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Spatial variability of soil and carbon sequestration in the Ganges moribund delta of Bangladesh

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***Keywords*:** Carbon sequestration, Ganges moribund delta, Spatial soil variability

Abstract

This study investigates the spatial variability and controlling factors of soil organic carbon concentration (SOCC) and soil organic carbon density (SOCD) in the Moribund Delta, emphasizing their importance in carbon sequestration. A total of 25 soil samples were collected from five distinct land-use sites at varying soil depths. The distribution patterns of SOCC and SOCD showed substantial spatial variation, with the Sara sub-surface soils at the grassland site exhibiting the highest values—attributed to land-use differences—compared to other sites. Histogram analysis confirmed that soil organic carbon (SOC) stocks in the study area varied widely. Correlation analysis revealed positive relationships between SOCC and total nitrogen (TN), cation exchange capacity (CEC), soil bulk density, and clay content, highlighting their significance in carbon sequestration. Cluster analysis grouped soils into three distinct classes based on depth and organic carbon levels. Notably, Sara sub-surface soils acted as stronger SOC sinks, indicating the highest carbon sequestration potential. Principal Component Analysis (PCA) further demonstrated that SOCC is closely associated with fine-textured, nutrient-rich soils and negatively associated with sandy, nutrient-poor profiles. Overall, the findings underscore the vital role of deltaic soils in organic carbon storage and the need to improve soil fertility and organic matter management to maximize SOC sequestration—offering key strategies for climate change mitigation in vulnerable deltaic regions.

Introduction

The Ganges-Brahmaputra-Meghna (GBM) Rivers Delta, also referred to as the Ganges-Brahmaputra Delta or simply the Ganges Delta(1), began forming about 125 million years ago and continues to evolve(2). It covers approximately 115,000 km^2(3,4), making it one of the world's largest river deltas. The Moribund Delta, a distinct sub-region of the GBM system, lies between 22°10′ N–24°40′ N latitude and 88°00′ E–90°00′ E longitude. It spans about 29,500 km^2 across Bangladesh and parts of India, including Murshidabad, part of Nadia

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district, and the Bangladeshi districts of Meherpur, Chuadanga, Kushtia, and the northern part of greater Jashore district of Bangladesh[5,6,2]. Unlike the active portions of the delta, this area receives little to no flooding from the Ganges. Many of its rivers have either dried up or been abandoned. A sharp decline in the Gorai River's flow has caused at least seven of its 15 dependent rivers—Hisna, Kaliganga, Kumar, Kamkumra, Harihar, and Chitra—to become nearly dead, while the remaining eight are also in declining. These rivers have lost connection to their parent channels and receive neither freshwater nor silt during floods. Confined within high levees, they cannot flood adjacent land[7], leading to land build-up and the spread of moribund conditions[8]. The Moribund delta is defined by a network of silted, desiccated river channels that have been cut off from the main river systems over long timescales. Its flat terrain is dotted with abandoned channels and oxbow lakes. Rivers such as the Hisna, Kaliganga and Kumar have experienced sharp declines in discharge due to land-use changes, resulting in the desiccation of multiple channels and the emergence of semi-arid conditions with minimal seasonal flooding[9,10]. The reduced flow has significantly altered the region's alluvial soils, which were once enriched through regular sediment input. Today, these soils show increased clay (argillaceous) deposits, changes in texture, and reduced fertility due to the lack of freshwater siltation[11-14].

This study examines the physical and chemical properties of soils—specifically bulk density, clay content, nitrogen content, soil organic carbon concentration (SOCC), soil organic carbon density (SOCD), and soil organic carbon stock (SOCS)—at varying depths and spatial scales within the Moribund Delta. Due to the limited research on this fragile deltaic zone, the study highlights the importance of understanding soil characteristics at different depths for climate change mitigation. The findings aim to support sustainable land management (SLM) practices, enhancing soil resilience against climate change impacts in an increasingly vulnerable environment[12,15].

Materials and Methods

Ishwardi upazila of Pabna district and the Bheramara upazila of Kushtia district in Bangladesh were the focal areas of the study, located at the heart of the Moribund Delta. The sampling location and the digital elevation map (DEM) of the study area are presented in Figure 1. It is situated between latitudes 24°02'N and 24°07'N and longitudes 88°59'E and 89°04'E. The regions fall under a humid subtropical climate with average annual temperatures ranging from 16.5°C to 29.0°C and mean annual rainfall of approximately 1,488.7 mm[16]. Land use within the Moribund delta is dominated by the cultivation of staple crops, including paddy, wheat, sugarcane, betel leaf etc.

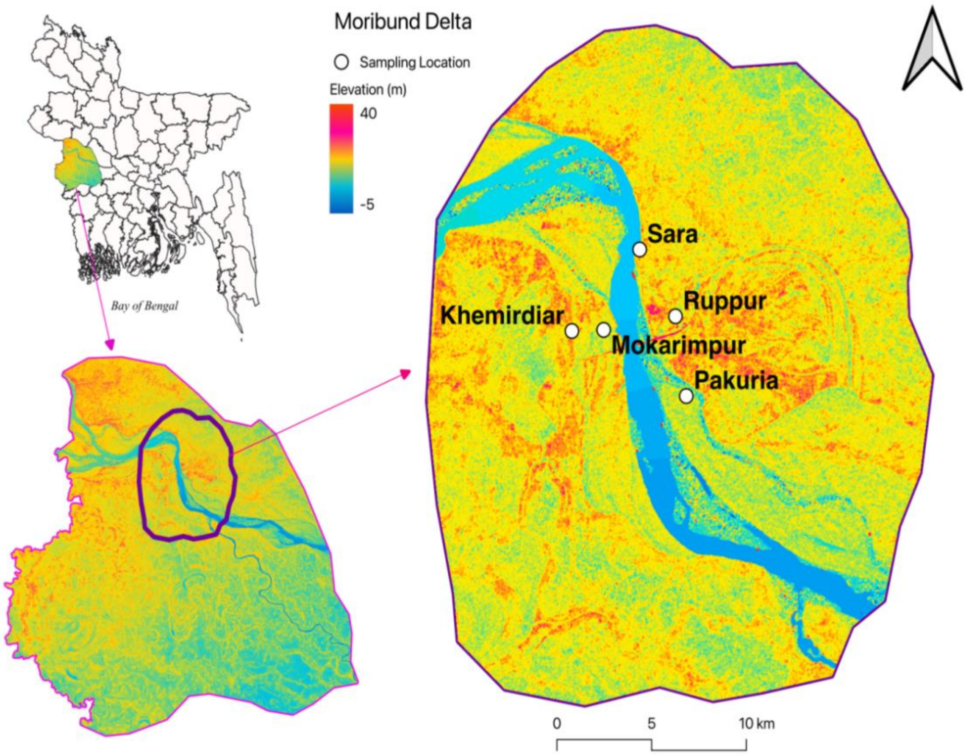

Fig. 1. Digital elevation map (DEM) of the sampling location of the Ganges Moribund Delta of Bangladesh.

The sampling covered five sites in the Ganges Moribund delta, namely Sara, Ruppur, Pakuria, Khemirdiar and Mokarimpur (Fig. 1). The land use of the sampling sites include grassland (Sara site), rice (Ruppur site), banana (Pakuria site), lichi (Khemirdiar site) and sugarcane (Mokarimpur site). At each site, a 1-meter depth soil profile was excavated and soil samples were collected at 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm depths. Each sample weighed 1 kg, collected using a spade and core sampler. A total of 25 soil samples were air-dried for a week, crushed and sieved through 2 mm and 0.5 mm mesh for physical and chemical analyses respectively. Moreover, 25 core samples were collected for soil bulk density analysis.

The current study involved measuring soil physical parameters of bulk density[(17)], particle size distribution[(18)]. The other parameters total nitrogen[(19)] and cation exchange capacity[(20)] was determined as reported. Soil pH was measured in soil: water suspension (ratio 1:2.5) using a pre-calibrated pH meter[(21)]. The organic matter contents of the soils were measured using Walkley and Black wet oxidation method[(22)]. The organic matter contents of the soils were calculated as SOCC multiplied by the Van Bemmelen factor of 1.73[(22)]. SOC concentration, SOC density and SOC stock were calculated using the formulas[(23,24)].

Results and Discussion

The distribution pattern of soil properties, soil bulk density (SBD), soil organic carbon concentration (SOCC), soil organic carbon density (SOCD) and soil organic carbon stocks (SOCS) in the Ganges Moribund delta of Bangladesh are presented in Fig. 2. SOCC revealed that substantial spatial variations from having lowest of 0.31 ± 0.1% in Pakuria site and highest of 0.962 ± 0.28% in Sara site, with an overall mean of 0.504 ± 0.313%. The highest SOCC was recorded in Sara site at 20-40 cm depths (1.22%), while the lowest was found in sample Ruppur site at 40-60 cm depths (0.13%). The average SOCD across the region was 0.0081 ± 0.0052 g C cm^{-3}. Sara site exhibited the highest soil organic carbon stock (30.9508 ± 7.2 Mg C ha^{-1}), while Pakuria site showed the lowest (9.6424 ± 3.43 Mg C ha^{-1}). The overall mean of SOC for the study area was 16.165 ± 10.28 Mg C ha^{-1}. The study indicated that the Sara site, at 20–40 cm soil depth, showed a higher organic matter content and therefore greater carbon sequestration potential. The higher SOC at the Sara site may primarily be due to its grassland habitat. Over time, the deposition of new alluvium on the surface above the grassland has contributed to an increase in SOC level at 20-40 cm soil depths.

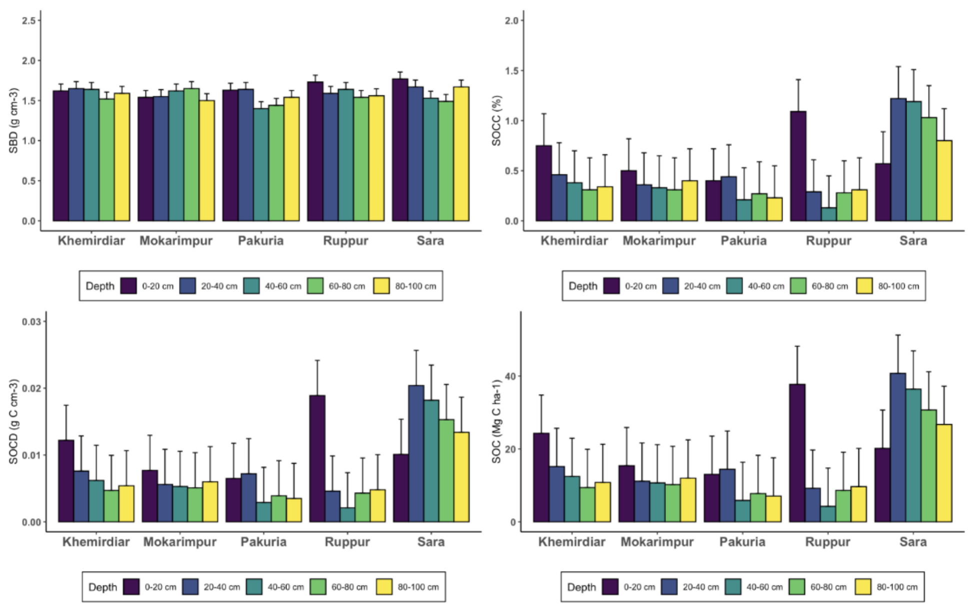

Fig. 2. Distribution pattern of soil bulk density (SBD), soil organic carbon concentration (SOCC), soil organic carbon density (SOCD) and soil organic carbon stocks (SOCS) in the Ganges Moribund Delta of Bangladesh.

Histogram of SOC stock of the Ganges Moribund delta showed (Fig. 3) that the SOC stock variations across the sites varied widely having minimum value of 4.264 Mg C ha^{-1}, maximum value of 40.748 Mg C ha^{-1}, with mean value of 16.165 Mg C ha^{-1}, whereas standard deviation of 10.489 Mg C ha^{-1} with variance of 110.028 Mg C ha^{-1}, and 64.89% coefficient of variance. The above analysis revealed that spatial variability SOC stock is extensive level.

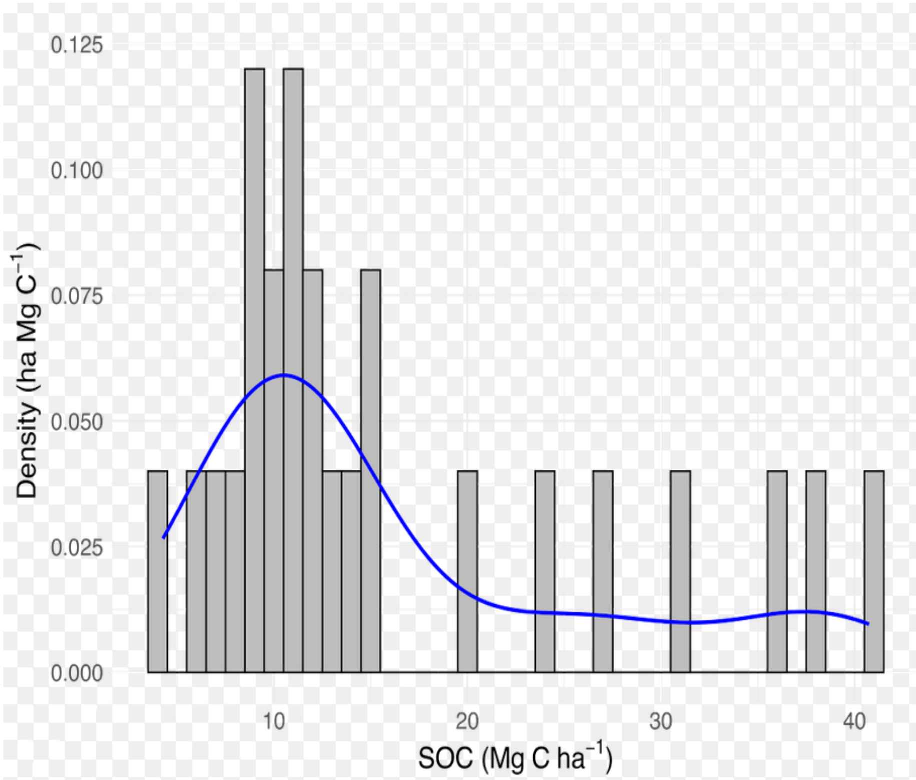

Fig. 3. Histogram of soil organic carbon stock (SOC) of the Ganges Moribund delta.

The correlation analysis of key soil properties (Fig. 4) provides crucial insights into its dynamics and interactions of SOCC, SBD, total nitrogen (TN), cation exchange capacity (CEC), pH, moisture, sand, silt, and clay. SOCC showed positive correlations with clay, SBD, TN and moisture content. It is also found that clay particles possess a positive role in retaining organic carbon in the soil aggregates. The strong positive correlations were found between CEC with TN that governs SOCC in enhancing in the carbon sequestration processes in the soils. Cation exchange capacity (CEC) is an important parameter that describes the adsorptive characteristics of soil(25) and it is influenced by the negative charges on the surfaces of clay minerals and organic carbon(26). In this connection, Zhou *et al.*(27) reported that the physical protection of aggregate particles is the main mechanism of newly added OC accumulation in several typical paddy soils in South China under good cultivation and fertilization, especially in paddy soils.

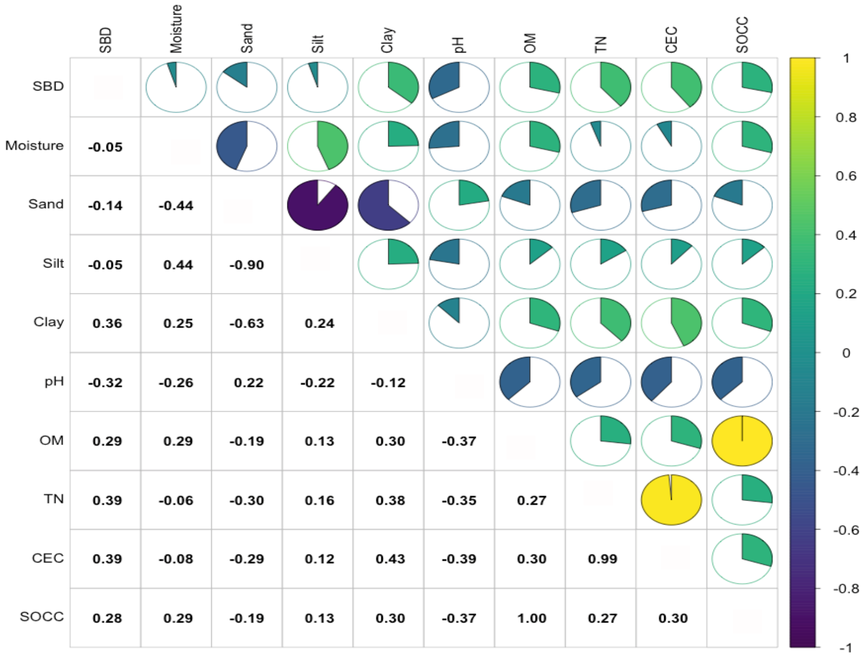

Fig. 4. Correlation analysis of soil physical, chemical and physicochemical properties of the Ganges Moribund delta of Bangladesh.

Hierarchical cluster analysis (Fig. 5), using Ward's method, grouped the soil samples into three distinct clusters based on similarities in soil properties. The first cluster (blue) includes deeper soil layers of Sara site at 80-100 cm, Mokarimpur site at 40-60 cm, Pakuria site at 40-60 cm, and Khemirdiar site at 60-80 cm, which exhibited lower SOCC and SOCD values, reflecting the reduced level of organic matter with lower carbon sequestration potential of deeper profiles. The second cluster (yellow) comprises intermediate and deeper layers of Mokarimpur site at 60-100 cm, Pakuria site at 20- 100 cm, Khemirdiar site at 20-100 cm, and Ruppur site at 60-100 cm with slightly higher level of SOCC and SOCD. The third cluster (red) groups shallow soil layers, including Sara site at 0-80 cm, Pakuria site at 0-20 cm, Khemirdiar site at 0-20 cm, Ruppur site at 20-60 cm, and Mokarimpur site at 0-40 cm depths are characterized by the highest level of SOCC and SOCD values. It is evident that SOCC in Sara site is 1.22 % at 20-40 cm soil depths with SOCD is 0.021%. It is more clearly evident that Sara sub-surface proximity sinks more organic matter and this site exhibits the highest carbon sequestration potential, with an SOC stock of 30.9508±7.209 Mg ha^{-1}. Similar observation of carbon sequestration was found in the sub-soil layers at depths below 30 cm[28,29]. It may be noted that most of the stable carbon belongs at depths below 30 cm due to the less disturbances by agricultural practices. The spatial variability of soil organic carbon takes place due to the variation of inundation land conditions and their management approaches[30].

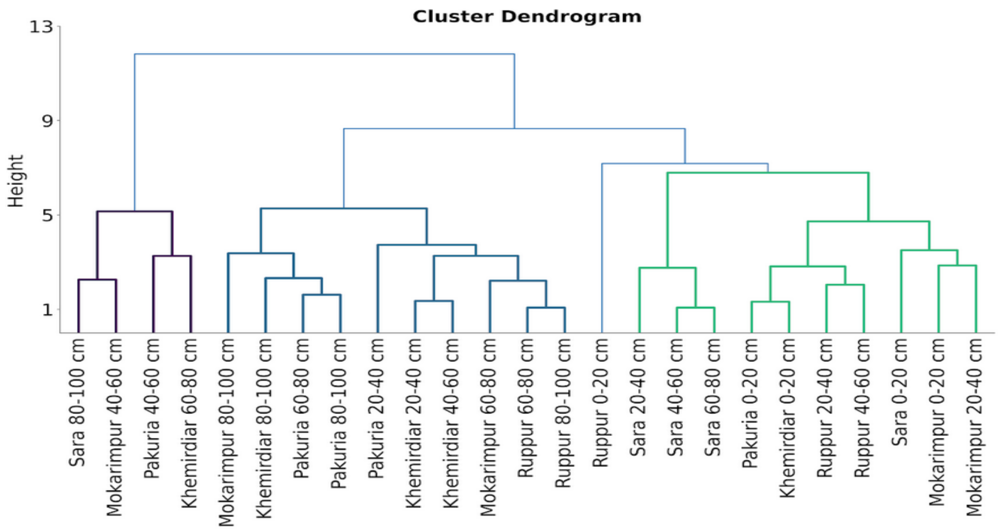

Fig. 5. Hierarchical cluster dendrogram of soils based on physical, chemical and physicochemical properties in the Ganges Moribund delta.

The Principal Component Analysis (PCA) analysis (Fig. 6) revealed that SOCC is strongly associated with high CEC, total nitrogen (TN), and clay content, as indicated by their negative loading on dimension-1 (where 38.5% of variance explained) as reported in correlation analysis also. In dimension -2 (where 21% of variance explained), based on their water retention and structural properties, with positive loadings for silt, moisture, and clay indicating soils with higher water-holding capacity, while bulk density aligns negatively, suggesting compacted soils retain less moisture. SOCC's position aligns with fine-textured, nutrient-rich, and moisture-retentive soils, while its negative relationship with sand underscores the limitations of sandy soils in carbon storage and fertility. These findings also emphasized the importance of nutrient and water holding capacity for enhanced carbon sequestration and enhancing soil health.

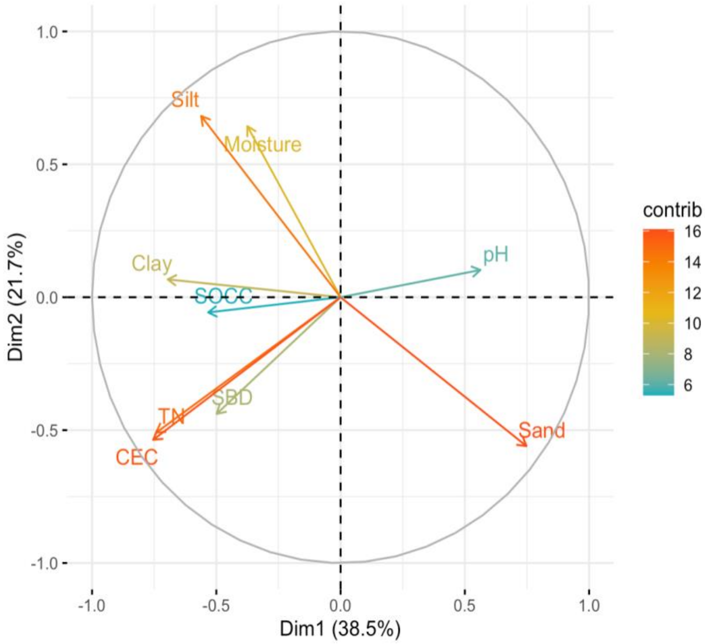

Fig. 6. Principal Component Analysis (PCA) biplot of soil properties in the Ganges Moribund delta, highlighting variance among sampling locations.

The findings revealed that significant spatial variability in SOC across the moribund delta, influenced by soil depth, clay contents and nutrient/water retention capacity. The correlation analysis demonstrated strong positive associations of SOCC with total nitrogen, CEC and clay content, highlighting their importance in enhancing soil fertility and organic carbon storage. Negative correlations with SBD and sand content indicate the challenges of organic matter retention in compacted and sandy soils. PCA reinforces these observations, showing that SOC is strongly associated with nutrient-rich, fine-textured soils and is limited in sandy, nutrient-poor soils. Cluster analysis supports this, grouping soils into distinct categories based on depth and organic carbon levels, with sub-surface soils exhibiting the highest potential for carbon sequestration and deeper layers showing reduced organic matter contents. These findings underscore the critical role of sub-surface soils in carbon storage and emphasize the need to enhance soil inherent capacity, fertility, and organic matter management to optimize SOC sequestration, foster sustainable soil health, and contribute to combating climate change effectively.

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