustment Factor (L) (Huete,1988; Gilabert et al., 2002; Zhen et al., 2021). The SAVI is calculated following the equations:

$$\text{SAVI} = \frac{(1+L)(\text{NIR}-\text{Red})}{(\text{NIR}+\text{Red}+L)} \quad \text{.....(1)}$$

where L represents soil brightness correction factor, typically 0.5. An L value of 0.5 was found to effectively minimize soil brightness variations and adjust for soil and vegetation differences, eliminating the need for further calibration across various soil types. Thus, it is generally used to represent L in SAVI calculations.

RESULTS AND DISCUSSION

Analysis of spatial dependence of soil properties on altitude and SAVI in a mountainous landscape

The results for the selected 96 soil samples as summarized in Table 1, showed that the altitude measured in m above sea level ranged from 426 m to 2303 m with a mean of 1651 m. In contrast, the SAVI ranged from 0.10 to 0.90 with a mean of 0.48. The standard deviation for altitude is higher than the mean altitude indicating that the altitude is spatial dependent, whereas the standard deviation for SAVI is much lower than its mean indicating that the SAVI is not spatial dependent. Other parameters including SOC, CEC, Ca, K, Na, P, TN and pH presented have means greater than the standard deviation indicating that they are not spatially dependent.

The spatial dependence of altitude suggests that there is a considerable amount of variability in altitude values among the different sample locations which is attributed to the complex nature of the study area which exhibits a rugged terrain with diverse landform features such as undulating hills, steep slopes, and deep valleys. The spatial dependence of SAVI and soil parameters in the study area could be attributed to the uniformity and stability of these characteristics in the surveyed locations, as a result of the absence of significant natural and human disturbances, such as continuous agriculture and deforestation, which alter vegetation and soil properties. This makes these parameters exhibit minimum variability across the study area, unaffected by spatial variations in altitude or other factors.

Table 1. Descriptive statistics for selected parameters of the study area (n= 96)

Parameter	Minimum	Maximum	Mean	Std. Deviation
Altitude (m)	426.00	2303.00	1651.09	493.12
SAVI	0.10	0.90	0.48	0.13
SOC (%)	2.10	6.20	4.04	1.03
TN (%)	0.16	0.41	0.28	0.06
CEC (cmolkg^{-1})	6.46	37.92	18.83	7.74
Ca(cmolkg^{-1})	4.31	36.15	16.51	7.29
K(cmolkg^{-1})	0.06	0.55	0.21	0.12
Na(cmolkg^{-1})	0.02	0.48	0.19	0.13
P (mg kg^{-1})	0.18	10.75	6.41	1.26
pH	5.50	7.50	6.63	0.53

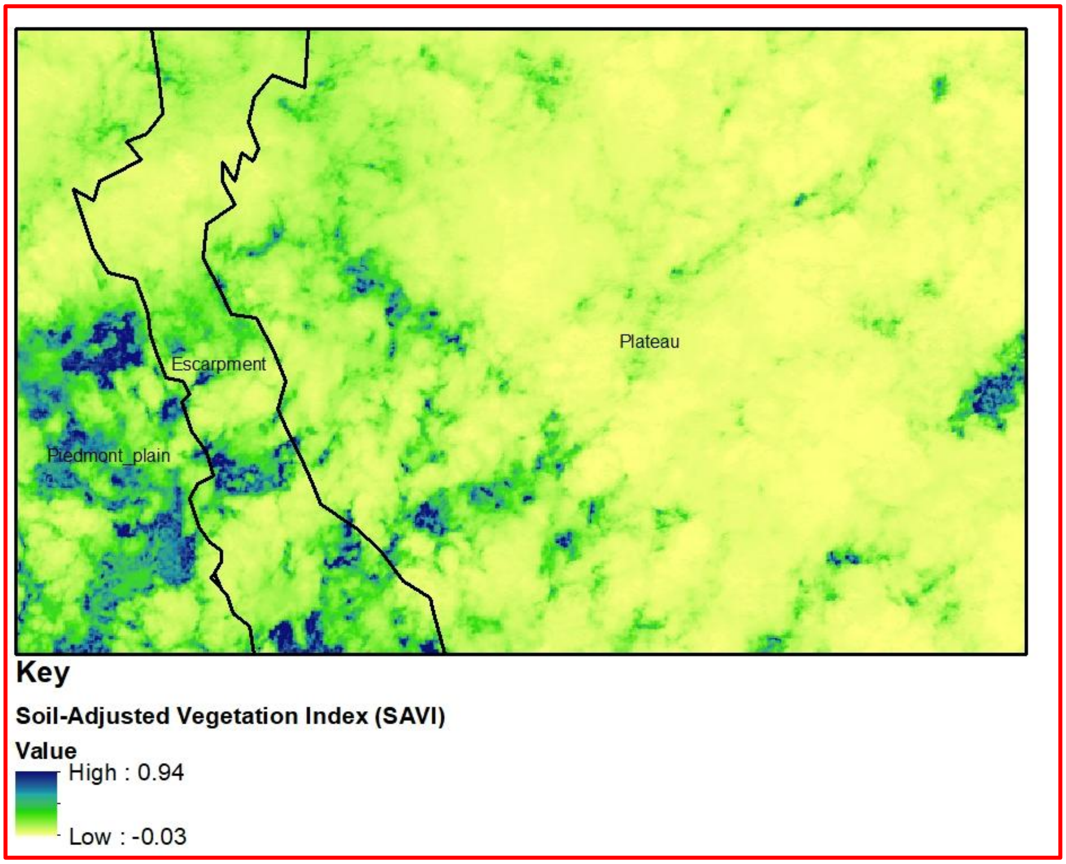

Figure 2. Map showing the spatial distribution of the Soil-Adjusted Vegetation Index (SAVI) across landscape units in the study area.

Spatial patterns of SOC in relation to landscape, elevation, and vegetation dynamics in the West Usambara mountains

The spatial distribution of soil SOC across the West Usambara Mountainous Landscape varies significantly depending on the Landscape unit, elevation, and vegetation cover. In the piedmont plain, which ranges in elevation from 426 m to 1002 m, SOC values ranged from 2.89% to 4.24%, with a mean of 3.672%. This narrow range indicates moderate variability in SOC content, and the mean SAVI value of 0.112 suggests modest vegetation cover. The lower elevation and associated climatic conditions could influence the SOC distribution, with lower SAVI potentially limiting organic matter inputs and decomposition rates. In the escarpment unit, with elevations ranging from 636 m to 2075 m, SOC values ranged from 2.76% to 4.45%, with a mean of 3.56%. Despite a broader elevation range, the SOC values remain relatively consistent and this suggests that factors such as steep slopes may limit organic matter accumulation. The mean SAVI of 0.075 is lower than that of the piedmont plain, reflecting sparser vegetation cover, which possibly is a result of the steep gradients and erosion processes in this region, both of which influence SOC distribution.

The plateau landscape, with elevations between 1275 m and 2303 m, exhibited the highest SOC range, from 2.93% to 5.70%, with a mean of 4.21%. The increased SOC in this region aligns with higher elevations, cooler temperatures, and likely denser vegetation. The higher SAVI value in this area supports the idea of increased biomass and organic matter inputs, fostering SOC accumulation. The relative flatness of the plateau may also reduce erosion, allowing SOC to stabilize. The spatial distribution of SOC across these landscape units is strongly influenced by elevation and vegetation dynamics. Higher elevations, as seen in the plateau, promote greater SOC accumulation due to favorable climatic conditions and denser vegetation, as indicated by higher

SAVI values. In contrast, the escarpment, with its steep slopes and lower SAVI, shows less stable SOC. The piedmont plain offers an intermediate scenario, balancing moderate elevation with vegetation cover.

Influence of altitude on soil properties

Correlation analysis revealed a positive association between altitude and SOC content, indicating an increase in SOC content with higher altitude. This phenomenon can be explained by the slower decomposition rate of leaf litter at higher altitudes due to lower temperatures, leading to the accumulation of SOC. Massawe (2011) observed a similar trend in the West Usambara Mountains of Tanzania. Semu et al. (2014) also found comparable results in the Miombi woodlands of Tanzania. These findings are supported by studies conducted by Maurya et al. (2014) and Banday et al. (2019) in Himalaya, India. Also, Nath and Deori (1976) noted increased organic matter content in high-altitude areas. Similarly, Shah et al. (2014) observed similar trends in the temperate Northwestern Himalayan region. Conversely, (Sheikh et al., 2009) reported a decrease SOC with increasing altitude, while Leifeld et al.(2005) found no significant correlation between SOC and altitude.

The TN increased with altitude as a result of the increased content of organic matter in high-altitude areas because the trend of spatial distribution of TN is largely dictated by SOC, as similar findings by Wibowo and Kasno (2021) have reported a positive correlation between TN and SOC. The available P is generally negatively correlated with altitude, indicating that it is high in soils throughout the foothill plain of the study area, which could be attributed to the soil parent materials as observed from other areas with similar physiographic features (Mwango et al., 2014).

Altitude was found to correlate negatively with exchangeable bases (Ca, K, and Na) and CEC (total exchangeable bases). This trend may be attributed to the erosion and runoff of nutrient-rich topsoil from higher altitudes, particularly in steep-sloped areas. Consequently, lower slopes and valleys in low-altitude area tend to accumulate more basic cations, while higher altitudes retain fewer. This downward increase of basic cations aligns with findings by Shanshan et al.(2018). Additionally, soil pH decreases with increasing altitude, likely due to the higher accumulation of basic cations in lower altitude areas, resulting in higher pH values compared to higher altitude regions where basic cations are depleted.

Table 2. Correlation analysis between Soil- Soil Adjusted Vegetation Index (SAVI) and Altitude and soil properties (*Correlation significant at the 0.05 level)

	SAVI	Altitude
	Peason correlation (r)	Pearson correlation (r)
Altitude (m)	0.238*	1
SAVI	1	0.238*
OC (%)	0.332*	0.263*
TN (%)	0.376*	0.276*
P(mg kg^{-1})	-0.152	-0.277*
CEC (cmolkg^{-1})	0.273*	-0.252*
Ca(cmolkg^{-1})	0.322*	-0.232*
K (cmolkg^{-1})	0.212*	-0.232*
Na(cmolkg^{-1})	0.257*	-0.260*
pH	-0.290*	-0.338*

Effect of SAVI on soil properties

The analysis of correlations revealed that as the SAVI increased, there was a corresponding rise in SOC levels. Conversely, the decline in SOC with decreasing SAVI values can be attributed to decomposition occurring at a slower pace in denser canopies due to reduced solar insulation within denser canopies. Banday et al. (2019) reported similar findings using NDVI to show a positive correlation between organic carbon and vegetation status.

The SOC exhibited a significant positive correlation with SAVI, as well as with other soil nutrients and CEC, while displaying a negative correlation with pH and available phosphorus. Interestingly, soils with higher SAVI values tended to be more acidic in this study. The observed decrease in pH at higher SAVI levels is likely a result of increased concentrations of H+ ions in the soil, stemming from organic matter decomposition similar to the observation by Massawe (2011) and Banday et al. (2019).

The spatial distribution of available phosphorus could be largely dictated by the nature of parent materials, decreasing with altitude and any parameter with a positive correlation with altitude, such as SAVI in this regard (Mwango et al., 2014). Furthermore, TN and exchangeable potassium, sodium, and calcium showed an increase with rising SAVI values. This rise in TN content can be attributed to the higher levels of organic carbon present in soils with higher SAVI ranges. Consequently, the current study underscores a strong positive correlation between soil nutrients and vegetation, similar to findings by Banday et al. (2019).

CONCLUSION

The current research has demonstrated that essential soil fertility measures such as SOC and TN exhibit an increase with altitude. This indicates that the high-altitude areas of the West Usambara landscape play a vital role in SOC provision and necessitate sustainable management, particularly by avoiding land practices that could result in depletion of SOC, such as deforestation or continuous agriculture. Instead, practices like conservation agriculture and soil erosion prevention are strongly recommended. Additionally, it has been determined that vegetation indices like SAVI, obtained through remote sensing, can serve as tools for evaluating SOC levels. In undisturbed areas covered by natural vegetation, canopy cover significantly influences soil's fertility status. The findings of this study could greatly aid in devising nutrient management strategies that support sustainability, environmental preservation, and efficient agricultural input utilization, such as supplying plant nutrients based on the observed distribution trends of nutrients across the landscape of the current study.

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AUTHORS CONTRIBUTIONS

FFM; fund acquisition, resources, conceptualization, investigation, data curation, formal analysis, methodology, software, data presentation, writing- original draft, writing–review and editing, and validation. JDL & SM; conceptualization, formal analysis, supervision, writing–review and editing.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

ETHICAL APPROVAL

Not applicable

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