Spatial Soil Variability and Carbon Dynamics in the Moribund Delta of the Ganges of Bangladesh

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# **Abstract**

This study explores the soil properties and carbon dynamics of the Moribund delta in Bangladesh's Ganges floodplain, revealing significant spatial and textural variability. Bulk density varied between 1.4 to 1.77 g/cm³ (average 1.59±0.084 g/cm³), decreasing with depth due to higher organic matter content. The soils were predominantly silt-rich (58.08±13.122%), with sand at 14.72% and clay at 27.4%, influencing nutrient and water retention. Soil organic carbon concentration (SOCC) ranged from 0.31±0.1% in Pakuria to 0.962±0.28% in Sara, with a mean of 0.504±0.313%. Soil organic carbon density (SOCD) averaged 0.0081±0.0052%, while the highest SOC stock (30.95±7.21 Mg ha⁻¹) was found in Sara, indicating its potential for carbon sequestration. Principal Component Analysis (PCA) identified sand and pH as dominant factors in PC1 (42.5% variance), while clay and organic matter influenced PC2 (19.5% variance). Cluster analysis revealed three distinct soil groups: deeper profiles in Sara and Mokarimpur, mixed sites in Pakuria and Khemirdiar, and shallower samples from Ruppur and Sara. These findings underscore the importance of targeted soil management strategies to optimize carbon storage and soil fertility, highlighting the delta’s potential role in mitigating climate change through enhanced carbon sequestration.

# **1. Introduction**

The Bengal Delta, also known as the Ganges Delta, is the largest and one of the most dynamic river deltas in the world. This extensive delta spans the Bengal region of the Indian subcontinent, encompassing large parts of Bangladesh and the Indian state of West Bengal. Formed by the confluence of the Ganges, Brahmaputra, and Meghna river systems, the delta covers an area exceeding 105,000 km², with approximately 67% of its expanse located in Bangladesh and the remaining 33% in India. The delta has been dubbed the "Green Delta" due to its lush, fertile soils and abundant water resources, which have historically supported dense populations and diverse agricultural practices [Mydans, 1987; WorldAtlas, 2017]. The Ganges Delta is classified as an arcuate (triangle-shaped) delta and is characterized by its rich alluvial deposits, which consist of fine silt, sand, and clay, transported by rivers from the Himalayas and the Tibetan Plateau. Within the vast expanse of the Bengal Delta lies the Ganges Moribund Delta, a less dynamic subregion that stretches across the greater Kushtia, Chuadanga, Meherpur, Pabna, and Jashore districts of Bangladesh, as well as parts of the Murshidabad and Nadia districts in India [Chowdhury & Hassan, 2012]. Unlike the active sections of the delta, where rivers continuously shape the landscape, the Moribund Delta is characterized by a network of silted-up and desiccated river channels, which have lost their connection to the main river systems over time. This area has a relatively flat topography with numerous abandoned river channels and oxbow lakes, indicating a decline in fluvial activity. The Gorai-Madhumati River, a critical distributary of the Ganges, marks the western boundary of this floodplain. The region's rivers, such as the Hisna, Kaliganga, and Kumar, have seen a dramatic reduction in flow, leading to the desiccation of several channels, thus transforming the landscape into a semi-arid terrain with limited annual flooding [Islam, 1995; Brammer, 1996]. The soils of the Moribund Delta are largely composed of alluvial deposits that have accumulated over centuries, but the lack of regular sediment influx from the river systems has impacted the soil's physical and chemical properties. The reduction in freshwater flow, combined with reduced silt deposition, has led to changes in soil texture, nutrient content, and overall soil fertility. This has significant implications for agricultural productivity, water retention, and carbon sequestration in the region. Understanding these soil dynamics is crucial for sustainable land management, especially in light of increasing climatic variability and anthropogenic pressures on the delta's natural resources. Given the ecological and socio-economic significance of this region, this study aims to provide a comprehensive analysis of the physicochemical properties of soils within the Moribund Delta. Specifically, it explores soil bulk density, moisture content, particle size distribution, organic matter concentration, and nutrient content across different depths and locations. By assessing these parameters, the study seeks to understand the impact of hydrological changes on soil carbon storage potential, nutrient cycling, and overall soil health. The findings from this research will offer valuable insights into the management of soils in deltaic regions facing similar challenges, contributing to strategies for sustainable agriculture, land use planning, and climate change mitigation.

# **2. Materials and methods**

## **2.1. Study area**

The focus of this study is on the Ishwardi upazila of Pabna district and the Bheramara upazila of Kushtia district in Bangladesh, located within the heart of the Moribund Delta. These regions, situated between latitudes 24°02'N and 24°07'N and longitudes 88°59'E and 89°04'E, experience 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 [Khan, 2012]. The area's agrarian landscape is dominated by the cultivation of staple crops such as paddy, wheat, and sugarcane, along with horticultural produce like betel leaf and litchi. However, the altered hydrological conditions have increasingly posed challenges for agricultural sustainability, affecting soil quality, crop yield, and livelihoods.

**Figure 1. MORIBUND DELTA STUDY AREA MAP**

## **2.2. Sample collection and preparation**

The fieldwork and sampling covered five moribund delta sites in the Ganges Bengal delta: Sara, Ruppur, Pakuria, Khemirdiar, and Mokarimpur (Table 1). At each site, a 1-meter soil profile was excavated, with soil samples collected at 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm depths, labeled as Sample-1 to Sample-5. Each sample weighed 1-2 kg, collected using a spade and core sampler. A total of 25 soil and 25 core samples were air-dried for a week, crushed, and sieved through 2 mm and 0.5 mm mesh for physical and chemical analyses. The processed samples were stored in labeled plastic containers for further testing.

## **2.3. Sample analysis**

The current study involved measuring soil quality parameters, including physical parameters of Bulk density, Particle size distribution, Moisture content, and Textural class, as well as chemical parameters such as pH, Salinity (Electrical conductivity), SOC concentration, SOC density, SOC stock, Organic matter, Total nitrogen, and CEC.

Measurement of soil bulk density (SBD) was conducted using the core method detailed by Blake and Hartge (1986) and the equation [6]:

In this case, WOD stands for the oven-dry weight of soil (g) in the core, and Vt stands for the sample's total volume (cm3) in each core.

Using the hydrometer method as outlined by Gee and Bauder (1986), the particle size distribution (%Sand, %Silt, and %Clay) of the samples was evaluated [7]. The USDA soil texture triangle was utilized to ascertain the soil textural classes of the specimens [8]. The gravimetric method was used to determine the soil's moisture content, as per Reynolds (1970) [9]. Using a precalibrated pH meter as directed by Thomas (1996), the pH of the soil was ascertained from the prepared soil-water suspension [10]. A calibrated digital EC meter was used to measure the standard method of measuring soil salinity, also known as electrical conductivity (EC) [11]. The Micro-Kjeldahl equipment, as described by Bremner and Mulvaney (1982), was used to measure the total nitrogen (TN) in soil [14]. The method outlined by Schollenberger and Simon (1945) was used to assess the samples' cation exchange capacity (CEC) values using 1N ammonium acetate [15].

The Walkley and Black (1934) wet oxidation method, as reported by Nelson and Sommers (1982), was used to calculate the soil organic carbon concentration (SOCC) [12][13]. The SOCC values were counted using the following equation:

Where W is the weight (g) of soil used for the analytical procedure, B is the amount (mL) of 1N FeSO4 solution needed in the blank experiment, T is the amount (mL) of 1N FeSO4 solution needed in the experiment with soil samples, and f is the strength (N) of 1N FeSO4 solution measured from the blank experiment.

Using the following formula, which Nelson and Sommers (1982) indicated, the organic matter (OM) contents of the soil samples were also calculated as SOCC multiplied by the Van Bemmelen factor (1.72) [13].

According to Warren et al. (2012), the following equation was used to compute soil organic carbon density (SOCD), having Soil bulk density multiplied by soil organic carbon concentration [16]:

As stated by Donato et al. (2012), Batjes (1996), and Yu et al. (2007), the following equation was used to calculate the SOC Stocks of the mangrove ecosystem [17][18][19]:

# **3. Results**

## **3.1. Soil physicochemical properties**

Soil bulk density: The Moribund delta soils had a bulk density that ranged from 1.4 to 1.77 g/cm3, with an average of 1.59±0.084 g/cm3. It was discovered that the mean SBD values in soil profiles from several sample locations followed the decreasing trend as indicated by Figure 2a, with Sara (1.626±0.114 g/cm3) > Ruppur (1.612±0.076 g/cm3) > Khemirdiar (1.604±0.052 g/cm3) > Mokarimpur (1.572±0.061 g/cm3) > Pakuria (1.53±0.109 g/cm3).

Moisture content: With a mean value of 27.63±5.222%, the Ganges Moribund delta soils showed a range of moisture levels, from 10.98 to 36.97%. At the various sampling locations, the mean moisture content values of the various soil profiles were 30.372±5.298, 28.8±1.824, 25.016±8.542, 23.46±3.139, and 30.52±2.087% at Sara, Ruppur, Pakuria, Khemirdiar, and Mokarimpur, respectively.

Particle size distribution: Across all test sites, the Moribund delta soils displayed a comparatively silt-heavy distribution of particle sizes, with moderate amounts of clay-sized particles and a range of low to moderate amounts of sand-sized fractions. The average sand fraction was 14.72±16.452%, with a range of 2 to 59.5% throughout the sampling sites. On the contrary, the mean value of the clay fractions was 27.4±7.459% and varied between 15.5 and 45.5% among the study locations. 18±24.02% in Sara, 8.9±3.7% in Ruppur, 14.6±22.36% in Pakuria, 8.5±11.94% in Khemirdiar, and 23.6±15.99% in Mokarimpur were the average sand fraction values found in the sampling locations. The sampling locations' mean silt fraction values were observed in the increasing order of 24.5±4.54% in Mokarimpur, 25.5±6.37% in Khemirdiar, 26.5±7.2% in Sara, 26.5±11.54% in Pakuria, and 34±5.48% in Ruppur, respectively. Most of the soil particles were identified as silt-sized, with an overall mean of 58.08±13.122% and a range of 25 to 72.5%. The average clay fraction values in the studied soils were 24.5±4.54% in Mokarimpur, 25.5±6.37% in Khemirdiar, 26.5±11.54% in Pakuria, 34±5.48% in Ruppur, and 26.5±7.2% in Sara. A Silt Loam texture was found in the P-4, P-5, K-1, K-4, K-5, M-1, and M-2 layers of the soil profiles, while two unusual Silty Clay textured R-1 and P-2 and three Sandy Loam textured S-5, M-3, and P-3 were also observed. The remaining 13 moribund delta soil samples were associated with the Silty Clay Loam textural class.

Fig. X.

Soil pH: The pH levels in the Moribund delta soils of the Ganges delta ranged from 7.69 to 8.84, falling between the USDA's slightly alkaline (7.4-7.8), moderately alkaline (7.9-8.4), and severely alkaline (8.5-9.0) pH classes [20]. In the study region, the average pH was 8.23±0.244. The average pH of the various soil profiles was 8.044±0.26 in Sara, 8.216±0.139 in Ruppur, 8.284±0.137 in Pakuria, 8.388±0.096 in Khemirdiar, and 8.21±0.421 in Mokarimpur.

Electrical conductivity: The average EC value of the Moribund delta soils in the Ganges delta was 0.1328±0.0416 dS/m, with a range of 0.06 to 0.262 dS/m. The studied soil samples are designated as non-saline (0-2 dS/m) soils [21]. From the overall observation, Ruppur (0.1632±0.056 dS/m) > Sara (0.1458±0.0308 dS/m) > Pakuria (0.1329±0.049 dS/m) > Khemirdiar (0.112±0.0301 dS/m) > Mokarimpur (0.1101±0.0299 dS/m) was the descending order of the mean values of EC in soil profiles from different sampling locations.

Organic matter: In the Moribund delta soil profiles under study, the mean organic matter concentration varied from 0.534±0.18% at Pakuria to 1.66±0.47% at Sara. The other three soil profiles had mean organic matter contents in the increasing order of 0.654±0.13% at Mokarimpur, 0.718±0.66% at Ruppur, and 0.772±0.31% at Mokarimpur. The Moribund Ganges delta's average soil organic matter content was 0.87±0.54% overall, with OM percentages varying from 0.23 to 2.11%. The concentrations of organic matter varied from 0.69 to 1.88% in the upper layers and from 0.4 to 1.38% in the lower layers of the soil profiles under study.

Total nitrogen: With a mean value of 0.042±0.029%, the TN content percentages of the investigated soil samples ranged from 0.02 to 0.12%. Sara, Ruppur, Pakuria, Khemirdiar, and Mokarimpur displayed the respective mean TN content values of 0.034±0.01, 0.062±0.04, 0.04±0.03, 0.038±0.03, and 0.036±0.03% for the various soil profiles among the sampling locations.

Cation exchange capacity: The average CEC contents in various soil profiles from the sampling sites in Sara, Ruppur, Pakuria, Khemirdiar, and Mokarimpur were 2.278±1.07, 4.556±3.74, 2.772±2.15, 2.516±2.24, and 2.556±2.24 meq/100g, in that order. The Moribund delta soils' CEC levels ranged from 0.59 to 6.44 meq/100g, with a mean value of 2.94±2.333 meq/100g overall.

## **3.2. Soil organic carbon stock**

**Figure 2. a) Soil bulk density, b) Soil organic carbon concentration, c) Soil organic carbon density, and d) Soil organic carbon stocks in the Moribund delta region of Bangladesh**

The Moribund delta region of Bangladesh's Ganges deltaic floodplain ecosystem represents the trends in soil bulk density and soil organic carbon stock (SOCC, SOCD, and SOC Stock) displayed in Table 3 and Figures 2a–2d.

Soil organic carbon concentration: The soil profiles of the Moribund delta showed a range of mean SOCC values, from 0.31±0.1 to 0.962±0.28%. The study area as a whole had an overall mean SOCC value of 0.504±0.313%. The R-3 sample had the smallest SOCC value of 0.13%, while the S-2 sample had the largest SOCC value of 1.22% within the study region. As shown in Figure 2b, the mean SOCC values found in the five soil profiles were in the decreasing order of 0.962±0.28% in Sara, 0.448±0.18% in Khemirdiar, 0.42±0.38% in Ruppur, 0.38±0.08% in Mokarimpur, and 0.31±0.1% in Pakuria.

Soil organic carbon density: Within the study area, the S-2 sample had the greatest SOCD value of 0.0204%, while the R-3 sample had the lowest SOCD value of 0.0021%. For the whole study region, the mean SOCD value was 0.0081±0.0052% based on the mean SOCD measurements of the soil profiles in the Moribund delta region, which varied from 0.0048±0.0017% in Pakuria to 0.0155±0.0036% in Sara. As seen in Figure 2c, the mean SOCD values for the remaining three soil profiles were 0.0069±0.0061% in Ruppur, 0.0072±0.0027% in Khemirdiar, and 0.0059±0.0059% in Mokarimpur.

Soil organic carbon stock: The SOC stock values in different depths of the Moribund delta soil profiles have been observed ranging from 20.178 to 40.748 Mg ha−1 in Sara, 4.264 to 37.714 Mg ha−1 in Ruppur, 5.88 to 14.432 Mg ha−1 in Pakuria, 9.424 to 24.3 Mg ha−1 in Khemirdiar, and between 10.23 and 15.4 Mg ha−1 in Mokarimpur. The average SOC stock values were found to be highest in Sara and lowest in Pakuria, with the values falling in the following order: Sara (30.9508±7.209 Mg ha−1) > Khemirdiar (14.436±5.2914 Mg ha−1) > Ruppur (13.8992±12.0628 Mg ha−1) > Mokarimpur (11.8964±1.8469 Mg ha−1) > Pakuria (9.6424±3.4254 Mg ha−1), as presented in Figure 2d. A mean SOC stock of 16.165±10.2775 Mg ha−1 was obtained for the entire study region under the Moribund Ganges deltaic floodplain ecosystem.

## 3.3. Correlation Studies

Correlation analysis of soil properties of the soils revealed significant relationships among bulk density, moisture, pH, and organic matter (Figure 4). Notably, clay and electrical conductivity (EC) were positively correlated with bulk density and total nitrogen (TN), indicating a link between soil texture and nutrient retention. Conversely, sand showed a strong negative correlation with silt and clay. The graphical plot highlights these interactions, providing insights into how soil properties influence carbon storage in mangrove ecosystems.

## 3.4. Principle Component Analysis

PCA was conducted to explore soil property variations across sampling sites in the Moribund delta, with the first two components explaining 62% of the total variance (PC1: 42.5%, PC2: 19.5%). The biplot (Figure X) shows that Sand and pH heavily influence PC1, while Clay and Organic Matter (OM) are more aligned with PC2. Clusters of sampling locations, such as Khemirdiar (linked with sand) and Mokarimpur (associated with clay and OM), reflect distinct soil characteristics, likely due to environmental or anthropogenic factors. These insights highlight how localized variations in soil composition may inform targeted soil management practices in the delta region.

## 3.5. Cluster Analysis

Cluster analysis using Ward's method was conducted to classify soil samples from the Moribund delta into distinct groups based on similarity in soil properties. The resulting dendrogram (Figure X) reveals three main clusters. The first cluster (blue) groups samples primarily from Sara and Mokarimpur at depths of 40–100 cm, indicating similar soil characteristics at these deeper levels. The second cluster (yellow) includes mixed locations such as Pakuria and Khemirdiar across various depths, suggesting moderate homogeneity among these sites. The third cluster (red) contains Ruppur and Sara samples from shallower depths (0–40 cm), reflecting unique soil properties in the upper layers. These clusters provide insight into depth-specific and location-based soil variations, which can inform targeted management strategies in the delta.

# **4. Discussion**

The soil analysis in the moribund delta of Bangladesh’s Ganges floodplain shows diverse physicochemical interactions, with bulk density ranging from 1.4 to 1.77 g/cm³ (average 1.59±0.084 g/cm³), generally decreasing with depth, indicating higher organic matter and lower compaction. Sara recorded the highest bulk density (1.626 g/cm³), while Pakuria had the lowest (1.53 g/cm³), suggesting variability in carbon retention potential. Soils were predominantly silt-rich (58.08±13.122%), with sand at 14.72% and clay at 27.4%. Sara had higher sand content, while Mokarimpur was clay-heavy, which correlated positively with total nitrogen (TN) and electrical conductivity (EC). TN averaged 0.042% and EC 0.1328 dS/m, with clay enhancing nutrient retention. Sand was inversely related to silt and clay, indicating distinct soil textural zones affecting water and nutrient retention. Soil organic carbon concentration (SOCC) exhibited spatial variability, with mean SOCC values ranging from 0.31±0.1% in Pakuria to 0.962±0.28% in Sara, resulting in a regional average of 0.504±0.313%. The highest SOCC (1.22%) was observed in sample S-2, and the lowest (0.13%) in sample R-3. Soil organic carbon density (SOCD)followed similar trends, with an average of 0.0081±0.0052% across sites, peaking at 0.0204% in sample S-2. SOC stockvalues varied across depths and locations, with Sara exhibiting the highest average (30.9508±7.209 Mg ha⁻¹) and Pakuria the lowest (9.6424±3.4254 Mg ha⁻¹), reflecting localized conditions' influence on carbon storage potential. Principal Component Analysis (PCA) indicates that PC1 (42.5% variance) is influenced by sand and pH, while PC2 (19.5% variance) is aligned with clay and organic matter. Sampling locations such as Khemirdiar (linked with sand) and Mokarimpur (with clay and organic matter) cluster based on distinct soil characteristics, suggesting that environmental or anthropogenic factors play a role in soil variability. Cluster analysis further identifies three groups: deeper layers (40–100 cm) in Sara and Mokarimpur, indicating consistent properties at depth; mixed sites in Pakuria and Khemirdiar; and shallower samples (0–40 cm) from Ruppur and Sara, highlighting unique surface characteristics. In conclusion, the soil properties of the moribund delta in Bangladesh’s Ganges floodplain exhibit significant spatial and textural variability, influencing nutrient retention and carbon storage capacities. Bulk density patterns, silt-dominated texture, and the correlations between clay, total nitrogen, and electrical conductivity highlight the region's heterogeneity, impacting soil fertility and carbon dynamics. Notably, higher soil organic carbon concentration (SOCC) and stock in areas like Sara emphasize the potential for targeted soil management strategies to enhance carbon sequestration. The findings underscore the importance of site-specific approaches, considering both surface and subsurface soil characteristics, to optimize soil health and carbon storage in deltaic environments.

# **References**