Research article

Ecology Journal

ISSN (Print): 2957-4471, ISSN (Online): 2957-448X, Website: https://journal.esbangladesh.org
Ecol. J. (2024) 6 (1) : 43-57

SOIL ORGANIC CARBON CONTENT ACROSS VARIOUS GEOMORPHIC UNITS IN MANGROVE FOREST: A CASE OF DUBLAR CHAR, SUNDARBANS

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Received: 22 January 2024, revised: 12 March 2024, accepted: 18 March 2024, DOI: https: //doi.org/10.59619/ej.6.1.6

ABSTRACT

Lying at the tidally active region of the Bengal Delta, the Sundarbans act as a terrestrial carbon sink and play a crucial role in climate change mitigation. However, this forest is underrepresented in term of soil organic carbon research. The purpose of this study was to investigate the Soil Organic Carbon dynamics across various geomorphic units within a small area of mangrove forest ecosystem of Dublar char of Sundarbans. Salinity and pH trends were also examined across geomorphic units to understand their interplay with soil organic carbon dynamics. Soil samples from 25 locations across various geomorphic units were collected and analyzed to determine soil organic carbon, salinity and pH levels. The Walkley-Black wet oxidation method was employed to determine the organic carbon content. Results indicate varying degree of organic carbon concentration across geomorphic units with Highland areas having high level of soil organic carbon concentrations with average concentration level of 2.05%, followed by Creeks with 1.55%. Salinity levels also varied across different geomorphic units with values ranging from 4.8 ppt to 12.7 ppt, with creek area having high level of salinity due to its close proximity to seawater. Fringe forest areas had the highest pH levels with average value of 7.4 and the lowest average pH value (6.86) was observed in Beach areas of the study area. The study holds immense significance in understanding the organic carbon dynamics of mangrove ecosystem in the Sundarbans, providing essential insights for long term climate-resilient land management and biodiversity conservation efforts.

Keyword: Geomorphology, Sundarbans, pH, salinity, soil organic carbon

Introduction

Mangrove forests are recognized amongst the world's most carbon-rich forest types because of their effective ability to sequester carbon into above-ground and below-ground carbon reservoirs (Alongi 2012, Donato *et al*. 2011, Aye *et al*. 2023). Mangrove wetlands worldwide can be found in the region of transition between terrestrial and marine surroundings (Breithaupt *et al*. 2012), providing various ecosystem services, such as fisheries production and nutrient regulation (Donato *et al*. 2011). Mangrove ecosystems have been demonstrated to mitigate the effects of coastal storms by diminishing waves generated by wind, dispersing currents, stabilizing sediment, lowering the level of storm surges (Guannel *et al*. 2015, Temmerman *et al*. 2013). The United Nations Environmental Programme (UNEP) identified the mangrove forest ecosystem as "Blue Carbon'' in recognition of its significance for sequestering carbon, alongside other blue carbon ecosystems like salt marshes and seagrass (Nellemann *et al*. 2009, Macreadie *et al*. 2019). However, the inconsistency and unpredictability in estimating soil organic carbon (SOC) present a major challenge to integrating mangroves (along with other blue carbon ecosystem) into international and national policy frameworks and tools (Rahman *et al*. 2021).

Mangrove forests flourish within dynamic coastal landscapes influenced by natural forces such as rivers, tides, and weaves, which regulates sedimentary processes, water flow paths, and reach-scale topography in the intertidal area (Boyd *et al*. 1992, Woodroffe 2002). The accumulation of organic carbon in tidal wetlands is governed by factors such as the origin of organic materials (Sanders *et al*. 2009), climatic elements like precipitation and temperature (Lovelock *et al*. 2014, Kauffman *et al*. 2020) and oceanographic dynamics such as offshore currents, morphology and tidal fluctuation (Wang *et al.* 2020). While numerous studies have contributed to the understanding of carbon sequestration in mangrove sediments through reports on sedimentation rates and carbon storage (Victor *et al*. 2004, Sanders *et al*. 2009, Zhang *et al*. 2012), there remains a lack of complete comprehension regarding the crucial influence of vegetation and geomorphology on organic carbon concentration. The interaction between geomorphology and soil chemical properties like pH and salinity is crucial for understanding the mangrove ecosystem dynamics and functions (Twilley *et al*. 2019). Geomorphological features affect various factors of mangrove forests like organic carbon decomposition interaction with salinity (Sha *et al*. 2018), water dynamics and nutrient status (Cardona and Botero 1998), vegetation dynamics (Duarte *et al*. 2005, Lunstrum and Chen 2014) and sediment deposition (Perri *et al*. 2017).

Sundarbans, the largest uninterrupted mangrove forest globally, lies within the tidal active delta plain of the Bengal Delta, spanning the border of India and Bangladesh (Giri *et al*. 2011, Tusar *et al*. 2023). This forest often either largely overlooked in global assessments of mangrove SOC, or inadequately represented as there is a scarcity of samples or obtained data quality (Kauffman *et al*. 2020, Twilley *et al*. 2018). Though several research have investigated soil organic carbon content in the Sundarbans (Allison *et al*. 2003, Hossain and Bhuiyan 2016, Khan and Amin 2019, Rahman *et al*. 2015), there is a scarcity of studies that have examined SOC in site specific scale across geomorphic gradients. To fill these knowledge gaps the study aims to investigate the influence of different geomorphic units on Soil Organic Carbon concentration, with especial emphasis on soil particle size distribution of the study area, and understanding the trends of salinity and pH level within each geomorphic unit and their influence on Soil Organic Carbon.

The overall study poses profound significance in depicting a clear picture of how the ecosystem of mangrove forest functions and their complex interplay between environmental and geographical aspects. Investigating how geomorphic features and environmental factors affect soil organic carbon, the study aims to provide critical information for designing and implementing climate-resilient land management strategies. Moreover, it also offers a proactive approach to anticipate and address the impact of climate change- driven alterations to soil biogeochemistry, water regimes, and overall ecosystem resilience.

Materials and Methods

Study area: The Sundarbans is geographically situated in the southwest region of Bangladesh (Islam *et al*. 2017). The research was conducted within the southwestern region of Dublar Char, encompassing a total study area of approximately 4.26 square kilometers. It is situated within the Polyhaline zone of Sundarbans mangrove forest (Rahman *et al*. 2021), characterized by an average salinity level of 27,500 µS/cm (Dasgupta *et al*. 2012).The soil in the study area is in general medium textured; with a higher percentage of silt and clay particles compared to sand (Khan and Amin 2019). The hydro-geochemical environment of Dublar Char is quite dynamic in nature with numerous crisscrossed drainage channels, intricate creeks and important coastal processes. The vegetation within the study area comprises a diverse array of species, including shrub vegetation such as Hargoza (*Acanthus ilicifolius*) and Tiger Fern (*Acrostichum aureum*), as well as various tree species such as Keora (*Sonneratia apetala*), Goran (*Ceriops decandra*), Gewa (*Excoecaria agallocha*) and Sundari (*Heritiera fomes*).

Preparation of geomorphological map of dublar char: A geomorphological map is the representation of the different features of the Earth's surface, illustrating landforms that have shaped the landscape (Zangana *et al*. 2023, LeiteMeira Gomes *et al*. 2022). It is a widely used technique crucial for understanding landscapes (Oguchi 2019). The geomorphological mapping involves several techniques including fieldwork, aerial photogrammetry, remote sensing and GIS method to create accurate and detailed representation of surface feature and landform classification (van der Meij *et al*. 2022). The preparation of the Geomorphological Map of Dublar Char for the purpose of the study included some step-by-step process. Firstly, this part of the study relied on the preliminary task of making a base map on the basis of available Google Earth Image and Satellite Imagery (Sentinel-2) pertaining to the study area. The entire base map was divided into 52 grids by using fishnet tool to cover the entire study area.

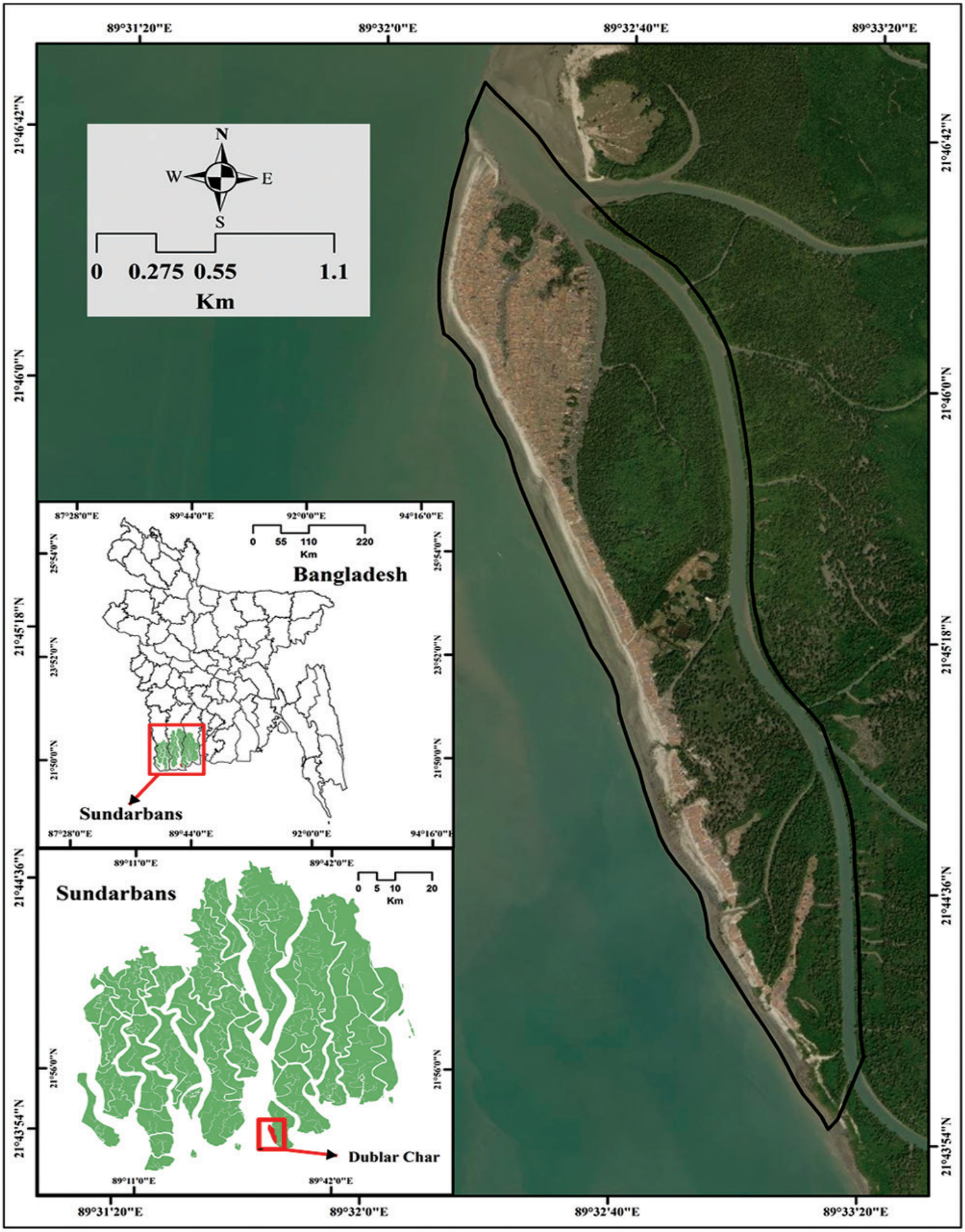

Figure 1. Map showing the study area (Dublar Char) in the Sundarbans.

Through field survey, plotting of each feature in particular grid was done on hard copy grid wise maps which was later transformed into digital format. Afterwards, through the use of georeferencing and digitization procedures in GIS platform the geomorphological map consisting of 5 distinct features in the study area was generated.

Fieldwork and sampling procedure: Soil samples were collected from the study area through which the Soil Organic Carbon (SOC) across five geomorphic units (beach, barren land, creek, fringe forest and highland) were investigated. At the time of fieldwork, the geomorphological data generated prior to data collection was used as a reference. Soil organic carbon in mangrove has been demonstrated to have a relationship with surface vegetation (Donato *et al*. 2011, Rahman *et al*. 2021, Akther *et al*. 2021), and research suggests that a significant amount of Soil organic carbon in floodplains originates from surface vegetation (Rahman *et al*. 2021), advocating the utilization of geomorphological data set for the identification of sampling locations. Within each geomorphic unit, soil samples were systematically collected from five distinct locations, with careful consideration given to presence of vegetation coverage

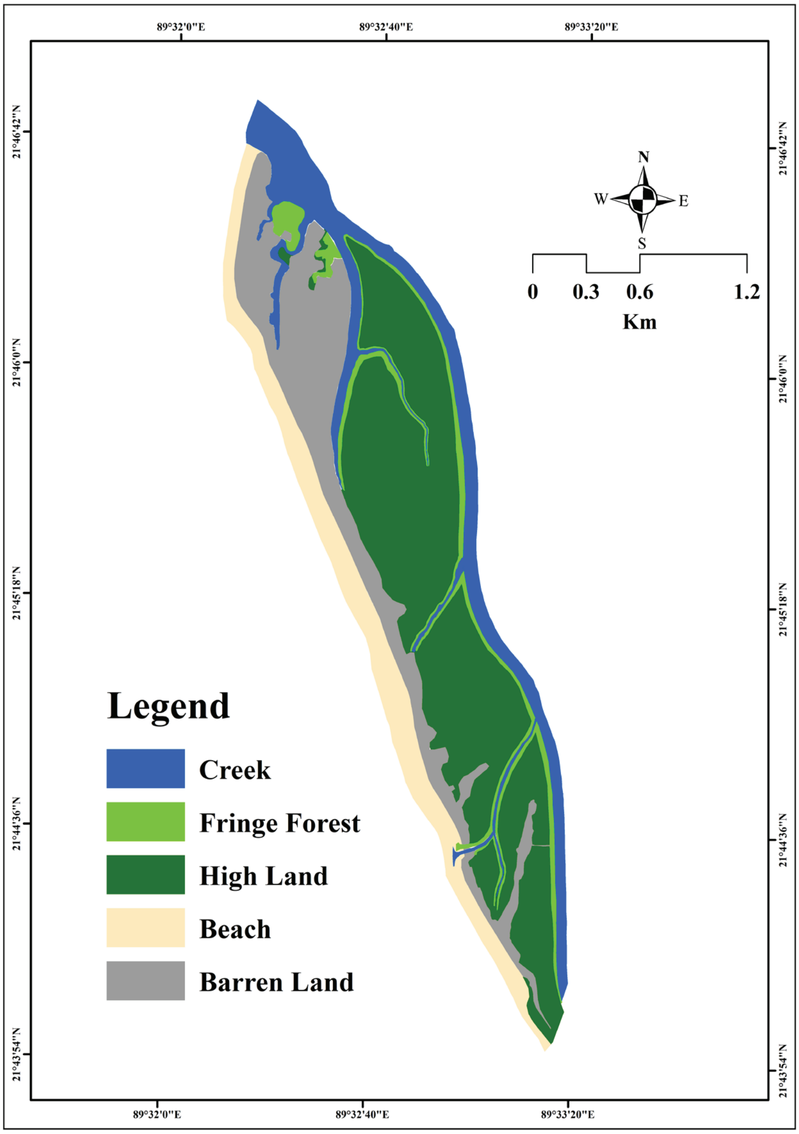

Figure 2. Geomorphological map of Dublar char.

Table 1. Classification of Geomorphic Types by Area Coverage

Units	Characteristics of the Feature in the Study Area	Area (Sq. Km)
Beach	Depositional landforms found in the western part of the study area. These are shaped by wave actions and coastal processes, serving as interface between land and sea.	0.56
Barren Land	Exposed areas that exhibit lack of vegetation coverage. Mostly concentrated along the north-western part of the study area	0.85
Creek	Linear landforms characterized by the presence of flowing water in a defined channel with variable widths and depths. Covers the entire eastern part of the study area with some branches making its way towards the center.	0.64
Fringe Forest	Transitional areas situated at the interface between terrestrial and aquatic environments found along the banks of the creeks.	0.26
Highland	Elevated landforms found at a considerable distance away from the waterbodies in the study area. Covers majority of the study area and inhabits most of the vegetation.	1.80

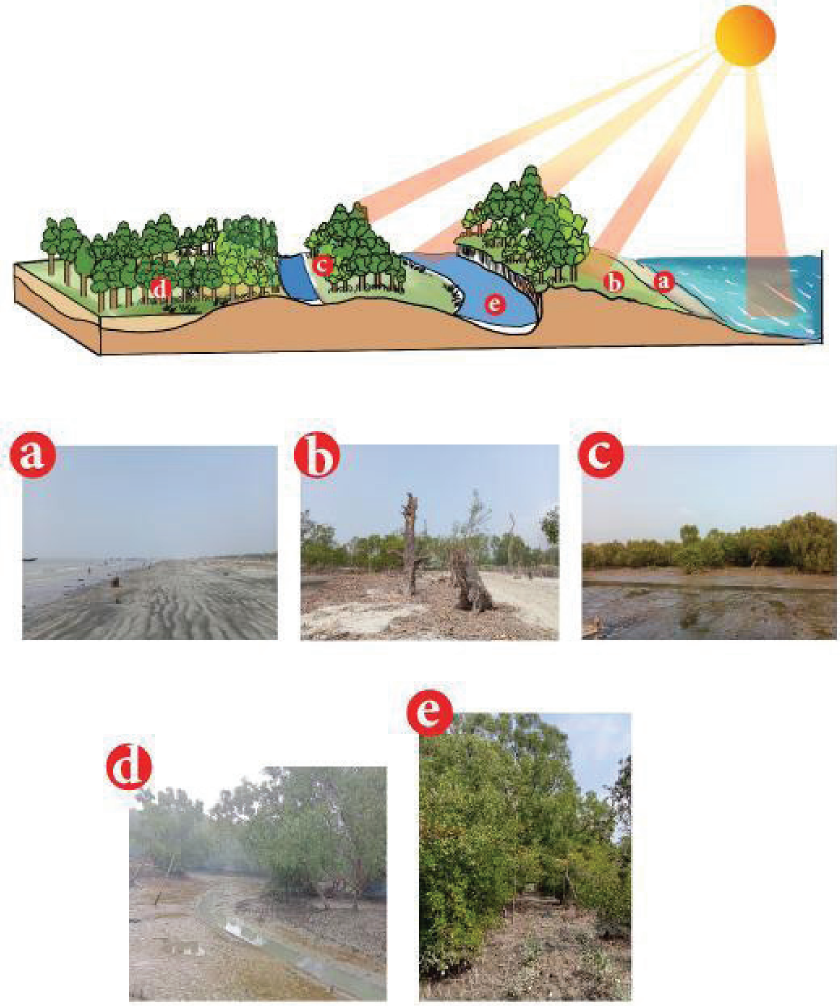

Figure 3. Conceptual diagram demonstrating the variation of SOC across geomorphic units. a) Beach, b) Barren Land, c) Fringe Forest, d) Highland and e) Creek.

and proximity to water bodies (sea and creek). Due to accessibility constraints, random selection of sampling points was not feasible. Nonetheless, our sampling strategy was devised to encompass the entire spectrum of variability within the study area by conducting sampling across various geomorphic units. A locally made Gauge Auger, equipped with a 1-meter-long gauge sampler and a handle, was utilized for the operation. A total of 25 locations, with 3 depth increments (0-15 cm, 15-50 cm and 50-100 cm) were taken at Creek, Fringe Forest and Highland. However, samples up to 50 cm depth in Beach and Barren Land area could only be collected due to some limitations pertaining to the instrument and geomorphological characteristics of those units. After collection the soil samples were stored in a dark and cool container to preserve their quality and were sent to the Environmental Lab, at the Department of Geography and Environment, University of Dhaka for analysis.

Analysis of soil physicochemical properties: The study assessed the soil texture utilizing USDA manual texturing techniques in the field then transformed each soil texture class into an average percent fine particle (clay + silt) employing a texture triangle (Thein 1979). This

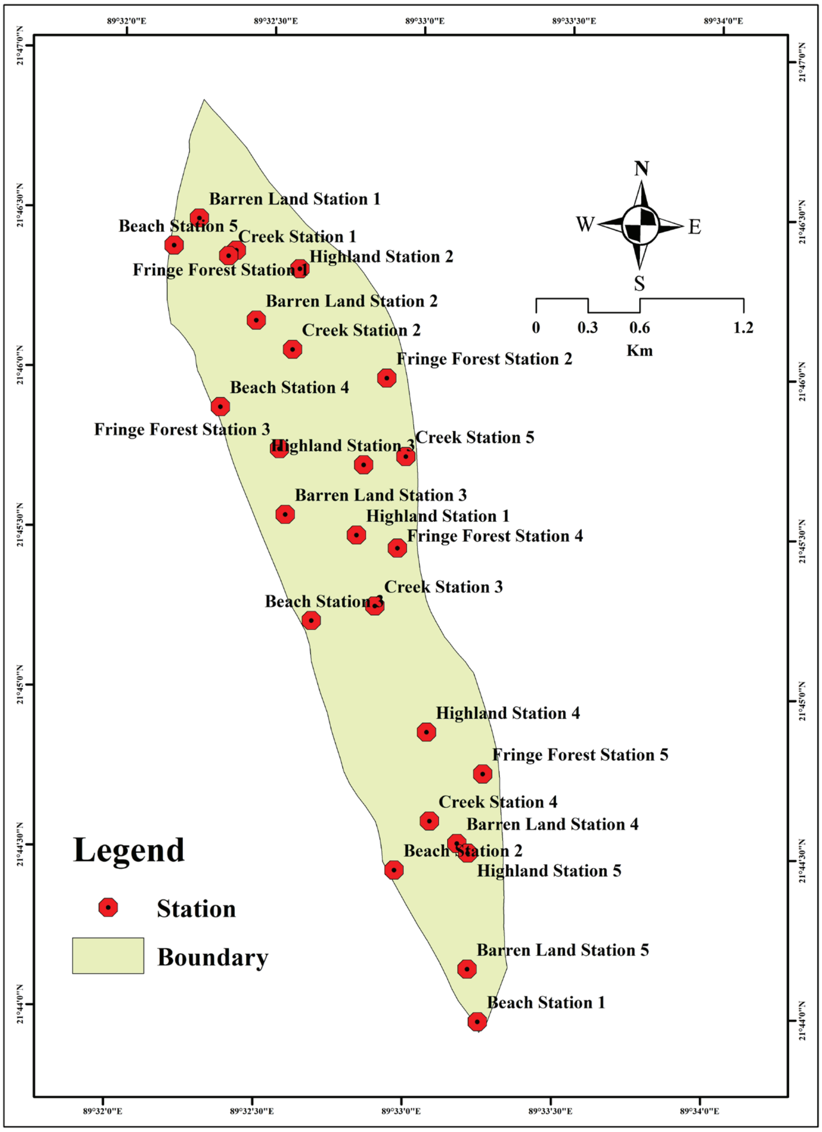

Figure 4. Locations of samples taken from different geomorphic units.

methodology enables the quantification of the average percentage of particles for each sample and depth. Prior to chemical analysis, the soil samples were air-dried and any visible detritus and roots were removed. Then, the soil samples were ground and sieved through a 2 mm mesh to eliminate coarse particles and plant debris. To determine the chemical parameters of pH and salinity, a soil-water ratio of 1:2.5 was used. This involved adding 25 g of distilled water to 10 g of dried soil, creating a 1:5 ratio. The pH of the soil samples was measured using a handheld HANNA HI 9813-6 Temperature Meter (Hardie and Doyle 2012). Salinity of soil was determined by Refractometer. All the instruments were calibrated prior to measurement.

Estimating soil organic carbon: To determine the Soil Organic Carbon (SOC) content, the Walkley-Black wet oxidation method was employed (Bornemisza *et al.* 1979). In the Walkley-Black method, organic matter in the soil was oxidized with potassium dichromate (K2Cr2O7) and sulfuric acid (H2SO4) using heat and either potentiometric or colorimetric titration. The study used colorimetric titration method where 1gm of soil was used for each sample location. Double titration was conducted for each soil sample. Blank readings were taken to account for any impurities or contamination in the reagents used or in the laboratory environment. Two blank readings were taken for each set of 5 samples to ensure that any inconsistencies or errors are detected and corrected.

To calculate the SOC content, the following equation was used:

$$\% \text{ of Organic Carbon in Soil} = (B - T) \times f / W \times 0.003 \times 1.3 \times 100$$

Here, B and T represent the volume of potassium dichromate used for blank and sample titrations, respectively, f is the factor used for titration calculation, W is the weight of the soil sample, 0.003 is the molecular weight of carbon, and 1.3 is the correction factor for loss of carbon during the oxidation process. The SOC content is expressed as a percentage of the weight of the soil sample.

Results and Discussion

The figure below represents depth wise salinity level in parts per trillion across different geomorphic units. Observation of the data reveals that certain geomorphic units have high levels of salinity due to their proximity to and influence of seawater. The highest average salinity values found across various depths in the study area was in Creek which was 11.11 ppt. This was followed by Beach area which had average salinity value of 10.73 ppt. The Fringe Forest areas have average salinity value of 9.81 ppt. Barren area comes in next with average salinity value of 6.02 ppt while the Highland area had the lowest salinity value with 5.21 ppt (Figure 5).

The pH levels in the different geomorphic units revealed a different scenario as the highest average pH level was found in Fringe Forest areas with 7.48 followed by Creek with 7.39 pH level. Highland areas had pH level of 6.96 pH. Barren and Beach areas also have lower pH values compared to other geomorphic units. The average pH level of Barren areas is 7.06 while for Beach areas it is 6.86. Soil type of Fringe Forests, Creek areas have been slightly basic while the Beach, and Highland areas are slightly acidic. The soil type of Barren areas is somewhat neutral as the value is closer to neutral level 7 (Figure 6).

The table 2 highlights the different types of soil texture in different geomorphic units in the study area. Barren land stations in the study area predominantly exhibit sandy loam texture with Barren land station number 4 exhibiting silty loam texture. Beach stations uniformly consist of sandy texture, reflecting the characteristics of coastal environments. Creek stations exhibit a mix of Silty Clay Loam, Clay Loam and Silty Loam, suggestive of the fine-grained nature of soils typically found in and around proximity of water. Fringe forest station displays clay loam texture, indicating the soil composition here has a balanced mixture of sand, silt and clay conducive to support coastal vegetation. Highland station uniformly demonstrates Silty Clay Loam texture, implying soils here having high proportion of fine particles like silt and clay, and likely to be influenced by elevation and drainage pattern.

The soil organic carbon across various depths and station in Barren Land area of the study area shows the value ranged from 0.3 to 0.1 percent that reveals a distinct pattern and variability (Figure 7). This variation can also be seen in same station across various depths. Station 5 here had the highest amount of soil organic carbon at 0.3 percent at shallow depth (0 to 15 cm) while the lowest amount of

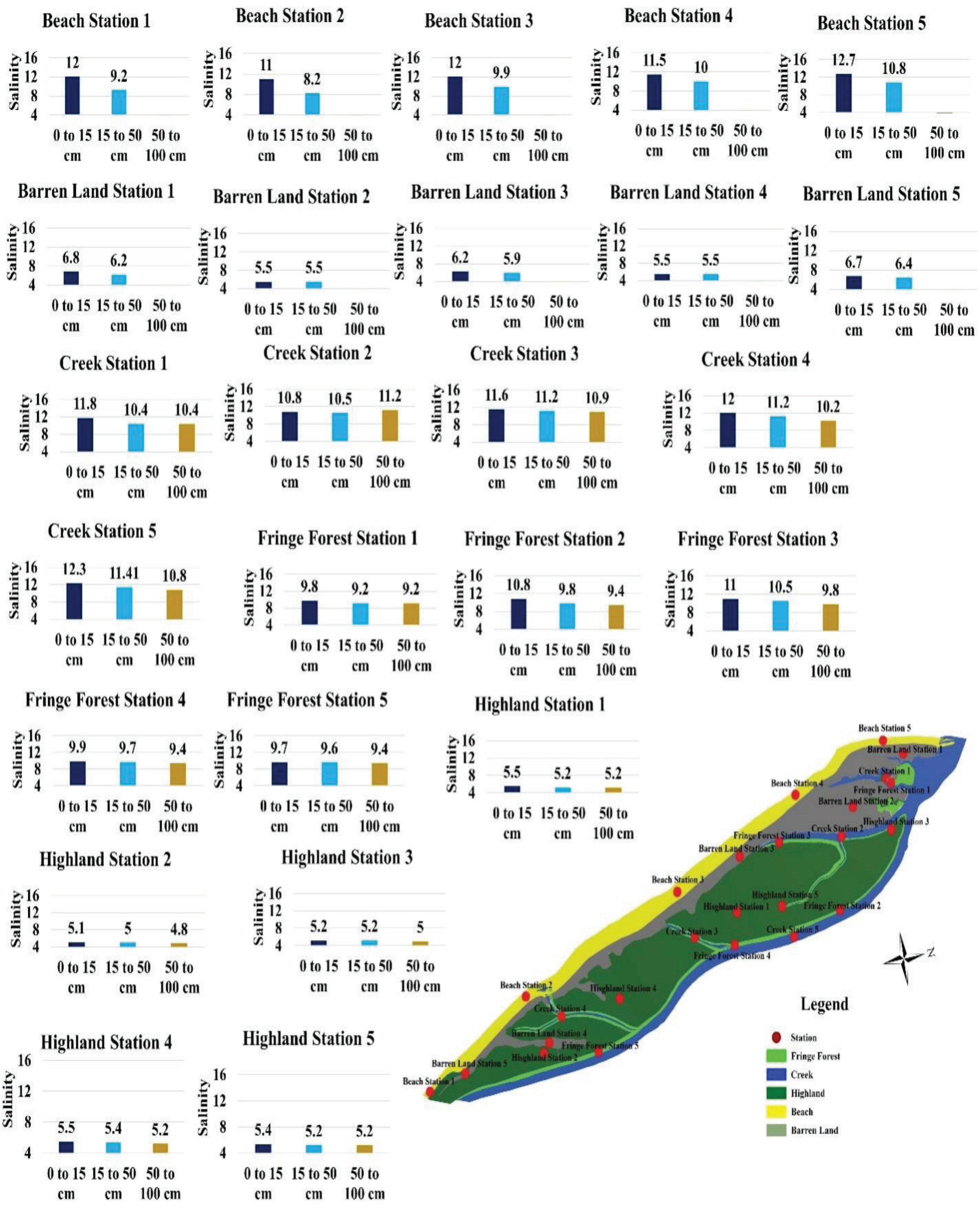

Figure 5. Soil salinity content (PPT) at various depths across different geomorphic units.

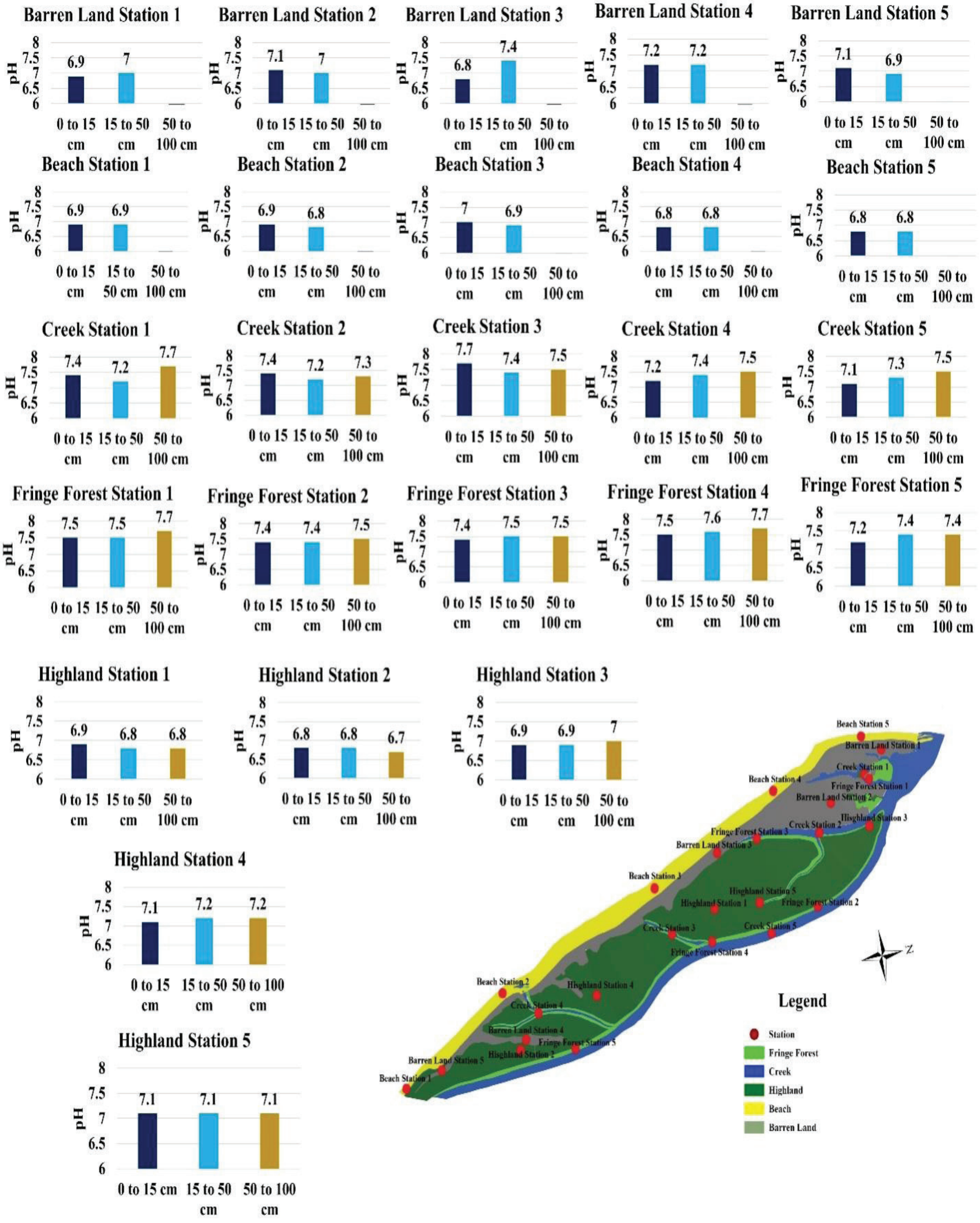

Figure 6. Soil pH level at various depths across different geomorphic units.

Table 2. Soil Texture across different geomorphic units in the study area

Texture	Geomorphic Unit
Clay Loam	Creek Station 2, Creek Station 4, Creek Station 5, Fringe Forest Station 1, Fringe Forest Station 2, Fringe Forest Station 3, Fringe Forest Station 4, Fringe Forest Station 5
Sand	Beach Station 1, Beach Station 2, Beach Station 3, Beach Station 4, Beach Station 5
Sandy Loam	Barren Land Station 1, Barren Land Station 2, Barren Land Station 3, Barren Land Station 5
Silty Clay Loam	Creek Station 1, Highland Station 1, Highland Station 2, Highland Station 3, Highland Station 4, Highland Station 5
Silty Loam	Barren Land Station 4, Creek Station 3

carbon at same depth was found 0.1 percent. At medium depth highest amount of organic carbon percentage was witnessed at station 3 and station 4 at 0.2 percent. In case of Beach area, variation of soc was witnessed across stations and across depth. The highest amount of SOC found here was 0.4 percent at shallow depth (0-15 cm) at station 2 while the lowest was at station 4 (0.1). However, at medium depth (15-50 cm) fairly consistent values are observed at station 1,4, and 5 with little variations at station 2 and 3.

Fairly high values of organic carbon percentage were observed across different stations in creeks of the study area. At shallower depth (0-15) cm, high value of organic carbon ranging between 2.35% to 2.14% was found. Moving deeper into the soil profile, at depths 15-50 cm the values of soil organic carbon varied between 1.8% to 0.94% and at depths 50-100 cm the values ranged between 1.5 to 0.72 percent. At the surface layer (0-15) cm, the organic carbon percentage range from 1.79% to 1.97%, with station 5 exhibiting highest value of organic carbon percentage. The value of soil organic carbon at the medium depth (15-50) cm ranged between 1.55% to 1.24% which is less than the values at the surface layer. Lastly, at depths of 50 to 100 cm, percentage of soil organic carbon varied between 1.25 to 0.97 with Station 1 having the maximum value and Station 4 having the minimum.

In Highland unit the value of soil organic carbon exhibits highest level of concentration with values ranging from 2.49 % to 1.7%. Elevated level of soil organic carbon presence was observed at shallow depth (0 to 15) cm with Station 2 having the highest value of 2.49 percent. At medium depth (15 to 50) cm, percentage range from 1.8% to 2.2 %, with Highland Station 2 having highest value. Similar observations were made at the depth of 50 to 100 cm where Highland Station 2 had the highest presence of soil organic carbon among the 5 different stations with 2.1%.

The observed variations in Soil Organic Carbon (SOC) concentration across various depths points out that higher concentration of organic carbon is present near the soil surface due to the decomposition of organic matter from plant litter and root exudates. As depth increases, organic carbon concentration declines due to reduced organic matter input and microbial activity, as well as potential leaching processes. The data from different geomorphic units, such as highland, fringe forest, creek, beach and barren land suggest spatial heterogeneity in SOC concentration within the mangrove ecosystem. This variation could be attributed to various environmental factors such as vegetation impact, hydrology, sedimentation rate etc. Highland areas had high level of organic carbon concentration due to the presence of different and dense vegetation which facilitated carbon generation through litter production, root biomass and decomposition rates. Creek areas also displayed high level of organic carbon concentration due to the effect of tidal flushing and allochthonous sources. The relationship between SOC and salinity is intricate and contingent upon various factors. High soil salinity impedes microbial activity and organic matter decomposition, slowing accumulation rates of SOC. In the present study, beach and barren land showed comparatively high level of salinity consistently and hence exhibited low organic carbon concentration levels. However, an exception was seen in the case of creek soil as it displayed higher SOC concentration despite having high degree of salinity. The presence of vegetation coverage around the creeks and sedimentation influence facilitated the autochthonous and allochthonous inputs of creek soil thus increasing its SOC

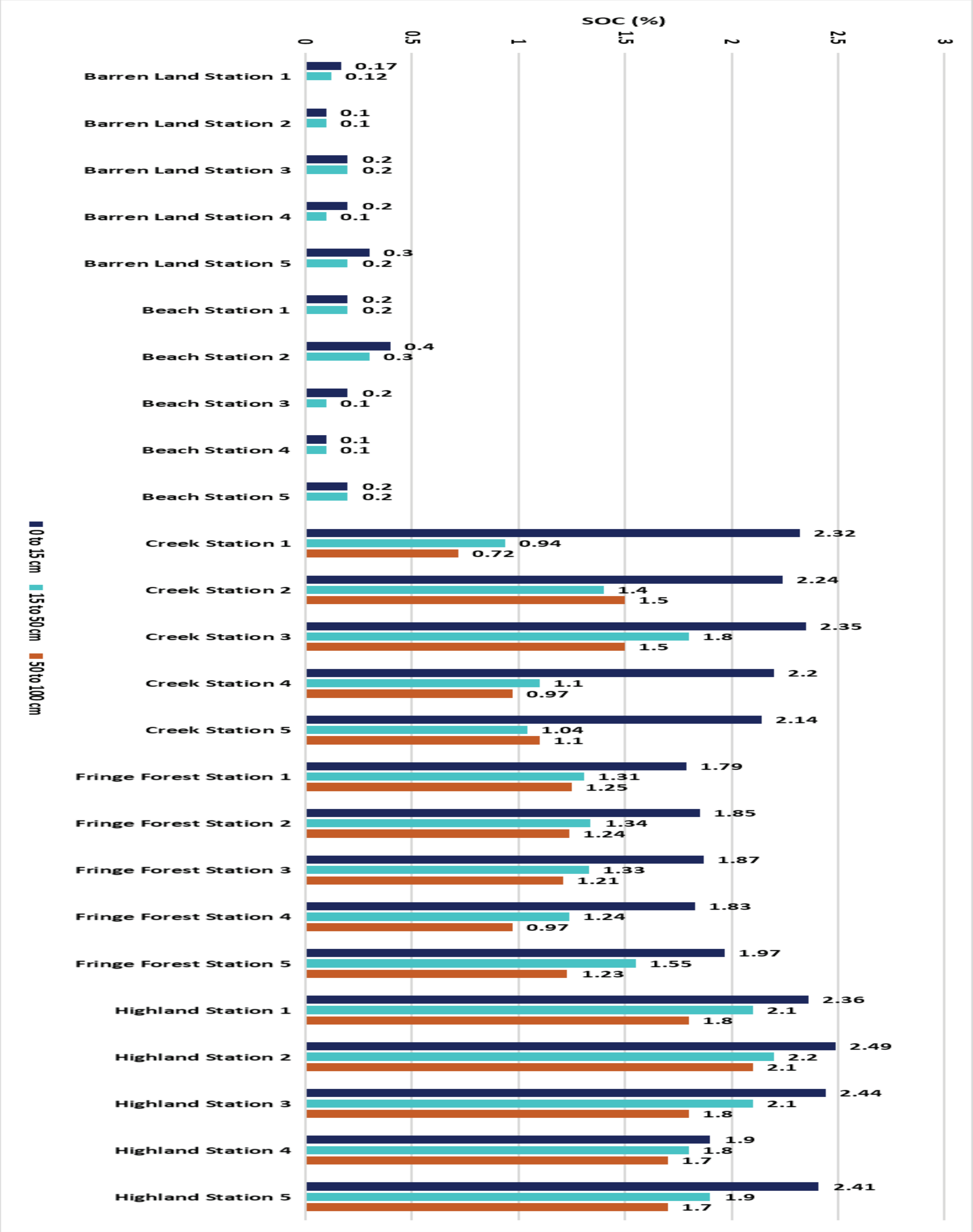

Figure 7. Soil Organic Carbon across different geomorphic units.

level. Soil pH and SOC content in mangrove ecosystem is pivotal and intricate with pH levels profoundly influencing SOC dynamics. Soil pH affects soil microbial activities, enzymatic process and decomposition rates, which play a critical role in organic matter turnover in soil leading to SOC accumulation. Soil generally having neutral to slightly acidic pH levels are conducive to optimal microbial activity and organic matter decomposition, leading to higher SOC concentration. In the present study, the organic carbon concentration in Highland areas is higher and the average pH level here is slightly acidic.

Soil Organic Carbon concentration is also influenced by soil moisture. Elevated soil moisture and saturated conditions have the potential to decelerate the decomposition rate of soil organic carbon (SOC) (Chapin III *et al*. 2012). Studies have shown that high long-term soil moisture can enhance SOC accrual by inhibiting microbial activity which results in reducing the decomposition or mineralization of organic matter in the soil. Additionally, soil moisture influences the physical protection of SOC within soil aggregates. Higher soil moisture levels can enhance aggregate stability, reducing the susceptibility of SOC to microbial degradation. In the present study, places without vegetation coverage such as beach and barren land have lower concentration of SOC. It is probable that soil drying leads to depletion of soil organic carbon (SOC) (Batson *et al*. 2015). Conversely, soil in the highland shows highest concentration of SOC due to vegetation coverage. SOC concentration in the fringe forest soil shows unusual pattern as per as moisture content is concerned. Though they have comparatively closer proximity to water bodies and moisture content than highland, they show a comparatively low concentration of SOC than the highland. This phenomenon arises from recurrent tidal fluctuations, supported by evidence indicating that frequent cycles of wetting and drying can elevate respiration rates and facilitate the release of organic carbon (West *et al*. 1992, Denef *et al*. 2001). SOC concentration decreases with increase in depth in creek, fringe forest and highland forest as soil moisture decreases with increase in sample depth, reiterating the influence of soil moisture on soil organic carbon content. Variations in grain size within geomorphic units may impact soil organic carbon (SOC) levels. Earlier research has suggested that the SOC levels may rise with greater distance from channel (Cierjacks *et al*. 2011). This association may potentially vary in accordance with grain size, wherein finer sediments deposited in both depositional and overbank environments may possess higher concentrations of organic carbon (Pinay *et al*. 1992, Cierjacks *et al*. 2011). Finer grain sizes are linked to increased organic carbon content due to enhanced capacity to stabilize organic carbon (Pinay *et al*. 1992, Jobbagy and Jackson 2000). Finer grain sizes exhibit greater moisture retention capability relative to coarser grain sizes (Dingman 2008). The present study showed beach and barren lands had sandy to sandy loam soil and hence lower concentration of SOC. Soil in highland is finer, which is Silty Clay Loam, than fringe forest which is Clay Loam and hence SOC concentration in the highland is higher than the fringe forest.

Conclusion

The comprehensive study attempts to unravel the intricate dynamics of Soil Organic Carbon concentration across various geomorphic units within the mangrove ecosystem of Dublar char. Through fieldwork, soil sampling and laboratory analysis, the study uncovered significant insights into the factors influencing SOC concentration, including geomorphic units, salinity, pH levels, soil moisture and grain size distribution. The quantification of SOC concentration across different geomorphic units highlights the influence of environmental factors such as vegetation, soil characteristics, hydrological process and sedimentation rates on organic carbon concentration. Furthermore, the relationship established between SOC with salinity, pH, soil moisture and grain size highlight the influence of these parameters in the soil organic carbon concentration of Dublar char. Overall, the research provides valuable insights into the complex interplay between geomorphic units, hydrological regimes and SOC dynamics. These hold significant implications for understanding the ecosystem health, resilience and carbon sequestration potential thereby informing climate resilient land management strategies. By elucidating the mechanisms driving SOC variations, the study contributes to the broader understanding of ecosystem functioning and highlights the importance of studies in the similar domain against the backdrop of growing concerns regarding climate change.

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