Original Research Article

Soil Organic Carbon Dynamics AcrossVarious Land Use Systems AlongElevational Gradients in the North-Eastern Himalayas

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ABSTRACT

Aims: To study soil organic carbon content across different land use systems along four elevational gradients in the Himalayan Region of West Bengal.
Place and Duration of Study: Kalimpong and Darjeeling districts of West Bengal, India, between Aprilto June 2019.
Methodology: Six major land use systems were selected spanning an altitudinal gradient of 400-500 m, 900-1000 m, 1400-1500 m, and 1900-2000 m, ensuring that each land use system was represented at every elevation. The land use systems included: 1. open cropland with rice, maize, winter vegetables, and pulses; 2. mandarin orchard; 3. large cardamom-based agroforestry under alder and Albizia species; 4. ginger-based agroforestry with mixed shade trees; 5. tea plantation under Albizia species; and 6. undisturbed forest.
Results: Undisturbed forests had the highest OC content (21.74g kg^{-1}), followed by tea plantations (19.28g kg^{-1}), large cardamom (17.86g kg^{-1}), ginger-based agroforestry (15.98g kg^{-1}) and mandarin orchard (13.94g kg-1). While, open crop fields had the lowest OC content (10.92g kg^{-1}) across various elevational gradients. Soil organic carbon showed a positive correlation with elevation and a decrease with soil depth. At higher elevations, high soil moisture and relative humidity enhance the production of above- and below-ground biomass, increasing soil organic carbon content, while lower temperatures reduce microbial decomposition, further promoting organic carbon sequestration.
Conclusion: These findings provide crucial insights for researchers and policymakers, providing valuable information to assist in decision-making for sustainable land use management.

Keywords: Land use change, Altitudinal variation, Soil organic carbon, North-Eastern Himalayan region

1. INTRODUCTION

Over the past few decades, a significant decline has occurred in the amount and extent of natural forests (Bonan, 2008). This decrease is primarily attributed to the growing demand for alternative land use patterns, such as the expansion of urban areas, agricultural lands, and plantation crops (Heino et al., 2015). Globally, the changes in land use system havebecome a significant concern in recent years due to their substantial impacts on greenhouse gas emission and global warming. Transforming natural forests into agricultural or urban areas not only affect carbon sequestration potential but also influence habitat loss, fragmentation, and alterations in local climatic patterns (Lungmuana et al., 2018). Soil organic carbon plays a crucial role in storing nutrients within terrestrial ecosystems. Consequently, the stoichiometric relationship between soil and terrestrial ecosystems helps to explain the variations observed across different land use systems. Furthermore, altitude, an essential topographic factor, determines the spatial differences in soil organic carbon within a small mountainous region (Jiang et al., 2019). The prevailing belief is that changes in altitude, which are associated with fluctuations in climate, significantly influence soil organic carbon, which is crucial for nutrient cycling.

The North-Eastern Himalayan region of West Bengal is a diverse and ecologically significant area, encompassing a range of land use types and altitudinal gradients. This region is characterized by a complex topography, with varied slopes, altitudes, and agro-climatic conditions, leading to a diversity of soil types and vegetation. The altitudinal differences, coupled with the region's physiography, contribute to significant climatic variations, from near-tropical to sub-alpine and sub-tropical conditions. Several studies have highlighted the importance of land use and altitudinal variations in shaping soil organic carbon dynamics. For instance, Dhaliwal and Singh (2013) found that organic carbon content varied across land use types, with forest systems showing the highest levels (0.56%) due to consistent organic matter input. Baishya and Sharma (2017) reported organic carbon levels ranging from 0.69% to 0.89% across different agricultural systems, attributed to surface debris breakdown. Chemeda et al. (2017) identified a significant interaction between land use and soil depth, with forest soils having the highest organic matter content (8.37%) in surface layers. Ganai et al. (1982) documented that apple plantation soils in Anantnag showed a decline in organic carbon with soil depth, ranging from 0.93% to 0.98% in surface layers. Chandrakala et al. (2018) found the highest mean organic carbon content (2.8%) in oil palm plantations, attributed to continuous organic matter incorporation. Khadka et al. (2017) and Wani et al. (2017) demonstrated elevation-dependent variations in soil organic matter, with higher altitudes showing higher organic content. Baissa et al. (2003) reported an average OC content of 3.24% in Ethiopian agricultural soils, influenced by elevation. Anup and Ghimire (2019) also observed elevation-dependent increases in soil OC, with higher levels at greater altitudes.

However, there is a lack of comprehensive studies on the specific impact of land use changes on soil organic carbon along the elevation in the North-Eastern Himalayan region of West Bengal, India. The natural forests in this region are consistently being converted into cultivation to support the livelihoods of hilly farmers, with the conversion involving the cultivation of tea plantations, Darjeeling mandarin, large cardamom, ginger, and other cereal-based crops. Monitoring and understanding land use changes are crucial for identifying sustainable land use practices. Therefore, our objective of this study is to assess the effect of different land uses and altitudinal variation on soil organic carbon, and to determine how organic carbon is related to different land use systems along with altitudinal variation in the North-Eastern Himalayan region of West Bengal.

2. MATERIAL AND METHODS

The study was conducted in the Himalayan region, specifically in the northern districts of Kalimpong and Darjeeling, West Bengal (Fig. 1). The study area lies between 26° 57' to 27° 04' N latitude and 88° 22' to 88° 43' E longitude. The soils in this region are predominantly shallow, characterized by Inceptisols, followed by Entisols and Ultisols. The area experiences an average temperature range of 7 to 28°C and is classified as a high-rainfall zone, with an average annual precipitation exceeding 2,000mm.

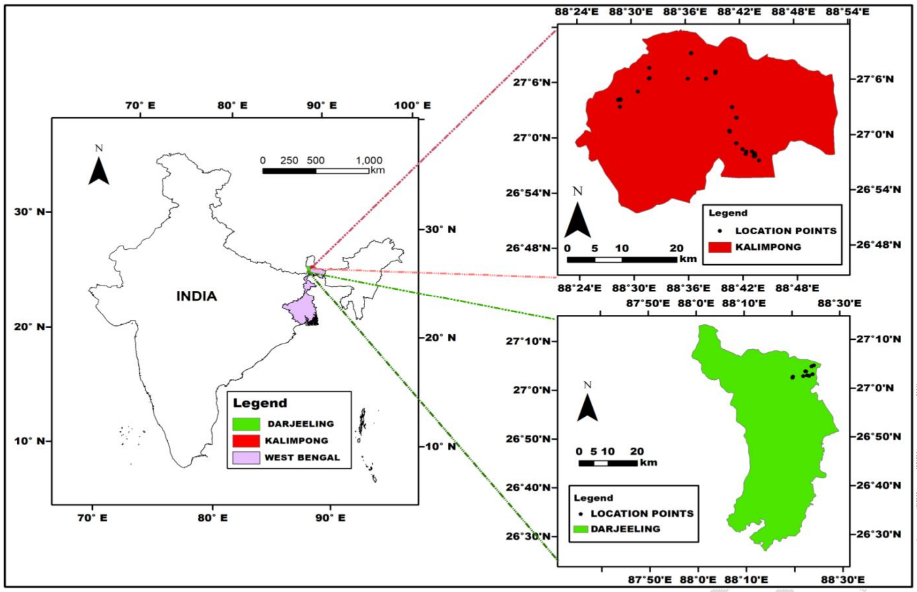


Fig. 1. Location of the Experimental site of North-Eastern Himalayan region of West Bengal.

We selected six major land use systems spanning an altitudinal gradient of 400-500 m, 900-1000 m, 1400-1500 m, and 1900-2000 m, ensuring that each land use system was represented at every elevation. The land use systems included: 1. open cropland with rice, maize, winter vegetables, and pulses; 2. mandarin orchard; 3. large cardamom-based agroforestry under alder and Albizia species; 4. ginger-based agroforestry with mixed shade trees; 5. tea plantation under Albizia species; and 6. undisturbed forest with tropical, subtropical, sub-temperate, and temperate tree species. Except for the tea plantation and undisturbed forest, which were over 50 years old, all the selected land use systems were between 10-20 years old.

The survey was undertaken during the months of May and June 2019. A plot measuring 10 × 10 m^2 was delineated for each land use at every elevation, with three replications. From each plot, 6 to 8 soil samples were collected with a soil auger and then made into a composite sample. Composite soil samples were collected from three distinct increment layers: 0–15 cm, 15–30 cm, and 30–45 cm. Soiloxidizable organic carbon was determined by wet oxidation method using potassium dichromate and concentrated sulfuric acid(Wakley and Black,1934).

A variance analysis (ANOVA) was performed according to the methodology described by Gomez and Gomez (1984). In order to get an in-depth comprehension of how various land use systems affect different soil properties, a statistical analysis known as Duncan's multiple range test (DMRT) was conducted at a significance level of $P< 0.05$. In addition, a least significant difference (LSD) test was conducted at a significance level of $p < 0.05$ to compare the means of different soil characteristics at various soil depths within each land use system. The DMRT and LSD analyses were performed using the SPSS 21.0 (SPSS Inc., Chicago, USA) Windows version software programs.

3. RESULTS AND DISCUSSION

The study observed distinct variations in oxidizable organic carbon (OC)content among the six land use systems, regardless of altitudinal differences (Table 1). The mean OC content ranged from 10.92g kg^{-1}in LU1 (open crop fields) to 21.74 g kg^{-1}in LU6 (undisturbed forests), indicating that land use significantly (*P*< 0.05) influences the accumulation and retention of organic carbon in soils. The sequence of land use change by OC content was as follows: LU6 (21.74 g kg^{-1}) > LU5 (19.28 g kg^{-1}) > LU4 (17.86 g kg^{-1})> LU3 (15.98 g kg^{-1})> LU2 (13.94 g kg^{-1}) > LU1 (10.92 g kg^{-1}). Undisturbed forests (LU6) exhibited the highest OC content, likely due to the minimal anthropogenic disturbances, high litterfall, and slow decomposition rates under dense canopy cover. Tea plantations (LU5) followed regular pruning practices that maintain soil cover and reduce erosion, enhancing organic carbon storage. Conversely, open crop fields (LU1) had the lowest OC content, attributed to intensive agricultural practices, limited vegetation cover, and higher rates of soil organic matter decomposition. The soils under LU3 (large cardamom agroforestry) and LU4 (ginger fields), showedhigher OC content compared open crop and mandarinas these systemsoften employ soil conservation measures (e.g., mulching) that minimize soil erosion and enhance organic matter accumulation. Similar findings were also observed by several researchers (Dhaliwal and Singh, 2013; Baishya and Sharma, 2017; Jiao et al., 2020).

Table 1. Duncan multiple range test (DMRT) for soil oxidizable organic carbon (g kg^{-1}) in respect of land use system (LU), altitude gradient (A) and soil depth (D) at Himalayan region of West Bengal.

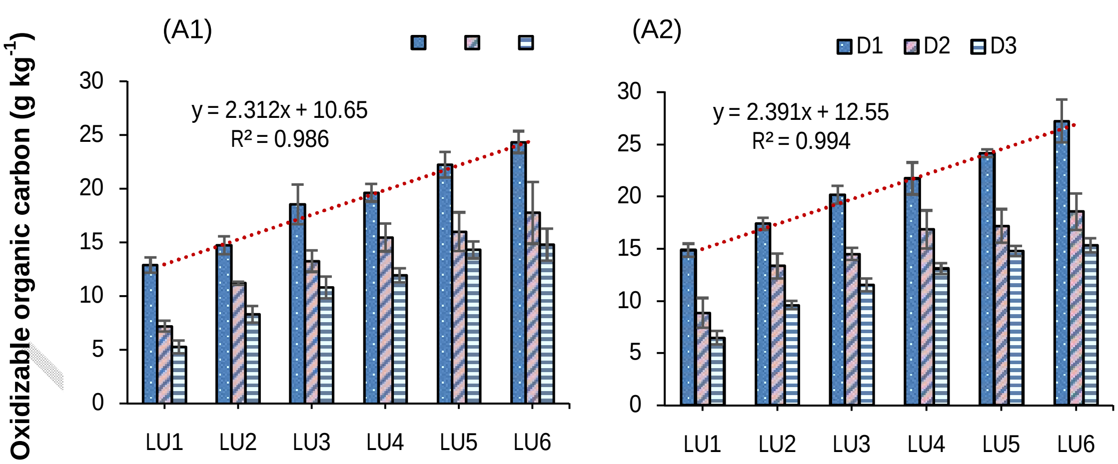
ALTITUDE	DEPTH	LAND USE SYSTEM						MEAN
		LU1	LU2	LU3	LU4	LU5	LU6	
A1	D1	12.90	14.66	18.56	19.67	22.30	24.39	18.75
	D2	7.22	11.21	13.49	15.48	16.02	19.20	13.77
	D3	5.28	8.33	10.83	11.97	14.23	14.83	10.91
MEAN		**8.47**	**11.40**	**14.29**	**15.71**	**17.52**	**19.48**	**14.48^{d}**
A2	D1	14.88	17.28	20.19	21.74	24.16	27.70	20.99
	D2	9.54	13.35	14.51	16.84	17.18	18.56	15.00
	D3	6.46	9.59	11.54	13.11	14.68	15.33	11.79
MEAN		**10.30**	**13.41**	**15.41**	**17.23**	**18.68**	**20.53**	**15.93^{c}**
A3	D1	18.00	18.98	20.83	26.48	26.06	31.46	23.63
	D2	11.05	14.52	15.47	17.76	18.13	20.49	16.24
	D3	7.29	10.69	11.39	13.54	15.03	16.53	12.41
MEAN		**12.11**	**14.73**	**15.90**	**19.26**	**19.74**	**22.82**	**17.43^{b}**
A4	D1	18.35	21.62	24.43	27.09	27.72	33.65	25.48
	D2	11.67	14.84	17.81	17.42	19.02	21.60	17.06
	D3	8.43	12.26	12.75	13.20	16.84	17.18	13.45
MEAN		**12.82**	**16.24**	**18.33**	**19.24**	**21.19**	**24.14**	**18.66^{a}**
MEAN (LAND USE)		**10.92^{f}**	**13.94^{e}**	**15.98^{d}**	**17.86^{c}**	**19.28^{b}**	**21.74^{a}**	
MEAN DEPTH		D1		D2		D3		
		22.21^{a}		15.52^{b}		12.14^{c}		
FACTORS		**LU**	**A**	**D**	**LU X A**	**LU x D**	**A x D**	**A X LU x D**
SEM (±)		0.238	0.194	0.168	0.475	0.412	0.336	0.823
CD (*P*<0.05)		0.663	0.541	0.469	NS	1.148	0.937	NS

LU1= open crop fields, LU2=mandarin orchards, LU3= large cardamom agroforestry, LU4= Ginger fields, LU5= tea plantations and LU6= Undisturbed forests, Three elevation: A1= 400-500 m, A2 = 900-1000 m, A3= 1400- 1500 and to A4= 1900-2000m and three soil depth (D1= 0-15 cm, D2= 15-30 cm and D3= 30-45 cm).

Soil organic carbon showed a strong upward trend with elevation, as shown by the fact that the average amount of organic carbon rose significantly ($P< 0.05$) with increasing elevation: 14.48 g kg^{-1} at A1 (400–500 m), 15.93 g kg^{-1} at A2 (900–1000 m), 17.43 g kg^{-1} at A3 (1400–1500 m), and 18.66 g kg^{-1} at A4 (1900–2000 m). The interaction of biological and climatic factors accounts for the variation in organic carbon accumulation at different elevations. Reduced temperatures at elevated elevations inhibit microbial activity, thereby decreasing the rate of organic matter decomposition and promoting increased OC sequestration. These results corroborated the findings of Anup and Ghimire (2019), who documented equivalent altitudinal differences in soil organic carbon within mountainous ecosystems. Wani et al. (2017) also reported that soil organic carbon levels varied depending on altitude and soil type, with differences observed between high-altitude surface soils.

The results (Fig. 2) clearly showed that the degree of OC increment [slope (m) = 2.81] with altitude is highest at 1900–2000 m altitude, while the tendency of OC increment [slope (m) = 2.31] is lowest at 400–500 m altitude. The land use change led to an increase in the degree of OC increment as elevation increased, with the slope (m) increasing from 2.39 to 2.64 for 900–1000 m to 1400–1500 m. This result suggests that the shift from forest land to other land use at higher elevation (1900–2000 m) is responsible for substantial loss of soil OC compared to lower elevation gradients.

The amount of organic carbon in the soil decreased significantly ($P< 0.05$) as its depth increased. Significantly ($P< 0.05$) highest quantity of OC (22.21 g kg^{-1}) was found in the topmost layer (0–15 cm) of soil. OC content decreased by 30.12% in the 15–30 cm depth and was found to be 15.52 g kg^{-1}, and it further declined by 22.77% in 30–45 cm depth and was found to be 12.14 g kg^{-1}. The main reason for this depth-dependent OC distribution is the high amount of organic matter that is added to the soil at the top. At the surface, plant litter, root exudates, and other organic matter build up, adding organic carbon to the soils. On the other hand, layers below the top get less direct organic input, which makes the OC concentrations lower as compared to the sub-surface layer (Hasanain et al., 2024).



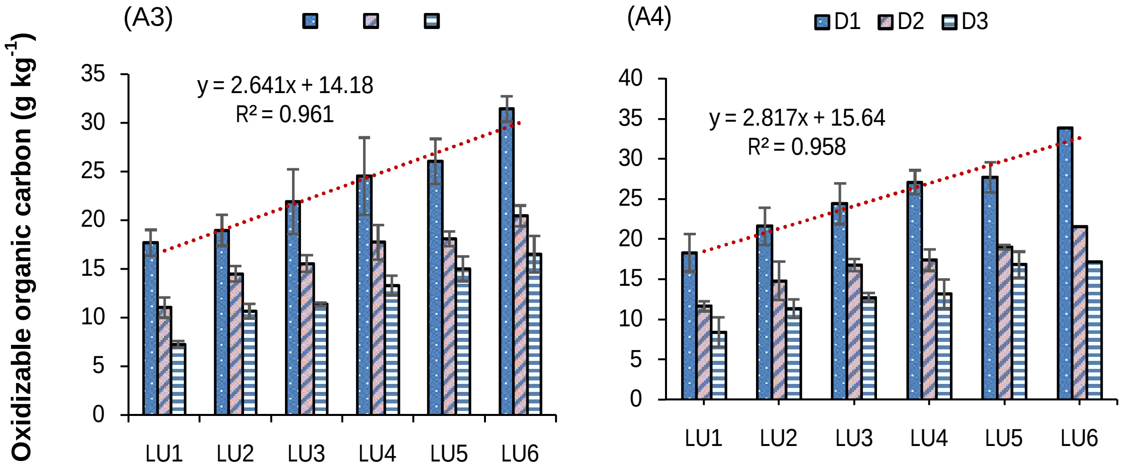


Fig. 2. Soil oxidizable organic carbon (g kg^{-1}) of different land use systems along with different elevation (A1= 400-500 m, A2 = 900-1000 m, A3= 1400- 1500 and to A4= 1900-2000m) and three soil depth (D1= 0-15 cm, D2= 15-30 cm and D3= 30-45 cm). Each bar represents mean ± standard deviation. LU1= open crop fields, LU2=mandarin orchards, LU3= large cardamom agroforestry, LU4= Ginger fields, LU5= tea plantations and LU6= Undisturbed forests

4. CONCLUSION

The study highlights the significant influence of land use systems and altitudinal gradients on soil organic carbon (OC) content in the North-Eastern Himalayan region of West Bengal. Undisturbed forests exhibited the highest OC levels, followed by tea plantations,ginger-based agroforestry, large cardamom, and mandarin. While open crop fields showed the lowest amount of organic carbon content. This variation is largely attributed to the differing levels of organic matter input and human disturbance across land uses. The changes were more prominent at upper soil depth (0-15 cm). The study also established a positive correlation between elevation and OC content, with higher altitudes supporting greater OC accumulation due to reduced decomposition rates at cooler temperatures. Additionally, OC content decreased with soil depth, emphasizing the role of surface organic matter in carbon sequestration. Our findings suggest that tea, ginger-based agroforestry, and large cardamom agroforestry systems would be better options with best management practices for carbon sequestration if forestland alteration is necessary. These findings underscore the importance of sustainable land management practices in maintaining and enhancing soil organic carbon, particularly in ecologically sensitive mountainous regions.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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