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Soil Organic Carbon Stocks along Altitudinal Gradient under *Shorea robusta* Gaertn. F. Plantations in Darjeeling Himalayas

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***Abstract*:** The carbon storage potentiality of forest land use systems has been recognized as a major factor in the recent climate change scenario. The current study was designed to quantify the soil organic carbon (SOC) stocks at three soil depths (0-20 cm, 20-40 cm and 40-60 cm) in *Shorea robusta* Gaertn. f. (Sal) plantations along the elevation gradients of 150-300 m, 300-450 m, 450-600 m and 600-750 m in the Darjeeling Himalayas. There was an increasing trend of SOC stock along the elevation gradient, reaching the maximum stock (67.53 Mg C ha^{-1}) at the mid elevational range of 450-600 m at the surface soil layer and the minimum (26.81Mg C ha^{-1}) at 150-300 m. The highest elevational range (600-750 m) was quantified with significantly lesser SOC stock (51.01 Mg C ha^{-1}) than 450-600 m elevational range. Correlation between elevation gradient and SOC stock exhibited moderate positive relationship between the two (R^2= 0.485).

Keywords: SOC stock, Sal plantations, Elevation gradient, Darjeeling Himalayas

Offsetting carbon dioxide (CO_2) emissions through carbon sequestration by vegetation is an efficient and viable mitigation tool for climate change. Forest ecosystem thus has been recognized as the custodian of biodiversity and carbon sinks in regulating the global climate (Dirzo and Raven 2003, Gibbs et al 2007, Fahey et al 2010). Plantation forests are also recognized as a receptacle of carbon stock like natural forests, since stand age is the leading factor affecting the total carbon pool of plantation ecosystems (Justine et al 2015). In India, increasing forest plantations, regenerating damaged forests, and protecting existing stands have all significantly increased productivity of ecosystem and carbon content in soil (Ravindranath et al 2008). The soil organic carbon (SOC) pool in forest soils is crucial for predicting and assessing the carbon sequestration potential of forests. In fact, SOC storage in soil is influenced not only by a variety of factors including vegetation, climate, interaction with soil organisms, soil properties but also topography (Bird et al 2004, Wang et al 2023). Globally, the recent estimate of SOC stocks is approximately 1500 Pg C while, 27 earlier global studies estimated the range within 504 to 3000 Pg C (Scharlemann et al 2014). Sal plantations/forest is spread over an area of about 13 million hectares in India (Deka et al 2012). The species has a high timber value, makes a major contribution to the permanent carbon stock of the tropical forest due to its high rotation age of more than 120 years (Siddique et al 2021). The sal forests confined to the Darjeeling Himalayas have been classified as moist sal forests (Kushwaha and Nandy 2012), with deep, moist and nutrient rich soil, distributed along the lower elevation gradients from 150 m to 750 m mean sea level, which is kept aside for carbon storage in a vast area.

The carbon storage in soil also depends on tree species (Gogoi et al 2017), where higher rotation age species like Sal and Teak have higher capacity to store carbon in soil for longer time than short rotation species like poplar and eucalyptus (Kaul et al 2010). Since, species specific studies have been explored only about above ground biomass and carbon stock in a few species like *Tectona grandis* (Gangopadhyay et al 2021), *Cryptomeria japonica* and *Pinus patula* (Banerjee and Prakasham 2012) in Darjeeling Himalaya, none of these studies examined the effect of altitude on SOC stock. Vegetation diversity pattern along the elevation gradient in the Darjeeling Himalaya have been explored previously by several researchers (Moktan and Das 2012, Das and Ghosh 2022, Rai and Moktan 2022, Vineeta et al 2022) but the effect of altitude on SOC stock under specific tree plantation is yet to be explored. Only a few studies have reported that soil carbon stock in forests of Darjeeling Himalayan region increases with increasing altitude (Banerjee 2014, Devi and Sherpa 2019). In this context, we hypothesised that SOC stock under Sal plantations in forests of Darjeeling Himalayas will also increase with increasing altitude. The present study was thus attempted with the objective of determining the effect of elevational gradient on SOC stock under Sal plantations with research question i.e., Does altitude influence the SOC stock of Sal plantations in Darjeeling Himalayas?

MATERIAL AND METHODS

Study Site: The study site is in the Darjeeling Himalayas, encompassed by Kalimpong and Darjeeling districts. This part of the eastern Himalayas lies at 27° 13′ N to 26° 27′ N latitude and 88° 53′ E to 87° 59′ E longitude. The elevation extends from >100 to 3636 m; nevertheless, the current study was only able to be carried out in the 150-750 m range due to the lack of sal plantings above this level. Climatically, the region is sub-tropical, influenced by the south-west and north-east monsoons, which provide rainfall in the range of 1877 mm to 2333 mm. The winter is cold and dry while, the summer is quite rainy. Pedologically, the area is distinguished by four different soil texture classes: gravelly-loamy, gravelly-loamy to loamy skeletal, gravelly-loamy to coarse-loamy and fine-loamy to coarse-loamy (Pramanik 2016). The Sal plantations are mainly distributed in the Teesta range of the Darjeeling Forest division. For better convenience, the study site was classified into four elevational ranges or classes i.e., 150-300 m (A1), 300-450 m (A2), 450-600 m (A3) and 600-750 m (A4). The study site covered different areas of Kalimpong and Darjeeling district such as Peshok, Mangwa, Teesta, Mungpoo, Bagrikote and Munsong (Fig. 1).

Soil sampling and analysis: Quadrates of 20 m x 20 m dimensions was laid out for extracting soil samples and estimate density of Sal plantations from all the elevational classes across its elevation, i.e., five quadrates in each class with a total of 20 quadrates. The soil samples were collected from every quadrate at three different depths (0-20 cm, 20-40 cm and 40-60 cm). In every quadrate three soil samples were collected diagonally (two at corners and one at centre) and then made into a composite sample for analysis. Soil samples were air dried, grinded, and sieved (2 mm sieve) before carrying out the analysis. Bulk density was estimated by core sampling method (Gupta and Dakshinamoorthy 1980) and SOC content was determined by wet digestion method (Walkley and Black 1934). The SOC stock was quantified multiplying the organic carbon content with the mass of the soil (bulk density and depth) for each soil depth (Pearson et al 2005) and was expressed as Mg C ha^{-1}.

Statistical analysis: The data were subjected to one-way analysis of variance to test the significance of the effects of different elevation gradients on SOC stock and SOC and DMRT were applied to test the pairwise comparison of means between the elevation gradients. Pearson's correlation was performed to assess the relationship between dependent variables (elevation gradient) and independent variables (SOC stock). All data were analysed using R Studio (4.3) and SPSS (21).

RESULTS AND DISCUSSION

SOC Content: The highest SOC content was estimated at altitude class A3 in all the studied three depths (Table 1). The significant difference is recorded among all altitudinal classes except between A2 (2.11%) and A4 (2.3%) at the top layer. Significant increase in SOC from A1 to A3 followed by a significant decrease in A4 at all depths. The SOC in different soil depths decreased from top to bottom layer of the soil in all altitudinal classes except in the A1 class, where the estimated SOC was lowest in the 20-40 cm (0.84%) depth.

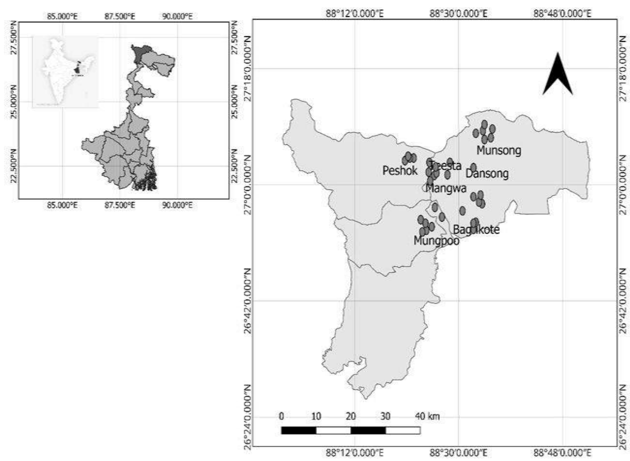

Fig. 1. Map of study area

Table 1. SOC and bulk density of sal plantations at different altitudinal classes

AC	Soil depth (in cm)					
	0-20	20-40	40-60	0-20	20-40	40-60
	SOC (%)			Bulk density (g cm^{-3})		
A1	1.22±0.24^{c}	0.83±0.33^{c}	0.84±0.32^{c}	1.11±0.03	1.20±0.05	1.24±0.06
A2	2.11±0.61^{b}	1.56±0.5^{b}	1.42±0.38^{b}	1.07±0.03	1.16±0.03	1.22±0.03
A3	3.20±1.16^{a}	2.40±0.8^{a}	2.12±0.70^{a}	1.06±0.04	1.15±0.04	1.22±0.04
A4	2.30±0.84^{b}	2.06±0.83^{ab}	1.51±0.68^{b}	1.09±0.05	1.18±0.05	1.25±0.08

AC = Altitude class; A1 = 150-300 m asl; A2 = 300-450 m asl; A3 = 450-600 m asl; A4 = 600-750 m asl

The significant increase in SOC along the elevation could be explained as due to an increase in Sal density from A1 to A3 altitude class (478.6 to 482.7 trees/ha, Fig. 2), which produces a denser canopy (Sheikh et al 2020) and higher accumulation of leaf litter, as well as temperature drop that decrease mineralization through lesser decomposition rates (Chan 2008, Choudhury et al 2016) with higher SOC at higher altitudes (Banday et al 2019). Moreover, anthropogenic disturbances were lesser in higher altitudes as compared to lower altitudes due to limited accessibility due to steeper terrain (Spracklen and Righelato 2014). However, SOC content decreased above the altitude class A3 which might be due to lesser tree density (Fig. 2). Tree density and temperature are simultaneously influencing the SOC along the altitudinal gradient of Sal plantations in the Darjeeling Himalayas. SOC content was highest in top soil layer at all altitudinal classes. The top layer's supremacy in organic matter could be due to the higher availability of leaf litter and higher microbial activity (Chimdessa 2023). Bulk density varied along the elevation gradient; maximum bulk density was observed at A1 altitude class and minimum at A3 class at all soil depths. Bulk density increased with increasing soil depth throughout the altitudinal gradient.

SOC Stock: The highest SOC stock was quantified at altitude class A4 in all the three depths i.e., 67.53 Mg ha^{-1} at 0-20 cm followed by at 20-40 cm and at 40-60 cm followed by A4 class, A2 class and the least at A1 altitudinal class with 26.81, 19.64, and 20.57 Mg ha^{-1}, respectively (Table 2 and Fig. 3). SOC stock significantly increased from altitudinal class A1 to A3 and then significantly decreased from A3 to A4. The stock increased by 71.4% from A1 to A2 and by 51.6% from A2 to A3 and thereafter decreased by 21.6% A3 to A4.

At higher altitudes, high annual precipitation and low mean temperatures favour a decline in the decomposition of organic matter and high plant biomass production, both of which influence the higher accumulation of SOC stock (Tornquist et al 2009). The trends of SOC stock along the elevation gradient in present study are similar to Devi and Sherpa (2019) and Banerjee (2014) in the Darjeeling Himalayan Forest along the altitudinal gradient. The maximum SOC stock up to 60 cm depth was quantified at altitude class A3 (174.2 Mg C ha^{-1}) and minimum at A2 class (67.02 Mg C ha^{-1}, Fig. 4). This was also evidenced from

Table 2. SOC stock (Mg ha^{-1}) of Sal plantations at different altitudinal classes

AC	SOC stock		
	0-20 cm	20-40 cm	40-60 cm
A1	26.81±4.4^{c}	19.64±6.9^{c}	20.57±7.1^{c}
A2	44.52±12.6^{b}	35.91±10.9^{bc}	34.44±8.6^{b}
A3	67.53±22.9^{a}	55.36±19^{a}	51.31±16.4^{a}
A4	51.01±18.1^{b}	48.39±20.1^{ab}	37.19±16.1^{b}

AC = Altitude class; A1 = 150-300 m asl; A2 = 300-450 m asl; A3 = 450-600 m asl; A4 = 600-750 m asl

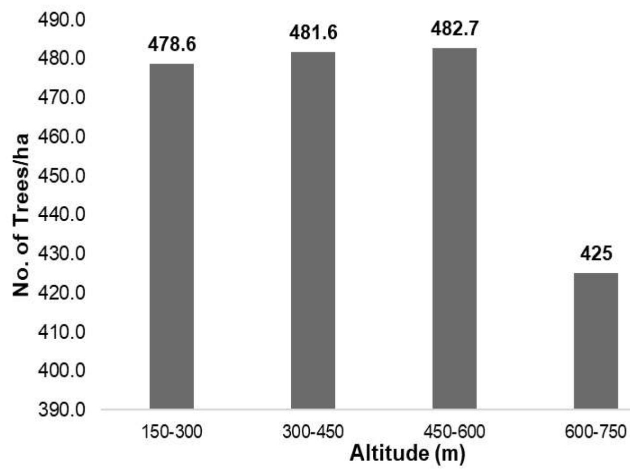

Fig. 2. Tree density of Sal plantations at different altitudinal classes

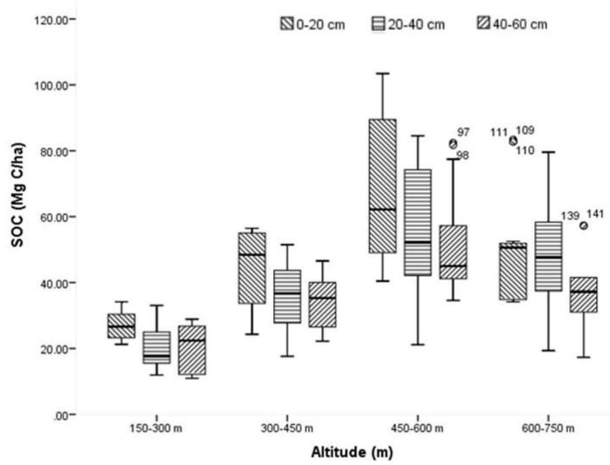

Fig. 3. SOC stock of Sal plantations at different soil depths

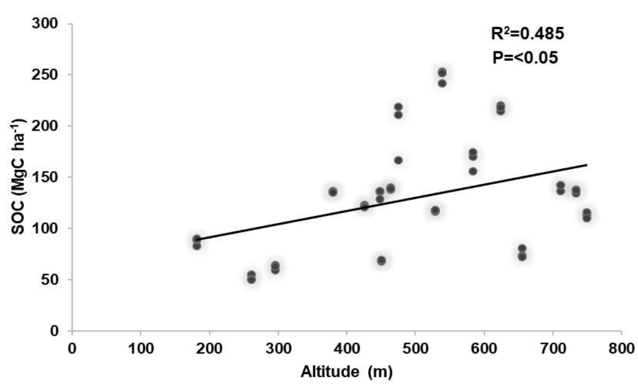

Fig. 4. Total SOC stock at different altitudinal class

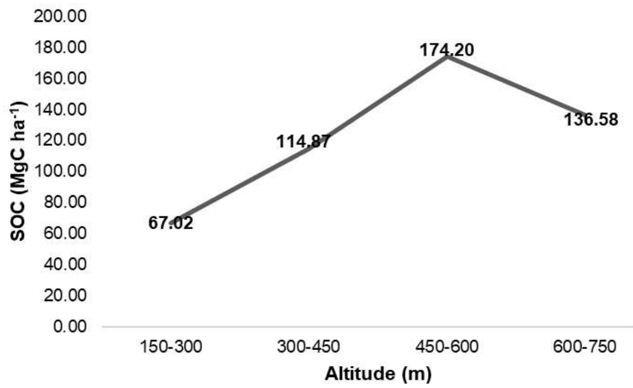

Fig. 5. Pearson correlation between altitude and SOC stock of Sal plantation

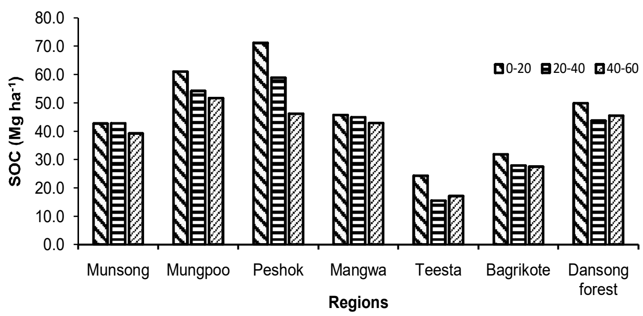

Fig. 6. SOC stock of Sal plantations in different regions of Darjeeling Himalaya

moderately positive and significant relationship between altitude and SOC stock (R^2= 0.485, $p < 0.05$, Fig. 5).

Regional SOC stock: Regional estimation of SOC stocks of top soil layer also indicated higher stock in places located at higher elevation (500 -750 m asl) like in Peshok region (71.1 Mg ha^{-1}), followed by Mungpoo and Dansong region than in places located at lower elevations like in the Teesta (24.3 Mg ha^{-1}) region (Fig. 6). Similarly, SOC stock of the entire soil layers i.e., up to 60 cm depth in these areas was 172.2 Mg C ha^{-1}, 167 Mg C ha^{-1}, 139 Mg C ha^{-1}, and 56.9 Mg C ha^{-1}, respectively. The sal plantations at places located in higher elevations have higher tree density. The temperature decreases at a rate of 0.62°C for every 100 m rise in elevation (Acharya et al 2011). Decreasing temperature reduces the microbial activity which decrease soil organic matter decomposition. The higher tree density in these regions indicates higher litter build-up resulting into higher SOC stock. Even though Teesta is not at the lowest altitude, the lowest SOC stock might be due to the location of the sal plantation, closer to the river Teesta.

CONCLUSION

The study estimated the SOC stock of Sal plantations up to 60 cm depth along the elevational gradient from 150 m to 750 m asl in four elevational steps of the Darjeeling Himalayas. The highest SOC stock was found at the surface soil layer throughout the elevational gradient. SOC stock varied with altitude exhibiting a significant and direct relationship. SOC stock gradually increased up to third elevational step and thereafter decreased. Factors like tree density, altitude, and temperature influenced the SOC stock of the Sal plantations. Increasing elevation resulting in to lower temperature reduced the decomposition rate of organic matter building-up higher SOC stock. It is thus recommended to conserve this Sal plantations in Darjeeling Himalayas for permanent storage of carbon to mitigate climate change.

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AUTHOR CONTRIBUTIONS

The material preparation, data collection and analysis were performed by Arshad A, Manendra Singh, Mendup Tamang, Kanchan, Shahina NN. The first draft of the manuscript was prepared by Arshad Aand all the corrections are made and the final manuscript was done Vineeta, Ganesh Ch. Banik, Gopal Shukla and Sumit Chakravarty.

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