Original Research Article

Soil Organic Carbon Dynamics Across Different Land Use Systems and Altitudinal 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 May 2019 to 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, followed by tea plantations, large cardamom, ginger based agroforestry and mandarin orchard. While, open crop fields had the lowest OC content. Soil organic carbon showed a positive correlation with elevation and a decrease with soil depth.

Conclusion: These findings provide crucial insights for researchers and policymakers, providing valuable information to assist in decision-making for sustainable land use management.

Comment [1]: It would be better to display/include the organic carbon content values of each land use system studied..
What is the basis for determining the positive correlation between elevation and subsidence with soil depth. It should be explained

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). Changes in land use can have substantial impacts on ecosystems, biodiversity, and natural resources. Transforming forests into agricultural or urban areas can result in 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

Comment [2]: I suggest how organic carbon relates to global warming, which is currently a world issue that we must address together.

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.

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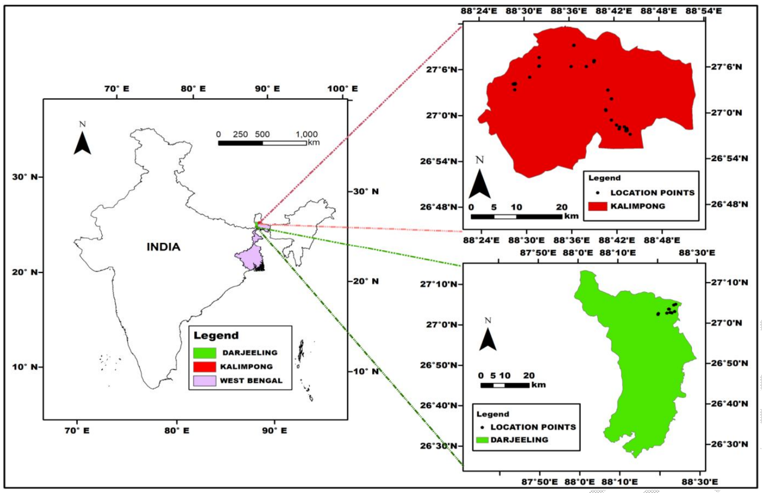

Fig. 1. Location of the Experimental site of North-Eastern Himalayan region of West Bengal.

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 15-20 years old.

The survey was undertaken during the months of May and June 2019. A plot measuring 10 × 10 m² 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. Soil samples were collected from three distinct increment layers: 0–15 cm, 15–30 cm, and 30–45 cm. Soil-oxidizable organic carbon was determined by the method of Wakley and Black (1934).

Comment [3]: I also suggest that it is better to take a complete sample, namely a ring sample, to determine the physical properties of the soil, especially the bulk density, soil permeability and particle density.

Comment [4]: Are the composite soil samples taken, also measured the organic matter content of each sample? If so, the organic matter content data should be displayed, because organic matter greatly influences the organic carbon produced.

Comment [5]: It would be better to mention and describe in the article the methods and tools used to measure organic carbon.

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 OC content among the six land use systems, regardless of altitudinal differences (Table 1). The mean OC content ranged from 0.65% in

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LU1 (open crop fields) to 0.99% in LU6 (undisturbed forests), indicating that land use significantly influences the accumulation and retention of organic carbon in soils. The sequence of LUS by OC content was as follows: LU6 (0.99%) > LU5 (0.09%) > LU4 (0.77%) > LU3 (0.75%) ≈ LU4 (0.71%) > LU1 (0.65%). 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 OC content in soils under LU3 (large cardamom agroforestry) is almost identical to that under LU4 (ginger fields), showing only a slight variation. Agroforestry systems like LU3 and LU4 often 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., 2020).

Comment [6]: It is observed that the LU5 value is 0.09% > LU4 is 0.77%. Is this appropriate?

Soil organic carbon showed a strong upward trend with elevation, as shown by the fact that the average amount of organic carbon rose significantly with increasing elevation: 0.64% at A1 (400–500 m), 0.73% at A2 (900–1000 m), 0.83% at A3 (1400–1500 m), and 0.99% 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. It was also evident (Fig. 2.) that the degree

Table 1. Duncan multiple range test (DMRT) for soil Oxidizable organic Carbon (%) in respect of Land Use System (LU), Altitude gradient (A) and Soil Depth (D) at Himalayan region of West Bengal.

Comment [7]: Its good

ALTITUDE	**DEPTH**	**LAND USE SYSTEM**						**MEAN**
		LU1	LU2	LU3	LU4	LU5	LU6	
A1	D1	0.74	0.77	0.78	0.83	0.98	1.12	0.87
	D2	0.56	0.54	0.74	0.62	0.68	0.72	0.64
	D3	0.28	0.31	0.35	0.31	0.56	0.57	0.40
MEAN		**0.53**	**0.54**	**0.62**	**0.59**	**0.74**	**0.80**	**0.64^{a}**
A2	D1	0.88	0.93	1.06	1.11	1.17	1.35	1.09
	D2	0.54	0.58	0.69	0.35	0.63	0.84	0.60
	D3	0.36	0.60	0.53	0.27	0.64	0.71	0.52
MEAN		**0.59**	**0.70**	**0.76**	**0.58**	**0.81**	**0.97**	**0.73^{b}**
A3	D1	0.94	1.04	1.10	1.23	1.34	1.41	1.18
	D2	0.66	0.67	0.62	0.86	1.05	1.06	0.82
	D3	0.41	0.54	0.57	0.67	0.38	0.39	0.49
MEAN		**0.67**	**0.75**	**0.76**	**0.92**	**0.92**	**0.95**	**0.83^{c}**
A4	D1	1.12	1.17	1.19	1.32	1.47	1.68	1.33
	D2	0.75	0.83	0.82	0.97	1.08	1.10	0.92
	D3	0.54	0.57	0.64	0.74	0.86	0.89	0.71
MEAN		**0.80**	**0.86**	**0.88**	**1.01**	**1.14**	**1.22**	**0.99^{d}**
MEAN (LAND USE)		**065^{a}**	**0.71^{b}**	**0.75^{c}**	**0.77^{c}**	**0.90^{d}**	**0.99^{e}**	
MEAN DEPTH		D1		D2		D3		
		1.12^{a}		**0.75^{b}**		**0.53^{c}**		
FACTORS		**LU**	**A**	**D**	**LU X A**	**LU x D**	**A x D**	**A X LU x D**

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SEM (±)	0.005	0.004	0.004	0.027	0.035	0.030	0.060
CD (P=0.05)	0.015	0.012	0.010	0.076	0.097	0.084	0.169

LU1= open crop fields, LU2=mandarin orchards, LU3= large cardamom agroforestry, LU4= Ginger fields, LU5= tea plantations and LU6= Undistributed 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).

of OC increment with altitude is greater in A4 (1900–2000 m) altitude (slope = 01094), whereas the tendency of increment of OC is lowest at A1 (400–500 m) altitude. This result suggests that the shift from forest land to other land use at A4 (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 as the depth of the soil increased. The highest quantity of OC (1.12%) was found in the topmost layer of soil (0–15 cm, D1). It decreased to 0.75% in the middle depth (15–30 cm, D2), and it declined even more to 0.53% in the deepest layer (30–45 cm, D3). 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.

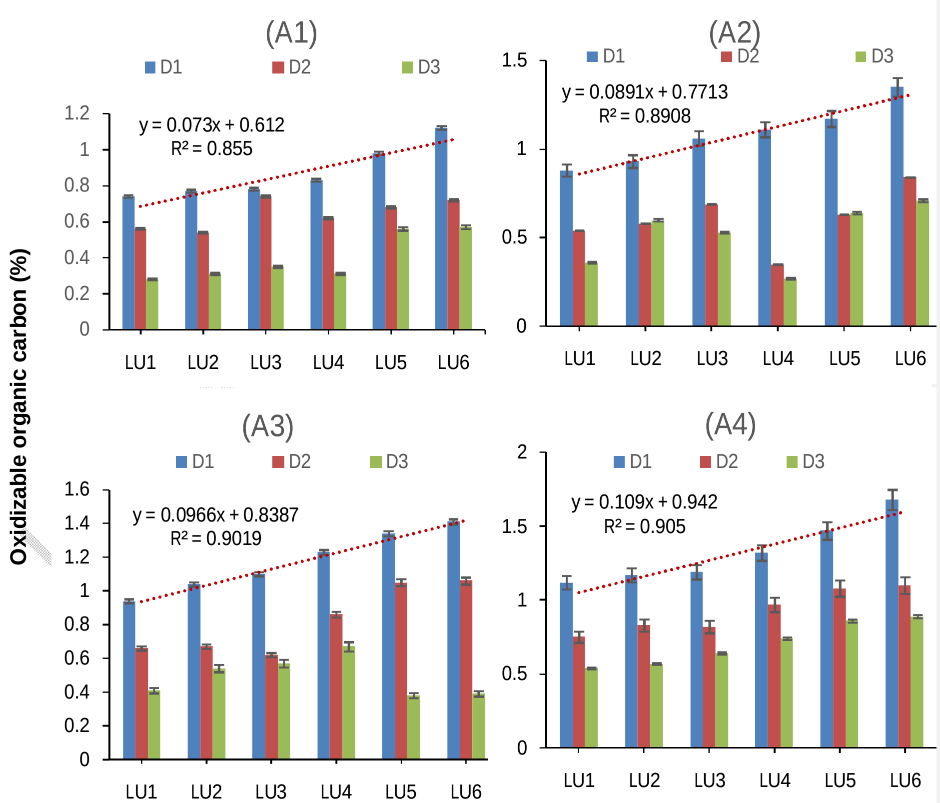

Fig. 2. Soil oxidizable organic carbon (%) of different land use systems along with different elevation (A1= 400-500 m, A2 = 900-1000 m, A3= 1400- 1500 and to A4= 1900-2000m) and three soil depth (D1= 0-15 cm, D2= 15-30 cm and D3= 30-45 cm). Each bar represents mean ± standard deviation. LU1= open crop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

Comment [8]: Its good

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, while open crop fields showed the lowest. This variation is largely attributed to the differing levels of organic matter input and human disturbance across land uses. 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. These findings underscore the importance of sustainable land management practices in maintaining and enhancing soil organic carbon, particularly in ecologically sensitive mountainous regions.

Comment [9]: It should be determined and recommended that for a sustainable land use system what is a good land use model at what elevation gradient and what is a good soil depth?
So that this recommendation can be used as a reference or policy in land use.

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Comment [10]: It is best to use references that are the most recent in the last 5 years.

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UNDER PEER REVIEW

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