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Pedogenic influence on profile distribution of total and DTPA - extractable micronutrients in rice growing hydric soils of Majuli river island, Assam, India

Influencia edáfica sobre la distribución de micronutrientes totales y extraíbles con DTPA en el perfil de suelos hidromorfos cultivados con arroz en la isla fluvial Majuli, Assam, India

Influência da pedogénese na distribuição da concentração total e extraível com DTPA de micronutrientes no perfil de solos hidromórficos cultivados com arroz na ilha fluvial de Majuli, Assam, Índia

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ABSTRACT

The rice-growing river floodplain ecosystems of Majuli island, India, have been recognized as a biodiversity hotspot with a high degree of variability in geomorphological forms and geochemical conditions for trace metals in hydric soils. Ten hydric soil series in rice-growing soils of Majuli island were studied with the aim of understanding the pedogenic influence on distribution and content of total and diethylenetriamine penta acetic acid (DTPA) extractable micronutrient cations (Fe, Mn, Cu and Zn) and their enrichment levels. The correlation analysis showed that these cations were closely linked with soil texture, organic carbon, cation exchange capacity and pH levels. The multiple regressions and cluster analysis was employed to identify the effect of river fed deposits on distribution pattern and lithological enrichment of metals. The contamination status was assessed through quantitative indexes with reference material. The negative geo-accumulation index values were used to conclude that these soils had been practically unchanged by anthropogenic influences. They showed moderate Cu contamination but were otherwise unpolluted (Pollution load index < 1) with respect to total elements under study.

RESUMEN

Los ecosistemas de llanura de inundación cultivados con arroz en la isla fluvial Majuli (India) se reconocen como un punto importante de biodiversidad, con elevada variabilidad geomorfológica y geoquímica para la distribución de metales traza en suelos hidromorfos. Se estudiaron diez suelos hidromorfos bajo cultivo de arroz con el objetivo de evaluar la influencia edáfica en la distribución y el contenido de micronutrients (Fe, Mn, Cu y Zn) totales y extraíbles con ácido dietilentriamina penta acético (EDTA) y sus niveles de enriquecimiento. Los análisis de correlación mostraron que la concentración de estos cationes estaba marcadamente asociada con la textura del suelo, el contenido en carbono orgánico, la capacidad de intercambio catiónico y el pH. Se realizaron análisis de regresión múltiple y cluster para identificar el efecto de los depósitos fluviales sobre los patrones de distribución y el enriquecimiento litológico de los metales. El estado de la contaminación se evaluó a través de índices utilizando material de referencia. Los valores negativos del índice de geo-acumulación indicaron que estos suelos prácticamente no habían sido modificados por la influencia humana. A pesar de que presentaban una contaminación moderada por Cu, no estaban contaminados (índice de contaminación < 1) con respecto a los elementos totales estudiados.

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RESUMO

Os ecossistemas da planície de inundação, onde se cultiva arroz, na ilha fluvial Majuli (Índia) têm sido reconhecidos como um hotspot de biodiversidade, com um alto grau de variabilidade geomorfológica e geoquímica, para a distribuição de metais vestígiais em solos hidromórficos. Estudaram-se dez solos hidromórficos onde se cultiva arroz com o objetivo de avaliar a influência da pedogénese na distribuição e concentração total e extraível com dietilenotriamina penta acético ácido (DTPA) de micronutrientes (Fe, Mn, Cu e Zn) e dos seus níveis de enriquecimento. As análises de correlação mostraram que a concentração destes catiões estava correlacionada com a textura do solo, com a concentração de carbono orgânico, a capacidade de troca catiónica e os valores de pH do solo. Realizaram-se análises de regressão múltipla e de cluster para identificar o efeito das características litológicas dos depósitos fluviais nos padrões de distribuição e de enriquecimento dos metais. O estado de contaminação foi avaliado através de índices quantitativos utilizando material de referência. Os valores negativos do índice de geo-acumulação indicam que estes solos não foram significativamente modificados por influência humana. Embora apresentem contaminação moderada em Cu, os solos, relativamente à concentração total dos elementos estudados, não estão contaminados (índice de contaminação < 1).

KEY WORDS
Clustering, colour indices, floodplains, paddy soils, contamination assessment.

PALABRAS CLAVE
Clustering, índices de color, llanuras de inundación, arrozales, evaluación de la contaminación.

PALAVRAS-CHAVE
Clustering, índices de cor, planícies de inundação, arrozais, avaliação da contaminação.

1. Introduction

Micronutrient research in India began with the report of *Khaira* disease in rice growing *tarai* soils of Pantnagar (Nene 1966). Later, the iron and manganese deficiencies were reported in coarse textured and low organic matter alluvial soils of the Indogangetic plains (Takkar and Nayyar 1979, 1981). The depletion in reserves of micronutrients in the country is attributed to the growth of high yielding varieties, use of high grade NPK fertilizers, and increased irrigation and cropping intensites over the last four decades (Singh 2008). The deficiency of micronutrients has become a major constraint in optimizing crop productivity and soil sustainability (Alloway 2008; Shukla et al. 2014). The availability of micronutrients in soil is dependent on the parent material, pedogenic processes and soil management techniques that may promote in some cases a reduction of cationic micronutrient contents (Pegoraro et al. 2006). The total content of micronutrients per se is a poor predictor of plant supply and micronutrient availability, although recommended DTPA critical limits delineate the occurrence of micronutrient deficiencies on large scale (Katyal and Sharma 1991). Earlier, benchmark soils were considered to explain the variability of micronutrient distribution in relation to soil taxonomy, agroclimate, profile development and soil processes on the Indogangetic plains of India (Sharma et al. 2000). In recent times, systematic surveys using GIS revealed micronutrient distributions and the extent of deficiencies in different areas of India (Minakshi et al. 2005; Shukla et al. 2015; Shukla et al. 2016a, 2016b).

Majuli, one of the largest river islands in the world with an area of 92,460 ha, supports 15.53% (0.16 million) of the population of the Jorhat district, Assam, India. The island has a low cropping intensity (ratio of total cultivated area to net sown area and multiplied by 100) i.e. 102% with an average productivity of rice of 487 kg ha^{-1} in the post-rainy season (November-February) and 1,325 kg ha^{-1} in the rainy season (June-November), compared to a district average productivity of 1700 kg ha^{-1}. One of the reasons for the lower productivity is the imbalanced use of NPK fertilizers and micronutrient deficiencies (Bhaskar and Sarkar

2013). It was estimated that about 34% of the soils of Assam were deficient in Zn (Takkar 1996) and that 44% and 34% of the alluvial and lateritic soils were deficient in boron, respectively (Borkakati and Takkar 2000). The micronutrient status of major paddy growing acid soils of India was reported by Behera and Shukla (2013). Later on, micronutrient contents of 270 georeferenced surface samples of Lakhimpur district, Assam were collected, and it was reported that 29.6% of soils were deficient in Zn. The soil pH, organic carbon, clay and cation exchange capacity are the main contributing factors for variability of micronutrient status in the soils (Bhuyan et al. 2014). The patterns of floodplains in Majuli River Island are subjected to annual seasonal floods that cause lateral and overland flood inundation and relatively slow physical turnover rates of habitats (Tockner et al. 2010). The flood pulse concept (FPC) suggested the pulsing of river discharge to be a major driving force that determines trace metal distribution across river-floodplain gradients (Junk 2004; Thorp et al. 2006; Schulz-Zunkel and Krueger 2009; Tockner et al. 2000). The flood plains of Brahmaputra river are crucial because of the complex mosaic of habitat patches differing in productivity, soil organic matter and seasonal heterogeneity of sinks and sources of micronutrients (Eisenmann 2002; Balabanova et al. 2016). So far random surveys mostly confined to to upper 30 cm were reported but vertical distribution of micronutrient status is poorly documented and understood with respect to climate and vegetation. We hypothesized that the influence of seasonal floods in the Brahmaputra valley could be a major determinant of variations in the vertical distribution of micronutrients in relation to textural stratification. This study was carried out to probe the answers to the questions like: What are the general vertical patterns of micronutrient forms with depth and the effect of soil texture in depositional landscapes of Brahmaputra valley? The aim of this paper is to provide preliminary answers, based on soil data sets for Majuli Island. The specific objectives of this study are (i) to study the soil properties and micronutrient distribution in hydric soil profiles, (ii) to examine the relationship among soil properties and micronutrient contents and (iii) to assess the lithogenic and anthropogenic influence on micronutrient distribution in the riverine floodplains of Majuli river island basin. The study provides baseline data regarding the distribution and accumulation of the selected metals in the soil, offers recommendations for the best management of the native soil resources, and provides information about the distribution of micronutrients in ecologically sensitive riverine wetlands of Majuli.

2. Material and Methods

2.1. Study area

The Majuli island (93°30'-94°35' E and 26°50'-27°10' N) is located in the north of the Jorhat district of Assam, India. The elevation varies from 60 to 85 m above mean sea level. The island is bounded by three major rivers viz., Kherkutia *Suti*, Subansiri and the Brahmaputra (**Figure 1**) and is marked by 70 *bils* (local name for small ponds). *Majuli* is one of the largest riverine islands in the world with a population of 0.16 million people. The literal meaning of '*Majuli*' is the land locked between two rivers, and it developed as the consequence of the sediment load redistribution that represents remnant floodplain after sudden channel diversions and a branching (Latrubesse 2008). Formation of Majuli-like landforms is attributed due to the variability in the sediment dispersal pattern or neotectonic influences and of course interplays of both (Takagi et al. 2007). The alluvium of the "Brahamaptura Arch" has a time span from upper Pleistocene to upper Holocene (Geological Survey of India 1989). The geomorphic history of the region reveals that formation of Majuli island in the late part of the 17th century was probably due to a series of frequent earthquakes and attendant floods that occurred during the period 1661-1696 as stated by Bhuyan (1968). Two major earthquakes of magnitude 8.7 on the Richter Scale (M) occurred in 1897 and 1950. Five more earthquakes above 7.0 M have taken place since 1930 together with

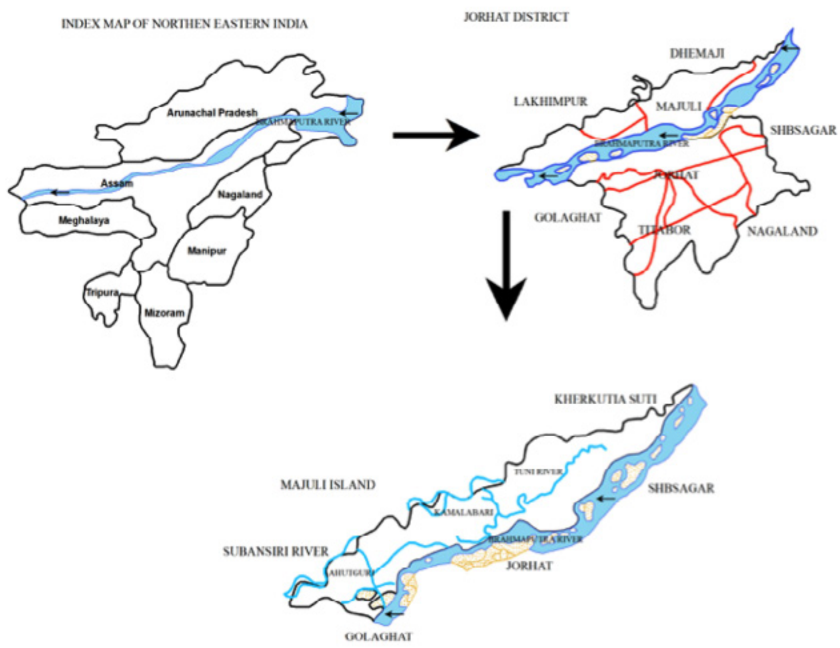

Figure 1. Location map of Majuli island.

numerous earthquakes of smaller magnitude (Valdiya 1987). Movements along active basement faults caused tilting of the recent alluvium, leading to shifts in the courses of many rivers (Sarma and Phukan 2004; Sarma 2005). Morphometric evolution of these islands has involved three stages- pre-bypass uplift, Majuli formation and abandonment. The Majuli Island in the Brahmaputra valley is presently passing through the abandonment stage and is gradually being incorporated into the flood plain of the valley (Lahiri and Sinha 2014).

Majuli Island experiences a subtropical monsoon climate with aquic/udic soil moisture regime and hyperthermic soil temperature regime. The island supports the growth of evergreen, semi-evergreen and deciduous trees, grasses and marshy vegetation (Bhagabati 2001). The grasses in wetlands include *Phragmites karka* Retz, *Arundo donax* L., *Chrysopogon aciculatus* Retz, *Imperata cylindrical* L., *Cynodon dactylon* L. and *Vetiveria zizaniodes* L. The marshy vegetation includes *Eichhornia crassipes* Mart., *Pistia stratiotes* L., *Nymphaea nouchali* Burm f., *Nelumbo nucifera* Willd, *Trapa bispinosa* Roxb, *Euryale ferox* Salisb., *Cyperus rotandus* L., *Alisma plantago* L., *Polygonum hydropiper* L., *Alpinia allughas* Retz, and *Ipomoea reptans* L.

2.2. Field survey

The IRS-ID (Indian Remote Sensing Satellite) geo-coded satellite images of 18th January, 2003 were visually interpreted (Jensen 1986) and seven geomorphic units delineated (**Figure 2**) in the floodplains of Majuli island as per the classification of Nanson and Croke (1992). The pinkish with red tones (mustard fields during winter season) in the middle of the island indicate the flat to gently sloping active floodplains whereas light blue with whitish tones, fine textured and associated with dark blue tones of water bodies indicate old alluvial plains. The tall grasslands of natural levees occurring along the river course have dark red tones with regular linear features of fine textures whereas flat featureless channel-fills in low-lying areas have light bluish with white tones with laminar rippled textural differences. The most conspicuous feature is the unvegetated sand bars in the meandering reaches of island that have white tones, whereas tall grasslands have bright red tones. The low lying water bodies

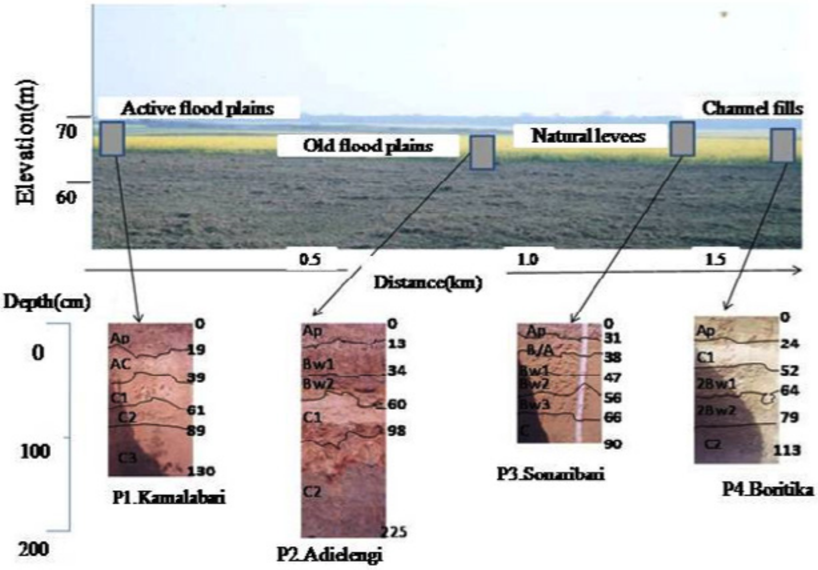

Figure 2. Soil-landscape relationships in Majuli island.

in swamps have dark blue tones whereas abandoned channels have whitish blue tones. The reconnaissance soil survey was carried out on a 1:50000 scale as per procedures outlined (Soil Survey Division Staff 1995) and latitude and longitude were recorded with the help of hand held GPS. The soil data set in Majuli island (1:50000 scale) was obtained from the soil resource inventory on a 1:50000 scale using Indian Remote Sensing (IRS-ID) satellite imagery and corresponding toposheets of Survey of India with the emphasis on transects that cut across the segments of inland valleys from the top to the bottom (Bhaskar et al. 2008).

Ten paddy-growing hydric soil series identified during reconnaissance soils survey of Majuli island were selected based on histories of paddy cultivation, parent materials and topography on five alluvial plains of Brahmaputra such as active flood plains (P1-Kamalabari, P2-Puranibari, P3-Dakshinpat), sand bars (P4-Majuli, P5-Garumara), swamps (P6-Bongaon), old flood plains (P7-Adielengi, P8-Chilkala) and channel fills (P9-Gayangaon, P10-Boritika). The soil of different series was diversely developed on the source of parent material, the texture sequence in the profile and the drainage. The typic pedons representing of ten soil series were described as per the guidelines given by Schoeneberger et al. (2012) and were classified in the subgroups of Entisols and Inceptisols as per Soil Survey Staff (2014).

The soil colour indices were computed using the following formulae:

(Eq.1) Redness rating (RR) (Torrent et al. 1983) = (10-H) x C/V

Where H = number preceding YR in Munsell hue (10YR = 0, 7.5YR = 2.5, 5YR = 5, 2.5YR = 7.5, 10R = 10 and 7.5YR = 12.5), C = chroma, V = value

- Colour indices (Evans and Franzmeier 1988)

(Eq.2) C1h = (matrix abundance x matrix index) + (mottle abundance x mottle index) + (argillan abundance x argillan index): (1 = argillan abundance) where the index is based only on chroma.

(Eq.3) C2h = (matrix abundance x matrix index) + (mottle abundance x mottle index) + (argillan abundance x argillan index): (1 = argillan abundance) where the index is based on hue and chroma.

2.3. Laboratory analysis

The horizon-wise soil samples were collected for laboratory analysis. The samples were air-dried, ground and passed through a 2 mm sieve for analysis of physical and chemical properties and micronutrient contents. Each sample was tested for the presence of carbonates using cold 1 M HCl, and if carbonates were present, the sample was treated with 0.5 M sodium acetate at 75 ºC for at least 1h. After acetate treatment, samples were washed with deionized water. These soil samples were further pre-treated by destroying organic matter using H_2O_2 (30%, w/w) at 65 ºC. After pretreatment, all samples were dried at 105 ºC for 24h. Prior to particle-size analysis, all soil samples were dispersed in sodium hexametaphosphate solution and shaken for 24h to destroy aggregates. For the pipette analysis, they were wet sieved with the hexametaphosphate solution at 1000-500, 250, 125 and 53 µm mesh sizes. The material smaller than 53 µm was analyzed by the pipette method (Gee and Bauder 1986). To obtain particle-size classes between 2 and 50 µm, sedimentation techniques based on Stoke's law were used. The pH of the soil samples was determined in 1:2.5 soil:water ratio. The suspension was stirred intermittently with a glass rod for 30 minutes and left for one hour. The combined electrode was inserted into supernatant and pH was recorded. The quantity of organic carbon in the soil was estimated by using Walkey-Black method (Walkey and Black 1934). Finally ground dry soil sample (1 g) was passed through a 0.5 mm sieve without loss and was placed in a 500 mL conical flask. To this 10 mL of 1 N potassium dichromate and 20 mL con. H_2SO_4 were added and the contents were shaken for a minute and allowed to set aside for exactly 30 minutes and then 200 mL distilled water, 10 mL phosphoric acid and 1 mL diphenylamine indicator were added. The solution was titrated against standard ferrous ammonium sulphate till the colour changed from blue violet to green. The blank titration was also carried out without soil.

Exchangeable Ca, Mg, Na, K were extracted using normal ammonium acetate (Jackson 1973). The exchangeable K and Na were determined by flame photometer while Ca and Mg were determined using atomic absorption spectrometer. Cation exchange capacity (CEC) was determined by distillation method as described by Jackson (1979). Percentage base saturation was calculated using the formula: % base saturation = Summation of exchangeable bases x 100 CEC. Total amounts of iron, manganese, copper and zinc in soil were determined in 1 g of finely ground soil and digested with a mixture of $HF:HNO_3:HClO_4$ (Committee of Soil Standard Methods for Analyses and Measurements 1986). After complete digestion, the content was transferred into a 100 mL volumetric flask, made to the mark, and analyzed for Fe, Cu, Mn and Zn using Atomic Absorption Spectrophotometer (PerkinElmer 100 analyst). The working standard solutions for each metal were prepared before every analysis. Concentrations of Fe, Mn, Cu, and Zn were measured by an air acetylene flame with detection limits of 0.02 µg mL^{-1} for Fe, 0.01 µg mL^{-1} for Cu and Mn and 0.005 µg mL^{-1} for Zn. The limits of detection (LOD) were based on the usual definition as the concentration of the analytic yielding a signal equivalent to three times the standard deviation of the blank signal, using 10 measurements of the blank for this calculation. The available quantities of iron, manganese, copper and zinc in these soils were extracted with DTPA-$CaCl_2$ reagent (Lindsay and Norvell 1978). The elements in the extract were determined with the help of atomic absorption spectrophotometer.

The assessment of soil or sediment enrichment can be carried out in many ways. The most common ones are the index of geo-accumulation and enrichment factors (Lu et al. 2009). In this work, the index of geo-accumulation (Igeo) and Enrichment Factor (EF) have been applied to assess metals (Cu, Fe, Mn, and Zn) distribution in hydric soils of Majuli Island. A quantitative measure of the extent of metal pollution was calculated using the geo-accumulation index proposed by Muller (1969). This index (Igeo) of heavy metal is calculated by computing the base 2 logarithm of the measured total concentration of the metal over its background concentration using the following mathematical relation (Ntekim et al. 1993).

(Eq.4): $Igeo = \log_2 (Cn/1.5Bn)$

where Cn is the measured total concentration of the element in the soil, Bn is the average (crustal) concentration of element n in shale (background) and 1.5 is the factor compensating the background data (correction factor) due to lithogenic effects. Loska et al. (2004) gave the following interpretation for the geo-accumulation index: Igeo < 0 = practically unpolluted, 0 < Igeo < 1 = unpolluted to moderated polluted, 1 < Igeo < 2 = moderately polluted, 2 < Igeo < 3 = moderately to strongly polluted, 3 < Igeo < 4 = strongly polluted, 4 < Igeo < 5 = strongly to extremely polluted and Igeo > 5 = extremely polluted. The back ground values for sedimentary rock (Vinogradov 1966) were used in computation of indices as: 3.33% for Fe, 700 mg kg^{-1} for Mn, 57 mg kg^{-1} for Cu and 80 mg kg^{-1} for Zn. Enrichment Factor (EF) has been employed for the assessment of contamination in various environmental media by several researchers. Its version adapted to assess the contamination of various environmental media is as follows:

(Eq.5)

$$EF = \frac{\left(\frac{Cx}{Cref}\right) \textit{sample}}{\left(\frac{Bx}{Bref}\right) \textit{background}}$$

where: Cx =content of examined element in the examined environment, Cref = content of the examined element in the reference environment, Bx = content of the reference element in the examined environment, Bref = content of the reference element in the reference environment.

An element is regarded as a reference element if it is of low occurrence variability and is present in the element in trace amounts. It is also possible to apply an element of geochemical nature which occurs in substantial amounts in the environment but which has no characteristic effects i.e. synergism or antagonism towards an examined element. The contamination categories are recognized on the basis of the enrichment factor: EF < 2 states deficiency to minimal enrichment, EF = 2-5 moderate enrichment, EF = 5-20 severe enrichment, EF = 20-40 very high enrichment and EF > 40 extremely high enrichment (Manno et al. 2006). In order to understand the level of contamination, Hakanson's formula (Hakanson 1980) was used and Contamination Factor of heavy metals was calculated as:

(Eq.6)

Contamination Factor (CF) = C metal / C shale value

where C metal is the average metal concentration and C shale value is the world average concentrations of the considered elements reported for shale (Vinogradov 1966).

The values of contamination factor are characterized as follows: CF < 1 (low contamination), 1 ≤ CF ≥ 3 (moderate contamination), 3 ≤ CF ≥ 6 (considerable contamination), 6 ≥ CF (very high contamination). CF was also calculated for each of the metals based on local pristine background values.

The level of pollution due to heavy metals was calculated by a simple method based on Pollution Load Index (PLI) (Tomlinson et al. 1980):

(Eq.7)

$$\text{Pollution load index (PLI)} = \sqrt[n]{CF1 \times CF2 \times CF3 \times \ldots \ldots \times CFn)}$$

where CFn = contamination factor and n = number of metals. The PLI index represents the number of times by which heavy metal concentration in the sediment exceeds the background concentration, and gives a cumulative indication of the overall level of heavy metal toxicity in a particular sample. The PLI value of > 1 is polluted, whereas < 1 indicates no pollution (Harikuma et al. 2009)

2.4. Statistical analysis

The correlations of soil total and DTPA-extractable heavy metal contents with physical and chemical characteristics were tested using Pearson's correlation and multiple regression analysis. The cluster analysis was made to test similarities with the average linkage method (within group) using PASW-18 version. The cluster analysis confirmed the groupings of soils of Majuli Island in establishing close relation of soil systematic units of individual layers and their interrelationships as reflected in the values of physical and chemical properties considered. The values of the seventeen measurements of association (sand, silt, clay, pH, organic carbon, CEC, DTPA-extractable Fe, Mn, Cu, Zn and total Fe, Mn, Cu, and Zn, redness rating, hue index and chroma index) were standardized to give each variable an equitable weight in the analysis. In the present approach of clustering, the attributes of soil horizons were used because it permitted the extraction of relevant information in an independent way. The standardization consisted of dividing the data values of each variable by the variable's range (Milligan and Cooper 1988) with the formula:

(Eq.8)

$$Z_{ij} = \frac{X_{ij}}{Max(X_i)-Min(X_i)}$$

Z_{ij} = the transformed value of each j^{th} datum of the X_i variable, *I = 1, 2, p, and j =1, 2, n.*
x_{ij}=j^{th} datum of the X_i variable.
Max (X_i) = the maximum value of the X_i variable.
Min (X_i) = the minimum value of the X_i variable.

3. Results

3.1. Soil morphology

The soil of Kamalabari (P1), Puranibari (P2) and Dakshinpat (P3) soil series occurring on active flood plains (16.3% of total area) have an Ap-AC-C horizon sequence with dark grey (10YR 4/1), clay loam to silt loam textured surface horizons. The AC horizons are dark grey (10YR 4/1) and loamy, but loamy sand in C horizons. The soils of Kamalabari (P1) series have decreasing trends of hue index (0.35 to 0.11) with little changes in chroma index (9.1 to 9.5) with depth. This soil has loamy soil material with chroma 2 or less without any redox depletions. The sandbars cover 43.2% of area with the dominant soil series of Majuli (P4) and Garumara (P5) on sand bars have olive grey to dark grey, coarse loamy surface horizons.

The swamps are low-lying, featureless flat surfaces of active or abandoned channels enriched with suspended sediments consisting of silt, clay and fine sands. This unit covers 14% of area. The Bongaon series (P6) on swamps have dark grey and silt loam texture with weak subangular blocky structures. The cambic B horizons have dark grey matrix with silt loam to silty clay loam and moderate angular blocky structures (Table 1).

Adi elengi (P7) and Chilkala (P8) soils occurring on old flood plains (6.3% of total area) have grey matrix, silt loam A horizons to dark grey silty clay B horizons with sand in C horizons. The Adi elengi soil shows low hue index (0.11) in upper 34 cm but increased to 0.55 in B horizons. This soil has low chroma index (2.3 to 2.97) with slight variations through. The channel fills are convex and the lower portions rich in fine sand, silt and clay. These channels are mostly concentrated in northern parts of Subansiri river banks. These channel fills cover 11.8% of total area. The Boritika (P9) and Gayangaon (P10) are dominant in channel fills (11.8% of total area) have Ap-B/A-Bw-BC horizon sequence. The Ap horizon is 13 cm thick, olive grey (5Y 5/2) and silty clay loam in texture. The B horizons are dark grey (5Y 4/1) to very dark grey (5Y 3/1) or dark greyish brown (2.5Y 4/2), silt loam in textures and have yellowish brown mottles. The Boritka soil (P9) has a hue index of 0.11 to 0.22 and chroma index of 2.25 to 2.36 with slight depth variations. The soils of Gayangaon series (P10) show inflections of hue index value of 0.7 in the upper 30 cm but lowered to 0.11 in C horizons whereas chroma index varies from 2.10 to 2.98.

3.2. Physical and chemical characteristics of soils

The particle-size composition within the geomorphic unit is the sand fraction, with a weighted mean of 52 to 72% for the majority of soils with gleying properties in the mineral horizons. The weighted mean for silt content more than 45% is recorded in P2 and P3, and the sand content is between 31 to 35%. These soils show distinct variation in clay distribution with weighted mean less or equal to 10% (P1, P4, P5, P6 and P7), 14 to 16.4% (P8, P9 and P10) and more than 20% (P2 and P3). There

Table 1. Morphology of soils in Majuli Island.

Land forms	*Depth (cm)*	*Horizon*	*Matrix colour*	*Texture[1]*	*Structure[2]*	*Mottles[3]*	*Boundary[4]*	*RR*
Active flood plains	*P1. Kamalabari – Humaqeptic Fluvaquent*							
	0-19	Ap	10YR 3/1	cl	m2 sbk		cs	8.33
	19-39	AC	10YR 4/1	sil	m2 sbk		cs	6.25
	39-61	C1	10YR 4/2	sl	flsbk		cs	12.5
	61-89	C2	10YR 4/1	sl	flsbk		cs	6.25
	89-130	C2	10YR 4/1	s	sg		cs	6.25
	P2. Puranibari series- Fluvaquentic Endoaquepts							
	0-14	Ap	10YR 5/1	l	m2 sbk	-	cs	5.0
	14-27	A/B	10YR 5/2	sil	m1 sbk	-	cs	10.0
	27-46	C1	10YR 6/1	s	sg	-	as	14.17
	46-71	C2	10YR 5/2	ls	m1 sbk	f2c, 7.5YR 4/3	cw	10.0
	71-86	2Bwg1	10YR 4/2	scil	m2 sbk	f2d, 7.5YR 3/3	cw	12.5
	86-105	2Bwg2	10YR 4/1	sic	m2 sbk	f1d, 7.5YR 4/4	gs	6.25
	105-175	2Bwg3	10YR 4/1	sic	m2 sbk	f1d, 10YR 4/3	gs	6.25
	P3. Dakhinpath series- Humic Endoaquepts							
	0-13	Apg	5Y 3/1	l	massive		cs	6.66
	13-34	Bwg1	5Y 4/1	sic	m3sbk		cs	5.00
	34-55	Bwg2	5Y 4/2	sic	m2 sbk		gs	10.00
	55-105	Bwg3	5Y 4/3	sic	m2 sbk		gs	15.00
	105-200	BC	5Y 5/4	sl	flsbk			20.00
Sand bars	*P4. Majuli series- Aquic Udorthents*							
	0-33	Ap	10YR 7/1	s	sg		cs	3.57
	33-57	AC1	10YR 4/2	ls	flsbk		gs	2.5
	57-82	AC2	10YR 4/1	ls	flsbk	10YR 3/3	gs	6.25
	P5. Garumara series- Fluvaquentic Endoaquepts							
	0-14	Ap	10YR 5/1	cl	m1sbk		cs	5.0
	14-43	Bw1	10YR 5/1	cl	m1sbk	7.5YR 3/3	cs	5.0
	43-64	Bw2	10YR 4/2	l	flsbk	m2d, 7.5YR 4/4	cw	12.5
	64-75	BC	10YR 4/1	cl	flsbk	f1d, 10YR 4/4	as	6.25
	75-160	C	10YR 8/1	c	sg			3.13
Swamps	*P6. Bangaon series- Typic Fluvaquents*							
	0-13	Ap	10YR 4/1	sl	flsbk		cs	6.25
	13-38	AC	10YR 5/1	l	m1 sbk	f1f, 10YR 4/4	cs	5.0
	38-68	C1	10YR 5/1	ls	m1 sbk	f1f, 10YR 4/4	cs	5.0
	68-80	Cg2	5Y 3/1	s	sg	-	cs	6.25
	80-105	Cg3	5Y 5/1	sl	flsbk	f1d, 10YR 4/3	cs	6.66
	105-170	Cg4	5Y 5/1	s	sg			4.00
Old flood plains	*P7. Adielengi series- Typic Endoaquepts*							
	0-13	Ap	10YR 5/1	sil	flsbk		cs	50
	13-34	Bw1	10YR 4/1	sicl	m2 sbk		gs	6.25
	34-60	Bw2	10YR 4/2	sicl	m2 sbk	m1f, 10YR 4/3	gs	12.5
	60-98	C1	10YR 4/2	s	sg		cs	12.5
	98-225	C2	10YR 7/1	s	sg		cs	3.57

	P8. Chilakala series- Typic Endoaquepts							
	0-16	Ap	10YR 5/1	sicl	m2 sbk		cs	5.0
	16-35	Bw1	10YR 4/1	sic	m3 sbk		gs	6.25
	35-59	Bw2	10YR 4/1	sic	m2 sbk		gs	6.25
	59-170	C1	10YR 6/1	s	sg		cs	14.17
Channel fills	*P9. Boritika series- Fluvaquentic Endoaquepts*							
	0-26	Ap	2.5Y 4/1	sicl	c2 sbk		cs	5.63
	26-52	C1	2.5Y 5/1	s	flsbk		cs	4.50
	52-64	2Bwg1	2.5Y 3/1	sicl	m2 sbk		cs	7.50
	64-79	2Bwg2	2.5Y 4/2	sicl	m2 sbk		cs	11.25
	79-113	C2	2.5Y 5/2	s	Sg		-	9.00
	P10. Gayangaon series- Typic Endoaquepts							
	0-13	Ap	10YR 5/1	sicl	m1 sbk		cs	5.0
	13-39	Bwg1	10YR 5/2	sicl	flsbk		cs	10.0
	39-54	Bwg2	10YR 5/2	sicl	m1 sbk	f1f, 10YR 3/4	gw	10.0
	54-72	Bwg3	10YR 3/1	cl	m2 sbk		gw	8.33
	72-94	Bwg4	10YR 4/1	cl	flsbk		gw	6.25
	94-169	C	10YR 8/1	s	Sg		as	3.13

[1]Texture: s = sand, l = loam, ls = loamy sand, sl = sandy loam, sil = silty loam, cl = clay loam, sic = silty clay, sicl = silty clay loam, c = clay.
[2]Structure: grade: 1 = weak, 2 = moderate, 3 = strong; size: f = fine, m = medium, 3 = coarse; type: sg = single grain, sbk = subangular blocky.
[3]Mottles: abundance: f = few (< 2%), c = common (2-20%), m = many (> 20%); size: 1 = fine (< 2 mm), 2 = medium (2-5mm); contrast: f-faint, d-distinct.
[4]Boundary: D –distinctness, a = abrupt, c = clear, g = gradual; T = topography: s = smooth, w = wavy.

is an increase of clay in the cambic B horizons (33% clay in Bwg1 horizon of Adielengi - P7, 34.5% in 2Bwg2 horizon of Puranibari - P2, 43.5% in Dakshinpat - P3 and 47% in Chilkala - P8). The distribution of clay is duplex positive in P2/P9, variable in P4/P6, gradationally negative in P1/P3/P5/P8, and duplex negative in P9/P10. The downward increase of clay was recorded in cambic Bw horizons of Dakshinapat series (P3), Adi elengi (P7) and Chilkala (P8). The silt content is more than 50% in soil control section of Dakshinpat - P3, Ade elengi - P7 and Gayangaon - P10 with a fine-silty particle size class (**Table 2**).

The Ap horizons in Dakshinpat (P3) and Chilkala (P8) soils are strongly acid but moderately acid to neutral in sub-soils in Kamalabari (P1), Garumara (P5) and Gayangaon (P10). The mean organic carbon in Ap horizons is 12.66 g kg^{-1} with coefficient of variation of 113.5%. The organic carbon shows gradational decrease with value of 6.57 g kg^{-1} in Bw horizon to 2.07 g kg^{-1} in C horizons (**Table 2**). The CEC of cambic B horizons is 14.9 $cmol_{(+)}$ kg^{-1} with 11 $cmol_{(+)}$ kg^{-1} for Ap horizons and 7.8 $cmol_{(+)}$ kg^{-1} in C horizons. Similar pattern of CEC and organic carbon in soils were reported from Brahmaputra valley (Bhaskar et al. 2009; Chakravarthy et al. 1984; Karmakar 1985).

3.3. Soil classification

These soils have long land use history of paddy cultivation and conditions are similar to that of paddy soils reported in China with hydra-agric anthrosols (Zhang and Gong 2003). These soils are classified in the subgroups of Inceptisols and Entisols considering the regular decrease in organic carbon, thickness of epipedon and land use history (Soil Survey Staff 2014). The Puranibari (P2), Garumara (P5) and Boritika (P9) soils show irregular depth trends of organic carbon but have 0.2% at 1.25 m. Hence these soils are classified as Fluvaquentic Endoaquepts. Adielengi (P7), Chilkala (P8) and Gayangaon (P10) have similar pattern of organic carbon distribution but have high chroma mottles (4 to 6). These soils are classified as

Table 2. Particle size distribution and chemical properties of soils in Majuli Island.

Depth (cm)	*Horizon*	*pH*	*OC (g kg^{-1})*	*CEC (cmol$_{(+)}$ kg^{-1})*	*Sand (2-0.05 mm)*	*Silt (0.05-0.002 mm)*	*Clay (< 0.002 mm)*	*Base saturation (%)*
						---------------------------- *(%)* ----------------------------		
P1. Kamalabari series- Humaqueptic Fluvaquents								
0-19	Ap	5.9	12.2	12.6	42.7	38.3	19.0	49
19-39	AC	6.8	4.8	12.3	40.4	43.1	16.5	43
39-61	C1	7.0	1.9	10.2	40.4	52.6	7.0	49
61-89	C2	7.1	2.5	11.2	49.5	42.0	8.5	64
89-130	C2	7.2	0.8	7.61	86.0	9.5	4.5	58
Weighted mean	6.4	3.63	10.27	57.1	33.2	9.7	54	
P2. Puranibari series- Fluvaquentic Endoaquepts								
0-14	Ap	6.1	6.1	14.0	59.4	26.1	14.5	30
14-27	A/B	6.6	4.9	15.9	35.1	48.4	16.5	37
27-46	C1	6.4	1.2	9.57	87.4	6.1	6.5	31
46-71	C2	6.5	2.9	13.2	71.3	15.7	13.0	41
71-86	2Bw1	6.4	5.3	18.9	15.6	58.9	25.5	47
86-105	2Bw2	6.5	6.3	20.6	5.4	60.1	34.5	48
105-175	2Bw3	6.5	1.8	20.1	6.1	64.4	29.5	48
Weighted mean	6.5	3.25	17.12	31.4	45.9	22.7	43	
P3. Dakhinpath series- Humic Endoaquepts								
0-13	Ap	5.5	57.0	25.6	6.6	57.9	35.5	61
13-34	Bw1	6.3	19.3	19.7	3.4	53.1	43.5	70
34-55	Bw2	6.9	7.3	14.5	9.1	66.4	24.5	71
55-105	Bw3	7.0	5.0	15.7	15.4	67.1	17.5	70
105-200	BC	7.2	2.1	10.0	61.9	26.6	11.5	67
Weighted mean	7.3	10.0	15.21	35.2	43.4	21.4	73	3.57
P4. Majuli series- Aquic Udorthents								
0-33	Ap	7.5	1.5	5.54	83.7	11.8	4.5	52
33-57	AC1	7.2	3.8	9.02	45.4	46.1	8.5	39
57-82	AC2	7.2	3.4	7.28	47.9	44.6	7.5	50
Weighted mean	7.3	2.75	7.09	61.6	31.8	6.6	48	6.25
P5. Garumara series- Fluvaquentic Endoaquepts								
0-14	Ap	4.8	9.6	10.6	45.9	37.1	17.0	38
14-43	Bw1	5.8	7.7	13.5	30.3	49.7	20.0	53
43-64	Bw2	6.3	3.9	12.2	45.4	40.6	14.0	59
64-75	BC	6.3	1.4	8.70	70.1	23.8	6.0	52
75-160	C	6.7	0.6	4.35	98.7	0.8	0.5	52
Weighted mean	6.3	3.16	7.88	72.7	19.6	7.6	52	4.00

P6. Bangaon series- Typic Fluvaquents								
0-13	Ap	7.7	8.3	9.78	37.1	55.4	7.5	58
13-38	Ac	7.8	5.0	8.80	33.4	60.6	6.0	38
38-68	C1	7.8	3.5	7.17	42.5	49.0	8.5	64
68-80	C2	7.9	3.3	6.41	73.7	19.8	6.5	63
80-105	C3	7.7	2.3	5.54	46.8	46.2	7.0	54
105-170	C4	7.7	1.2	1.41	94.5	2.7	3.0	60
Weighted mean	7.7	3.02	5.19	62.3	32.2	5.5	56	4.00
P7. Adielengi series- Typic Endoaquepts								
0-13	Ap	7.1	9.7	11.1	14.7	74.3	11.0	83
13-34	Bw1	6.8	16.7	14.1	15.7	51.3	33.0	69
34-60	Bw2	7.0	5.8	12.5	22.4	56.6	21.0	53
60-98	C1	7.2	1.4	7.89	75.0	16.0	9.0	70
98-225	C2	7.2	1.4	3.48	96.3	1.3	5.0	57
Weighted mean	7.1	3.82	6.69	70.0	20.0	10.0	61	60
P8. Chilakala series- Typic Endoaquepts								
0-16	Ap	5.5	13.8	11.6	6.6	54.9	38.5	54
16-35	Bw1	6.4	10.5	11.0	5.8	47.2	47.0	84
35-59	Bw2	6.8	8.1	11.5	14.5	48.5	37.0	65
59-170	C1	7.2	0.6	4.78	95.7	0.8	3.5	80
Weighted mean	6.9	4.0	7.07	65.8	17.8	16.4	76	57
P9. Boritika series- Fluvaquentic Endoaquepts								
0-26	Ap	7.0	12.3	17.9	29.4	46.6	24.0	58
26-52	C1	7.5	1.6	11.9	77.5	16.5	6.0	43
52-64	2Bw1	7.2	11.0	19.6	13.3	52.2	34.5	54
64-79	2Bw2	7.3	4.3	20.0	17.1	53.4	29.5	52
79-113	C2	7.6	0.6	8.89	92.5	1.0	6.5	33
Weighted mean	7.4	5.11	14.26	56.1	27.5	16.4	46	57
P10. Gayangaon series- Typic Endoaquepts								
0-13	Ap	6.0	10.0	17.1	3.3	71.7	25.0	57
13-39	Bw1	7.2	5.1	14.4	15.8	68.2	16.0	74
39-54	Bw2	7.3	6.1	16.5	2.5	75.5	22.0	69
54-72	Bw3	6.9	10.8	14.7	22.5	51.0	26.5	56
72-94	Bw4	6.9	7.4	10.7	39.1	39.4	21.5	56
94-169	C	7.1	0.8	4.78	94.6	0.9	4.5	55
Weighted mean	7.0	4.56	10.1	52.4	33.6	14.0	60	57

Typic Endoaquepts. The Dakshinpat series (P3) having organic carbon of 0.91% in Ap to 0.43% in Bwg3 is classified as Humic Endoaquepts. The irregular depth trends of organic carbon in Bangaon series (P6) with 0.2% at a depth of 125 cm is classified as Typic Fluvauents. The Majuli series (P4) has aquic conditions with a chroma of 1 within 100 cm to classify under Aquic Udorthents whereas Kamalabari series (P1) is classified as Humaqueptic Fluvaquents having value of 3 or less (moist) in the upper 15 cm, organic carbon of 12.2 g kg^{-1} and base saturation less than 50% (**Table 2**).

3.4. Total micronutrient status

The profile distribution of total and DTPA-extractable micronutrients are presented in **Table 3** and its descriptive statistics in **Table 4**.

Table 3. DTPA extractable and total microelements

Depth (cm)	*DTPA-extractable*				*Total*			
	(mg kg^{-1})				*(g kg^{-1})*		*(mg kg^{-1})*	
	Fe	*Mn*	*Cu*	*Zn*	*Fe*	*Mn*	*Cu*	*Zn*
P1. Kamalabari								
0-19	114.0	11.0	4.7	0.54	30.1	0.37	28	109
19-39	23.5	5.8	1.3	0.40	33.2	0.38	29	110
39-61	16.0	4.1	0.2	0.02	32.0	0.51	27	117
61-89	17.5	4.0	0.4	0.06	31.1	0.48	25	109
89-130	15.0	3.5	0.1	0.02	23.1	0.40	14	116
Weighted mean	31.48	5.16	1.04	0.16	28.91	0.43	22.9	112.7
P2. Puranibari								
0-14	2500	30.8	3.34	0.52	32.5	0.57	23	64
14-27	1598	23.2	1.6	0.48	36.9	0.69	21	73
27-46	309	10.1	0.4	0.62	27.1	0.49	19	52
46-71	815	11.2	1.4	0.58	29.9	0.51	22	60
71-86	25	10.7	2.6	0.56	47.1	0.78	43	95
86-105	40	9.6	2.4	0.48	47.6	0.77	52	101
105-175	19	4.5	1.2	0.38	50.7	0.70	50	99
Weighted mean	482.77	10.64	1.59	0.48	42.04	0.65	37.9	83.5
P3. Dakhinpath								
0-13	495	30.0	10.5	0.52	39.5	0.54	52	94
13-34	142	15.5	11.5	0.14	42.7	0.62	52	118
34-55	40.5	7.5	4.2	0.02	38.7	0.59	44	83
55-105	19.5	30.5	2.8	0.12	40.2	0.75	42	89
105-200	37.5	13.0	0.9	0.12	34.7	0.51	21	65
Weighted mean	74.03	18.17	3.46	0.14	37.65	0.59	33.9	80.3
P4. Majuli								
0-33	34	9.5	7.4	1.3	24.6	0.49	17	63
33-57	30	11.0	1.2	0.5	28.1	0.59	21	69
57-82	11	8.0	1.1	0.4	28.7	0.55	22	68
Weighted mean	25.82	9.48	3.66	0.79	26.87	0.54	19.7	66.3

P5. Garumara								
0-14	227	2.5	3.8	0.62	32.6	0.48	29	189
14-43	84	9.9	2.7	0.16	41.2	0.80	32	133
43-64	44	23.6	1.4	0.12	40.5	0.76	31	96
64-75	13.5	9.9	0.3	0.10	26.4	0.54	24	102
75-160	9.5	2.5	0.1	0.06	14.6	0.24	6.0	60
Weighted mean	46.84	7.12	1.08	0.14	25.21	0.45	17.2	92.1
P6. Bangaon								
0-13	81.5	7.5	3.9	0.30	30.5	0.67	30	74
13-38	8.0	7.0	2.7	0.20	32.5	0.62	29	79
38-68	11.5	7.0	2.3	0.20	31.6	0.62	29	68
68-80	13.5	4.5	2.4	0.22	31.8	0.57	27	73
80-105	25.0	7.0	3.8	0.18	32.8	0.58	20	74
105-170	14.5	2.5	0.7	0.06	22.4	0.40	13	55
Weighted mean	19.61	5.14	2.10	0.15	28.34	0.53	21.5	66.3
P7. Adielengi								
0-13	1.5	5.1	4.4	0.48	38.3	0.64	39	77
13-34	2.2	2.6	3.3	0.40	44.1	0.70	42	94
34-60	4.5	5.4	0.9	0.34	41.5	0.81	44	81
60-98	209	2.4	0.2	0.24	28.5	0.56	23	55
98-225	138	0.7	0.04	0.18	14.6	0.26	5	30
Weighted mean	114.0	1.96	0.72	0.25	24.18	0.44	17.9	48.8
P8. Chilakala								
0-16	156	1.0	7.5	0.58	36.2	0.52	45	105
16-35	25	0.8	4.3	0.32	38.2	0.50	42	113
35-59	25	5.1	2.6	0.24	31.2	0.47	36	103
59-170	38	1.6	0.2	0.10	16.9	0.29	10	46
Weighted mean	45.82	1.95	1.68	0.19	23.11	0.36	20.5	67.1
P9. Boritika								
0-26	445	13.3	6.0	0.54	36.2	0.58	36	87
26-52	275	1.4	0.7	0.32	23.4	0.36	18	53
52-64	242	2.7	3.4	0.40	36.5	0.42	44	88
64-79	479	1.5	1.3	0.32	38.9	0.43	49	90
79-113	256	1.4	0.1	0.34	18.8	0.36	8	36
Weighted mean	331.97	4.29	2.11	0.39	28.41	0.43	26.0	64.3
P10. Gayangaon								
0-13	101	3.6	5.7	0.36	38.2	0.44	38	138
13-39	22.5	6.7	2.6	0.12	36.7	0.51	33	144
39-54	23.5	8.0	3.1	0.20	40.1	0.60	38	142
54-72	25.0	22.7	5.0	0.22	36.4	0.58	38	143
72-94	9.0	25.1	2.4	0.14	28.8	0.49	28	161
94-169	4.0	3.6	0.1	0.08	17.4	0.23	10	90.0
Weighted mean	18.93	9.30	2.00	0.14	27.49	0.39	23.5	121.5

3.4.1. Iron (Fe)

The distribution of total iron is irregular in soils of active flood plains (P1, P2 and P3) whereas gradational increases are evident in Majuli (P4, 21.5 to 28.5 g kg^{-1}), Garumara (P5, 32.6 to 40.5 g kg^{-1}), Bangaon on swamps (P6, 30.5 to 32.8 g kg^{-1}), Adielengi (P7, 44.1 g kg^{-1}) and Chilkala (P8, 38.2 g kg^{-1}). The irregular depth a trend of total iron is observed in soils of channel fills with its maximum concentration in B horizons (36.5 to 38.9 g kg^{-1} in P9 and 36.4 to 40.1 g kg^{-1} in P10). Similar observations were reported in paddy soils of Bangladesh by Moslehuddin and Egashira (1996) and Bhaskar and Sarkar (2013) from India. The mean total iron content is 32.48 ± 8.4 g kg^{-1} with its high concentration cambic B horizons (38.89 ± 5.96 g kg^{-1}) followed by Ap horizons (33.93 ± 4.71 g kg^{-1}), AC horizons (30.66 ± 2.63 g kg^{-1}) and C horizons (25.27 ± 6.55 g kg^{-1}, **Table 4**).

Table 4. Horizon wise descriptive statistics for hydric soils

Horizon		*DTPA (mg kg^{-1})*				*Total (g kg^{-1})*			
		Fe	*Mn*	*Cu*	*Zn*	*Fe*	*Mn*	*Cu*	*Zn*
Ap									
	Mean	530.80	12.42	5.28	0.57	33.93	0.54	32.20	98.60
	SD	839.18	11.34	2.57	0.27	4.71	0.10	11.10	39.56
	CV (%)	158.10	91.33	48.60	48.03	13.88	19.06	34.48	40.12
AC									
	Mean	18.13	7.95	1.58	0.38	30.66	0.54	25.25	81.50
	SD	10.38	2.22	0.75	0.13	2.63	0.11	4.35	19.64
	CV (%)	57.27	27.97	47.90	33.55	8.59	20.04	17.23	24.10
Bw									
	Mean	64.77	10.87	2.85	0.24	38.90	0.61	38.38	105.00
	SD	109.48	8.33	2.34	0.15	5.97	0.13	9.55	26.35
	CV (%)	169.02	76.66	82.24	60.76	15.34	21.32	24.87	25.09
C									
	Mean	141.90	4.39	0.86	0.21	25.27	0.44	17.73	69.87
	SD	217.72	3.13	1.12	0.19	6.56	0.13	8.00	27.12
	CV (%)	153.43	71.17	130.37	88.56	25.94	29.24	45.09	38.81

3.4.2. Manganese (Mn)

The distribution of total manganese is similar to that of total iron but its concentration is greater in the B horizons (mean 0.61 ± 0.13 g kg^{-1}). These soils have a mean Mn content of 0.53 ± 0.14 g kg^{-1} and coefficient of variation (CV) of 27.4%. It is noted that soils of the Bangaon series (P6) show decreasing trends of Mn with a weighted mean of 0.53 g kg^{-1}. The B horizons in soils of the Adi elengi series (P9) have 0.70 to 0.8 g kg^{-1} of Mn with a minimum of 0.26 g kg^{-1} in C horizons. Based on the weighted mean of Mn, the soils are arranged in descending order as: swampy soils (0.58 ± 0.09 g kg^{-1}) > active flood plains (0.57 ± 0.13 g kg^{-1}) > sandbars (0.56 ± 0.17 g kg^{-1}) > old floodplains (0.53 ± 0.18 g kg^{-1}) and channel fills (0.45 ± 0.11 g kg^{-1}).

3.4.3. Copper (Cu)

These hydric soils have total Cu contents from 5 to 52 mg kg^{-1} with a mean of 29.32 ± 12.8 mg kg^{-1}. These values are in agreement with the reported values of Cu content in paddy soils of Bangladesh (Domingo and Kyuma 1983) and in soils of Indo Gangetic plains of India (Sharma et al. 2000). The gradational decrease of Cu is recorded in soils of active flood plains (P1 and P3) and swamps (P6) but gradational increases in the soils on sand bars (P4 from 17 to 22 mg kg^{-1}). These soils are grouped on the basis of weighted mean of total Cu as: P2 (37.94 mg kg^{-1}) > P3 (33.94 mg kg^{-1}) > P9 (26.0 mg kg^{-1}) > P10 (23.5 mg kg^{-1}) > P1 (22.92 mg kg^{-1}) and > P6 (21.49 mg kg^{-1}) (**Table 4**). A concentration of copper is within the normal background range (6-60 mg kg^{-1}) as reported by Kabata-Pendias (2010).

3.4.4. Zinc (Zn)

The total Zn content varies from 30 mg kg^{-1} (C2 horizon of P7) to 189 mg kg^{-1} (Ap horizon of P5) with a mean of 90.62 ± 32.63 mg kg^{-1} and coefficient of variation of 35.9%. With respect to landforms, the mean for total zinc is 106.55 ± 41.30 mg kg^{-1} for P9/P10 and 70.50 ± 8.36 mg kg^{-1} for P6. The coefficient of variation is more than 35% in soils of sand bars, channel fills and old flood plains. Concentrations of zinc are within the normal background range (17-125 mg kg^{-1}) as reported by Kabata-Pendias (2010).

3.5. DTPA-extractable micronutrient status

3.5.1. Iron (Fe)

The DTPA-extractable iron varies from 4 to 2500 mg kg^{-1} with a mean of 182.64 ± 423.01 mg kg^{-1}. The vertical distribution of DTPA-extractable Fe is irregular in terms of its enrichment in Ap horizons (mean of 530.8 ± 839.2 mg kg^{-1}) followed by C horizons (mean 141 ± 217.7 mg kg^{-1}) and B horizons (64.7 ± 109.5 mg kg^{-1}). Similar depth trends were reported in soils of Indo Gangetic plains of India (Siddhu and Sharma 2010). These soils are ranked in the descending order as active flood plains (mean of 366.26 ± 687.86 mg kg^{-1}) > channel fills (mean of 171.1 ± 178.1 mg kg^{-1}) > old flood plains (mean of 66.58 ± 78.97 mg kg^{-1}) > sand bars (mean of 56.63 ± 73.0 mg kg^{-1}) > swamps (mean of 25.7 ± 27.94 mg kg^{-1}).

3.5.2. Manganese (Mn)

The DTPA-extractable Mn varies from 0.7 mg kg^{-1} in the C2 horizon (P1) to 30.8 mg kg^{-1} in Ap horizons (P2) with a mean of 8.86 ± 8.1 mg kg^{-1} and constituting 16.6% of total Mn (**Table 3**). These values are considered to be lower than that of the values reported in floodplain soils of Bangladesh (Khan and Ahmad 1997). The DTPA-Mn showed a gradual decrease in the Kamalabari series (P1) but increased with depth in Gayangaon series (P10) but no specific pattern in other soils. Sangwan and Singh (1993) also observed an irregular pattern in available Mn with soil depth. The weighted mean for DTPA-Mn in soils on active floodplains is 18.17 mg kg^{-1} for P3 and 10.64 mg kg^{-1} for P2 but low values in soils on old flood plains (P7 and P8), 1.9 mg kg^{-1}.

3.5.3. Copper (Cu)

The DTPA-Cu varies from 0.04 mg kg^{-1} (P7) to 11.5 mg kg^{-1} in the Bw horizon of P3 with a mean of 2.67 ± 2.55 mg kg^{-1}. The DTP-Cu decreased with depth except in soils on channel fills (P9/P10) and in Puranibari soil (P2) on active floodplains where irregular trends are noticed.

3.5.4. Zinc (Zn)

The DTPA-Zn constitutes less than 0.5% of total Zn, decreasing with depth except in P2 where irregular trends are observed. The DTPA-Zn varies from 0.02 mg kg^{-1} (in Bw2 horizon of P2 and C2 horizon of P1) to 1.3 mg kg^{-1} in Ap horizon of Majuli series on sand bars (P4). The DTPA-Zn shows enrichment in surface horizons (mean of Ap horizon = 0.57 ± 0.27 mg kg^{-1}) but subsequent decrease in AC horizon (0.38 ± 0.13 mg kg^{-1}), Bw horizon (0.24 ± 0.15 mg kg^{-1}) and C horizons (mean = 0.21 ± 0.19 mg kg^{-1}).

3.5.5. Contamination assessment

The overall mean of geo-accumulation index values for these soils is negative with reference to background values and ranked as unpolluted (mean of -0.64 for Fe, -1.02 for Mn, -1.77 for Cu and -0.55 for Zn). The enrichment factor (EF) shows variable trends in soil horizons with values less than 2 (mean of 0.99 for Fe, 0.57 for Mn and 1.15 for Zn) but more than 2 for Cu indicating moderate enrichment. There is a striking depth trend of contamination factor

(CF) for Fe, Mn and Cu despite overall mean value of less than 1. The soil horizons having CF values > 1 in P10, P5, P3 and P1 indicate moderate contamination and CF values are > 1 for Zn. The pollution load index (PLI) is found to be generally low (<1) but exceeding 1 in the horizons of P2, P3, P5 and P7 indicating sediment pollutants of Zn, Fe and Mn in these soils (**Table 5**).

Table 5. Pollution indices for soils of Majuli Island

Profile Number / Soil series	*Depth (cm)*	*Igeo accumulation index*				*Enrichment factor*				*Contamination factor (CF)*				*Pollution load index*
		Fe	*Mn*	*Cu*	*Zn*	*Fe*	*Mn*	*Cu*	*Zn*	*Fe*	*Mn*	*Cu*	*Zn*	
P1. Kamalabari	0-19	0.72	1.50	1.61	0.14	0.91	0.58	0.49	1.49	0.91	0.53	0.49	1.36	0.57
	19-39	0.58	1.47	1.56	0.13	1.01	0.53	2.76	1.37	1.01	0.54	0.51	1.38	0.62
	39-61	0.63	1.04	1.66	0.04	0.97	0.55	2.33	1.51	0.97	0.73	0.47	1.46	0.70
	61-89	0.67	1.13	1.77	0.14	0.94	0.56	2.24	1.45	0.94	0.69	0.44	1.36	0.62
	89-130	1.10	1.39	2.61	0.05	0.70	0.76	1.29	2.07	0.70	0.57	0.25	1.45	0.38
P2. Puranibari	0-14	0.61	0.88	2.03	0.72	0.98	0.54	1.85	0.82	0.98	0.81	0.40	0.80	0.51
	14-27	0.42	0.61	2.17	1.21	1.12	0.47	1.48	0.79	1.12	0.99	0.37	0.91	0.61
	27-46	0.87	1.10	1.96	1.00	0.82	0.64	2.33	0.83	0.82	0.70	0.33	0.65	0.35
	46-71	0.73	1.04	0.99	0.34	0.91	0.58	4.12	0.83	0.91	0.73	0.39	0.75	0.44
	71-86	0.07	0.43	0.72	0.25	1.43	0.37	3.16	0.88	1.43	1.11	0.75	1.19	1.19
	86-105	0.06	0.45	0.77	0.28	1.44	0.37	3.01	0.81	1.44	1.10	0.91	1.26	1.35
	105-175	0.03	0.58	1.17	0.52	1.54	0.34	2.14	0.82	1.54	1.00	0.88	1.24	1.29
P3.Dakshinpat	0-13	0.33	0.96	0.72	0.02	1.20	0.44	3.77	1.14	1.20	0.77	0.91	1.18	0.99
	13-34	0.21	0.76	0.96	0.53	1.29	0.41	2.95	0.88	1.29	0.89	0.91	1.48	1.24
	34-55	0.36	0.83	1.03	0.43	1.17	0.45	3.11	0.91	1.17	0.84	0.77	1.04	0.89
	55-105	0.30	0.49	2.03	0.88	1.22	0.43	1.50	0.77	1.22	1.07	0.74	1.11	1.03
	105-200	0.51	1.04	1.33	0.58	1.05	0.50	2.80	0.88	1.05	0.73	0.37	0.81	0.48
P4.Majuli	0-33	1.01	1.10	2.03	0.80	0.75	0.71	2.45	1.01	0.75	0.70	0.30	0.79	0.35
	33-57	0.82	0.83	1.96	0.82	0.85	0.62	2.24	0.98	0.85	0.84	0.37	0.86	0.48
	57-82	0.79	0.93	2.12	0.86	0.87	0.61	1.97	1.02	0.87	0.79	0.39	0.85	0.47
P5.Garumara	0-14	0.60	1.13	1.42	0.15	0.99	0.54	2.81	1.33	0.99	0.69	0.51	2.36	0.90
	14-43	0.26	0.39	1.46	0.32	1.25	0.42	2.16	0.98	1.25	1.14	0.56	1.66	1.15
	43-64	0.29	0.47	1.83	0.23	1.23	0.43	1.70	1.59	1.23	1.09	0.54	1.20	0.93
	64-75	0.91	0.96	3.83	1.00	0.80	0.66	0.65	1.70	0.80	0.77	0.42	1.28	0.58
	75-160	1.76	2.13	2.31	0.38	0.44	1.19	3.38	1.51	0.44	0.34	0.11	0.75	0.11
P6.Bangaon	0-13	0.70	0.65	1.56	0.60	0.92	0.57	2.72	1.00	0.92	0.96	0.53	0.93	0.66
	13-38	0.61	0.76	1.56	0.82	0.98	0.54	2.56	0.89	0.98	0.89	0.51	0.99	0.66
	38-68	0.65	0.76	1.66	0.72	0.96	0.55	2.45	0.95	0.96	0.89	0.51	0.85	0.61
	68-80	0.64	0.88	2.10	0.70	0.96	0.55	1.80	0.93	0.96	0.81	0.47	0.91	0.58
	80-105	0.59	0.86	2.72	1.13	0.99	0.53	1.14	1.01	0.99	0.83	0.35	0.93	0.52
	105-170	1.14	1.39	1.99	0.86	0.68	0.78	2.75	0.97	0.68	0.57	0.23	0.69	0.25
P7.Adi elengi	0-13	0.37	0.71	1.03	0.35	1.16	0.46	3.14	0.88	1.16	0.91	0.68	0.96	0.84
	13-34	0.17	0.58	0.96	0.57	1.34	0.40	2.86	0.81	1.34	1.00	0.74	1.18	1.08
	34-60	0.25	0.37	1.89	1.13	1.26	0.42	1.59	0.80	1.26	1.16	0.77	1.01	1.07
	60-98	0.80	0.91	4.10	2.00	0.86	0.61	0.50	0.85	0.86	0.80	0.40	0.69	0.44
	98-225	1.76	2.01	2.26	1.30	0.44	1.19	3.51	0.83	0.44	0.37	0.09	0.38	0.07

P8.Chilkala	0-16	0.45	1.01	1.03	0.09	1.10	0.48	3.32	1.22	1.10	0.74	0.79	1.31	0.92
	16-35	0.37	1.07	1.25	0.22	1.16	0.46	2.70	1.36	1.16	0.71	0.74	1.41	0.93
	35-59	0.67	1.16	3.10	1.38	0.95	0.56	0.92	1.12	0.95	0.67	0.63	1.29	0.72
	59-170	1.55	1.86	2.06	0.84	0.51	1.03	3.48	1.20	0.51	0.41	0.18	0.58	0.15
P9.Boritika	0-26	0.45	0.86	2.25	1.18	1.10	0.48	1.42	0.93	1.10	0.83	0.63	1.09	0.79
	26-52	1.08	1.54	0.96	0.45	0.71	0.75	5.39	0.99	0.71	0.51	0.32	0.66	0.28
	52-64	0.44	1.32	0.80	0.42	1.11	0.48	3.85	0.95	1.11	0.60	0.77	1.10	0.75
	64-79	0.35	1.29	3.42	1.74	1.18	0.45	0.59	0.79	1.18	0.61	0.86	1.13	0.84
	79-113	1.40	1.54	1.72	0.90	0.57	0.93	3.96	0.93	0.57	0.51	0.14	0.45	0.14
P10.Gayangaon	0-13	0.37	1.25	1.37	0.26	1.16	0.46	2.48	1.62	1.16	0.63	0.67	1.73	0.91
	13-39	0.43	1.04	1.17	0.24	1.11	0.48	2.97	1.46	1.11	0.73	0.58	1.80	0.92
	39-54	0.30	0.81	1.17	0.25	1.22	0.43	2.72	1.62	1.22	0.86	0.67	1.78	1.11
	54-72	0.44	0.86	1.61	0.42	1.10	0.48	2.20	2.31	1.10	0.83	0.67	1.79	1.04
	72-94	0.78	1.10	3.10	0.42	0.87	0.61	1.00	2.13	0.87	0.70	0.49	2.01	0.78
	94-169	1.51	2.19	1.86	0.02	0.53	1.00	3.87	1.82	0.53	0.33	0.18	1.13	0.18

3.6. Characterization of the soil clusters

The cluster analysis shows four distinct soil horizon groupings with horizon sequences Ap-AC-C in P1/P6, Ap-AC in P4, Ap-A/B-C in P2/P9, Ap-Bw-C in P7/P7/P8 and Ap-Bw-BC in P3/P10 (**Figure 3**). Group A includes twelve horizons, mostly C and AC horizons in soils of sandbars (P4/P5), swamps (P6) and active floodplains (P1/P3). These horizons are neutral with a low content of organic carbon (mean of 3.73 g kg^{-1}), clay (mean of 9.08%, **Table 6**), CEC (mean of 9.16 cmol$_{(+)}$ kg^{-1}) and DTPA-Zn (0.23 mg kg^{-1}). The Group B includes 15 horizons, mostly cambic B horizons (neutral), consisting of channel fills (P9/P10), old flood plains (P7/P8) and active flood plains (P2/P3). This group shows high contents of silt (mean = 58.74%), clay (mean = 26.7%), DTPA-Cu (mean = 3.01 mg kg^{-1}), total Fe (mean = 39.74 g kg^{-1}), total Mn (mean = 0.62 mg kg^{-1}), total Cu (mean = 41.0 mg kg^{-1}), total Zn (mean = 107.53 mg kg^{-1}) and a low sand content (mean = 15.06%). These soils are closely associated with topography and parent materials of alluvial sediments. The Group C consists of 10 horizons belonging to soils of sandbars (P5) and swamps (P6) usually associated with floodplains (P1, P8 and P10). These horizons are slightly acid with low total Fe (26.91 g kg^{-1}) and Mn (0.41 g kg^{-1}) indicating that these soils have high percolation rates and near to the river Brahmaputra with high contents of sand (mean = 63.76%) and low CEC (mean = 8.73 cmol$_{(+)}$ kg^{-1}) and clay (mean = 11.4%). The Group D comprising of 10 horizons (neutral in reaction) consist of soil associations of channel fills (P9), active and old flood plains (P2/P3/P7) and sand bars (P5). This group is characterized by large amounts of DTPA-Fe (mean = 672.53 mg kg^{-1}) and Mn (mean = 12.29 mg kg^{-1}).

4. Discussion

4.1. Pedogenic characteristics of paddy soils

Riverine floodplains of Majuli Island are formed by the periodical deposition of suspended sediments from the Brahmaputra river during flood events and the soils are considered as semi-terrestrial with aquic or epiaquic moisture regimes. These flood plains are intensively used for paddy cultivation in the island. Soils of this study occur on five dominant land forms: a) active flood plains (P1-Kamalabari, P2-Purnanibari and P3-Dakshinpat, 16.3% of total area), b) sand bars (P4-Majuli and P5-Garumara, 42.2% of TGA), c) swamps (P6-Bangaon, 14% of TGA), d) old flood plains (P7-Adielengi and P8-Chilkala, 6.3% of TGA) and e) channel fills (P9-Boritika and P10-Gayangaon, 1.8% of TGA).

Table 6. Clusterwise descriptive statistics of soil properties

Descriptive statistics of clusters	*Sand*	*Silt*	*Clay*	*pH*	*OC (g kg^{-1})*	*CEC cmol$_{(+)}$ kg^{-1}*	*DTPA-extractable* (mg kg^{-1})				*Total*				C1	C2	RR
	-------------(%)-------------										*(g kg^{-1})*		*(mg kg^{-1})*				
							Fe	*Mn*	*Cu*	*Zn*	*Fe*	*Mn*	*Cu*	*Zn*			
C1																	
Mean	47.03	43.88	9.08	7.31	3.73	9.16	26.58	8.54	1.80	0.23	32.29	0.57	25.92	83.50	0.55	9.35	7.95
SD	11.03	11.36	3.25	0.49	1.75	2.21	20.55	5.44	1.22	0.15	3.17	0.10	3.96	19.01	0.47	1.24	4.77
CV (%)	23.44	25.88	35.74	6.64	46.80	24.14	77.29	63.67	67.88	64.77	9.80	17.01	15.30	22.77	85.95	13.25	59.94
C2																	
Mean	14.53	58.74	26.73	6.86	7.79	15.06	34.9	9.8	3.0	0.29	39.7	0.62	41.0	107.5	0.32	5.14	11.56
SD	9.03	10.52	9.34	0.29	3.55	3.44	58.5	8.9	1.14	0.16	5.9	0.12	6.1	26.9	0.30	3.19	11.00
CV (%)	62.13	17.91	34.93	4.30	45.54	22.87	167.3	91.4	37.89	53.6	14.8	20.34	14.8	24.9	92.76	62.03	95.21
C3																	
Mean	63.76	24.86	11.40	6.32	5.31	8.73	83.40	4.32	2.19	0.26	26.91	0.41	20.90	112.50	0.31	7.71	5.90
SD	34.14	25.28	8.98	1.02	4.88	4.94	85.47	3.30	2.19	0.25	9.33	0.16	11.39	51.41	0.17	2.62	3.28
CV (%)	53.54	101.68	78.81	16.15	91.82	56.62	102.48	76.43	100.21	94.62	34.68	39.56	54.48	45.70	55.33	33.96	55.52
C4																	
Mean	56.50	28.32	15.18	6.73	8.52	13.96	672.23	12.29	2.35	0.42	30.74	0.51	26.82	69.64	0.28	3.03	8.63
SD	29.47	19.89	10.30	0.65	16.43	5.53	738.24	11.13	3.22	0.16	6.70	0.10	13.41	21.04	0.18	1.46	3.24
CV (%)	52.16	70.25	67.82	9.68	192.85	39.60	109.82	90.58	137.09	39.07	21.79	19.24	49.99	30.21	65.47	48.24	37.57

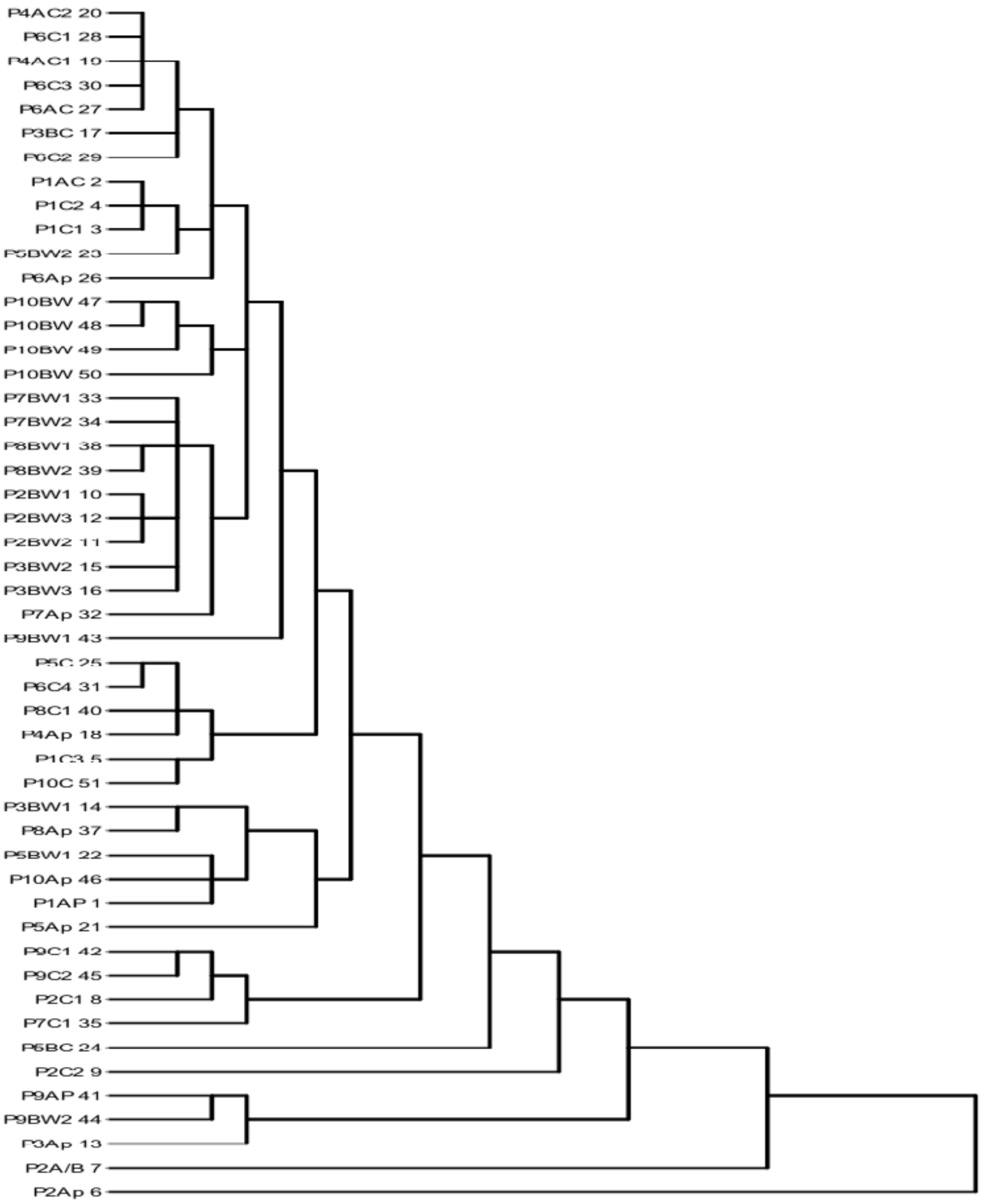

Figure 3. Soil grouping based on micronutrient content.

The 60 to 80% of seasonally inundated hydric soils in Majuli Island are oxidized and aerobic throughout the root zone during the growing season. Thus, soil morphology descriptions as recorded in these soils were associated with the development of a grey matrix. Iron depletions and Fe-accumulations were associated with relatively short water saturation periods. These soils have a strong relationship between CI index and total Mn (r = 0.36*, significant at 5% level) in horizons across soil series. The development of grey mottles and matrix chroma of one and two in these soils are important indicators of water saturation for longer period and development of anoxic soil conditions. Similar observations were reported in anthraquic soils of Tiwan (Jien et al. 2004). The pedons having redoximorphic features (P2, P5 and P6) imply more anoxic moisture regimes and the sand separate has greater concentrations of Fe and Mn. Thus, micro variation in the soil morphology is reflected by the intensity of the differences in soil processes and there is a weak relationship of soil colour indices with total Fe/Mn ratio. This observation is in concurrent with variations in redoximorphic features of hydric soils of Missouri (Aide et al. 2016).

The mean organic carbon in Ap horizons is 12.66 g kg^{-1} with a coefficient of variation of 113.5%. The organic carbon shows decreasing trend with 6.57 g kg^{-1} in Bw horizon and 2.07 g kg^{-1} in C horizons. These soils have 14.9 $cmol_{(+)}$ kg^{-1} of CEC in cambic horizons but have 11 $cmol_{(+)}$ kg^{-1} in Ap horizon and 7.8 $cmol_{(+)}$ kg^{-1} in C horizons. The river sediments are mainly composed of silt and clay with sediment layering due to seasonal floods in the region. Generally, these soils undergo ferrolysis that has resulted in low cation exchange capacity (1.41 $cmol_{(+)}$ kg^{-1} in the C4 horizon of the Bangaon series (P6) to 25.6 $cmol_{(+)}$ kg^{-1} in the Apg horizon of the Dakshinpat series (P3). The Bw horizon appears to be an illuvial horizon, where ferrous iron is formed and absorbed on the exchange sites. The absorbed iron is oxidized and forms an iron enriched cambic horizon with eluviation of organic matter resulted in greyization. These soils are grouped into three types depending upon soil moisture regime and associated redox conditions with distinct genetic horizons and profile structure such as (1) reducing paddy soils (P2, P3, P6, P9 and P10), (2) oxidizing reducing paddy soils (P1, P7 and P8) and (3) oxidizing paddy soils on sloping uplands (P4 and P5). The important pedogenic processes observed in paddy profiles are enriched Fe/Mn oxides in cambic B horizons (38.89 ± 5.95 g kg^{-1} Fe, 0.61 ± 0.13 g kg^{-1} Mn), base leaching and surface accumulation of organic carbon (> 1%) in P1, P3, P8 and P9 and poorly structured, compact cultivated horizons (P3, P4, P6 and P7). It is further observed that the presence of an endoaquic moisture regime in alluvial plains favours the increase of clay, total Fe, Mn, Cu and Zn in B horizons with a relative decrease in its proportions in C horizons. Similar pedogenic observations were reported for paddy cultivated soils of alluvial plains (Zhang and Gong 2003).

4.2. Total micro nutrient contents in relation to landforms and soil properties

There are distinct and perceptible variations in the profile distribution of total micronutrient contents (Fe, Mn, Cu and Zn) with respect to landforms of the river island Majuli. It was reported that total copper of < 12, zinc < 80 and manganese < 200 mg kg^{-1} are considered as deficient according to Bradford et al. (1967).

In the young soils on sand bars (P4 and P5) with less developed horizons; the amounts of the total iron is nearly equal throughout the profiles but with time, there is an accumulation of iron in B horizons as noticed in active and old flood plains (P1, P2, P7 and P8). A similar Fe distribution was reported within the soil profiles of saga polder lands in Japan (Gotoh 1976). In these soils, the total iron may partly participate in clay migration as shown by a significant correlation between the total iron and clay content (r = 0.712**, significant at 0.01% level). The relation of total Fe with soil properties is expressed in a multiple regression equation as:

Total Fe (g kg^{-1}) = 23.00 - 0.97 (pH) - 0.19 (organic carbon, g kg^{-1}) + 0.59 (CEC, $cmol_{(+)}$ kg^{-1}) -
0.002 (sand %) + 0.19 (silt %) + 0.13 (clay %)
F = 34.56, R^2 = 0.85** (significant at 1% level)

The Mn in the Adielengi series (P9) on old flood plains have reached maxima of 0.70 to 0.81 g kg^{-1} in B horizons and then decreased to 0.26 g kg^{-1} in C horizons. The weighted mean for Mn is in the order swampy soils (0.58 ± 0.09 g kg^{-1}) > active flood plains (0.57 ± 0.13 g kg^{-1}) > sandbars (0.56 ± 0.17 g kg^{-1}) > old floodplains (0.53 ± 0.18 g kg^{-1}) and channel fills (0.45 ± 0.11 g kg^{-1}). The distribution of total Mn can best be described by three general types: (1) more variation with depth, (2) surface or sub-surface eluviation followed by a steady increase with depth, and (3) irregular distribution. A uniform concentration of total Mn in the sub-surface horizons of alluvial plains is attributable to restricted leaching, whereas Pedon 5 showed more leaching of Mn due to coarse textured soils (**Table 3**). Low content of total Mn is possibly because of more Mn (II) leaching for considerable time. The total Mn content in these soils is positively and significantly correlated at 1% level with silt (r = 0.64**) and CEC (r = 0.83**) but at 5% level with clay (r = 0.33*). Similar observations were reported in soil profiles of rice fields in polder lands of Kojima basin (Kawaguchi and Matsuo 1955) and in paddy soils of Bangladesh (Moslehuddin et al. 1999). The hue index has strong positive relationships with Fe (r = 0.43*) and Mn contents (r = 0.42*) where as the chroma index has a negative weak relationship with Fe (r = -0.32) and Mn (r = -0.42). Similar relationships were reported in hydric soils of Brahmaputra valley (Bhaskar et al. 2009). The mean concentration of total Cu in soils of active floodplains is 33.18 ± 13.2 mg kg^{-1} but decreases with landscape position in the order of old floodplains (31.78 ± 15.3 mg kg^{-1}) > channel fills (30.91 ± 13.48 mg kg^{-1}) > swamps (24.67 ± 6.77 mg kg^{-1}) > sand bars (22.75 ± 8.55 mg kg^{-1}, **Table 4**). The distribution of total Cu was significantly and positively correlated with clay content (r = 0.847**), organic carbon (r = 0.55**) and CEC (r = 0.39*). A similar relationship between total Cu, clay and CEC was reported in the paddy soils of Bangladesh (Moslehuddin et al. 1999). These hydric soils in general have more Cu concentration in B horizons as compared to A and C horizons. The multiple regression equation is derived between total Cu and soil properties with coefficient of determination (R^2) of 0.904** and F value of 68.93, significant at a 1% level as:

Total Cu (mg kg^{-1}) = 5.024 + 1.31 (pH) + 0.057 (organic carbon, g kg^{-1}) + 0.538 (CEC, $cmol_{(+)}$ kg^{-1} + 0.010 (sand %) + 0.249 (silt %) + 0.499 (clay %)

No specific distribution pattern of total zinc is reported due to the aquic/udic moisture regime favouring intense leaching and seasonal floods causing depositional episodes in the island. The surface horizons have high content of zinc though lower layers generally retained less content due to downward movement of water. The zinc is considered as deficient in the soils of Majuli (P4), Bongaon (P6), Adielengi (P7), Chilkakla (P8) and Boritika (P9) with weighted mean below 80 g kg^{-1}. The total Zn is positively and significantly (1% level) correlated with silt (r = 0.52**) and clay (r = 0.46**). The total Zn can be approximated using a multiple regression equation with a coefficient of determination (R^2) of 0.468 and F value of 6.44:

Total Zn (mg kg^{-1}) = 229.79 + 23.34 (pH) - 0.48 (organic carbon, g kg^{-1}) - 1.35 (cation exchange capacity, $cmol_{(+)}$ kg^{-1}) + 0.014 (sand %) + 0.803 (silt %) + 0.417 (clay %)

4.3. DTPA-extractable micronutrient contents in relation to landforms and soil properties

Distribution of micronutrients with depth in soils indicates that parent material and geomorphic/physicochemical processes control the total micro elemental content and biogeochemical processes affect the DTPA-extractable content (Sharma et al. 2000). Generally, the DTPA-extractable micronutrient content of surface horizons was higher than that of the lower horizons. Accretion of organic matter in surface horizons by biological process associated with natural vegetation and crop production appears to have resulted in relatively higher extractable values (Sharma et al. 2009). The variability in DTPA-extractable Fe in soils occurring on different landscape elements is due to soil moisture regimes that influence the Fe solubility in the soil (Katyal and Sharma 1991). All soils have DTPA-Fe above the critical value of 4.5 mg kg^{-1} (Lindsay and Norvell 1978). Iron deficiencies are not common in flooded rice, because flooding enhanced the reduction and solubility of soil iron (Patrick et al. 1985). High concentration of Mn is observed in active flood plains (mean = 13.24 ± 9.55 mg kg^{-1}) followed by sand bars (9.61 ± 6.56 mg kg^{-1}) and channel fills (8.18 ± 8.5 mg kg^{-1}). It is observed that DTPA-Mn is greater in Ap (mean = 12.42 ± 11.34 mg kg^{-1}) and Bw horizons (mean= 10.87 ± 8.33 mg kg^{-1}) than in AC (7.95 ± 2.23 mg kg^{-1}) and C horizons (4.39 ± 3.12 mg kg^{-1}). The high coefficient of variation (more than 70%) is recorded for Ap, Bw and C horizons. There is a significant (at 1% level) positive correlation between DTPA-Mn and organic carbon (r = 0.388**) and CEC (r = 0.394**). This kind of relationship is in conformity with the findings of Mahajan et al. (2007) in soils of North West Himalayas and soils of Central parts of Punjab in India (Verma et al. 2005). The distribution of DTPA-Cu does not show any relationship with landforms but has slight variations in mean values from 2.25 ± 2.41 mg kg^{-1} in soils of sand bars to 2.91 ± 3.34 mg kg^{-1} in soils on active flood plains. The availability of Cu is strongly influenced by fineness of texture with its strong significant relation with silt (r = 0.45**) and clay (r = 0.59**). The combined influence of pH, organic carbon, CEC, silt and clay on approximation of DTPA-Cu in these hydric soils is explained with 62% of variation from a multiple regression equation (R^2 = 0.62, and F value of 14.79) as expressed below:

DTPA-Cu (mg kg^{-1}) = 1.09 - 0.29 (pH) + 0.19 (organic carbon, g kg^{-1}) - 0.115 (CEC, $cmol_{(+)}kg^{-1}$) + 0.021 (silt %) + 0.062 (clay %)

In these river island soils, the mean DTPA-Zn is greater in sand bars (0.41 mg kg^{-1}), active floodplains (0.33 mg kg^{-1}), old floodplains (0.32 mg kg^{-1}), channel fills (0.28 mg kg^{-1}) and swamps (0.19 mg kg^{-1}). Zinc deficiency is prevalent in these paddy soils (Bhaskar and Sarkar 2013) although total Zn contents of floodplain soils are sufficient (**Table 3**). The reasons behind Zn deficiency in paddy soils is submergence (Bhaskar et al. 2008) and interaction with phosphate ion (Moslehuddin et al. 1999).

4.4. Clustering of soils

The cluster analysis (**Figure 3**) proved to be useful in grouping diverse soils into distinct classes based on micronutrient availability and associated soil properties in 57 benchmark soils of India by Katyal and Vlek (1985); in alluvial paddy soils of tropical Asian countries (Kawaguchi and Kyuma 1975) and in the Kootenai River valley in Northern Idaho to establish relationships between mapping units and geographical areas to predict tendencies of micronutrient deficiencies (Li and Mahler 1992). The clusters established in this study clearly indicate the variation in micronutrient related to texture, CEC, pH and organic carbon. The soil horizons are grouped into four clusters based on similarities in micronutrient contents. Group B consists of fifteen cambic horizons having high contents of silt (mean = 58.74%), clay (mean = 26.7%), DTPA-Cu (mean = 3.01 mg kg^{-1}), total Fe (mean = 39.74 g kg^{-1}), total Mn (mean = 0.62 mg kg^{-1}), total Cu (mean = 41.0 mg kg^{-1}), total Zn (mean = 107.53 mg kg^{-1}) and low content of sand (mean = 15.06%, **Table 5**). On contrary to Group C horizons of sandbars (P5), swamps (P6) and floodplains (P1, P8 and P10) have slightly acid with low total Fe (26.91 g kg^{-1}) and Mn (0.41 g kg^{-1}) indicating that high rates of percolation rates due to closeness to river Brahmaputra with high contents of sand (mean = 63.76%) and low CEC (mean = 8.73 $cmol_{(+)}$ kg^{-1}) and clay (mean = 11.4%). The Group D has ten neutral horizons of channel fills (P9), active-old flood plains (P2/P3/P7) and sand bars (P5). The differences in composition between the oxic and anoxic sediment layers constitute driving forces for the transport of several components. When the oxic–anoxic interface is situated in the floodplain soil, the composition of the oxic layer will also be changed due to the flux from the anoxic layer with the enrichment of Fe and Mn in the oxic surface layer. This effect and the differences in kinetic parameters between oxidation and reduction reactions determine the transport of components from the anoxic layer to the surface waters (Salomons et al. 1987). In this study, the relation of micronutrients with physical and chemical characteristics are quantified and set up a base for soil surveys to enhance soil series information and also facilitate objective placement of new paddy soils in the region. These soils are closely associated with topography and parent materials of alluvial sediments. These clusters were characterized by zinc deficiencies in relation to soil mapping units and geography (Rezapour et al. 2014). The contents of trace elements are almost constant with similar behavior of trace metal distribution along Brahmaputra course. These soils are moderately enriched with Cu (EF between 2 and 5) and contamination of Zn, Fe and Mn in subsurface horizons indicates the influence of suspended particulate matter through sedimentation processes (**Table 5**). A similar subsurface enrichment of these elements was reported for the Sundarban and Hooghly river basins of India (Banerjee et al. 2016). These soils are practically unpolluted and unchanged by anthropogenic influences (Igeo index < 1). These elements have extremely low concentrations in the river through which they are transported and deposited as detrital materials in the island. The Fe-Mn oxy-hydroxides are considered to play a major role in accumulating Cu and Zn in specific horizons due to localized activities of run-off, frequent dredging of navigation channels, mechanized boat movements and fishing activities. The contamination of Zn is recorded as greater than

1 followed by the pollution load index exceeding 1 in the horizons of active floodplains indicating the presence of Zn, Fe and Mn pollutants. The Cu enriched in surface and subsurface soil horizons of these soils, suggests a transfer of metal-rich sediments along the soil pore network with water movement as stated by Adamo et al. (2006).

5. Conclusions

The focus of this study was to understand pedogenic influence on vertical distribution patterns of total and DTPA-extractable micronutrients (Fe, Mn, Cu and Zn) in ten rice-growing soils of Majuli island in relation to soil morphology, lithological units and metal loading/ enrichment. These soils showed a strong relationship of clay with total Fe (r = 0.712**, significant at 0.01% level) whereas total Mn content is positively and significantly correlated with silt (r = 0.64**), clay (r = 0.33*) and CEC (r = 0.83**). The DTPA-Mn in active flood plains as compared to sand bars and channel fills have a strong positive relationship with organic carbon (r = 0.388**) and CEC (r = 0.394**). The total zinc (< 80 ppm) and also DTPA-extractable zinc (< 0.8 mg kg^{-1}) are reported to be below the critical limit, with surface enrichment. The cluster analysis was used to identify geochemical associations indicating moderate enrichment of Cu in sub-soils and moderate contamination of Zn, Fe and Mn. The geo-accumulation index in soils qualified for placement under grade 0 (unpolluted) and are practically unaffected by anthropogenic influences. This study suggests a geopedological approach to geochemical investigations of seasonally flooded and riverfed deposited soils of Majuli and in quantification of enrichment factors to trace out geochemical markers in floodplains for future investigations.

REFERENCES

• Adamo P, Zampella M, Gianfreda L, Renella G, Rutigliano FA,Terribile F. 2006. Impact of river overflowing on trace element contamination of volcanic soils in south Italy: Part I. Trace element speciation in relation to soil properties. Environ Pollut.144(1):308-316.

• Aide M, Braden I, Clark H, Lowman S, Mauk D, McVay B, Mueller W, Svenson S, Weathers J. 2016. Variation in redoximorphic features of four adjacent Inceptisols. Int J Appl Agric Res.11(2):129-141.

• Alloway BJ. 2008. Micronutrients and crop production. In: Alloway BJ, editor. Micronutrient Deficiencies in Global Crop Production. Netherlands: Springer Science Business Media BV. p. 1-39.

• Balabanova B, Stafilov T, Šajn R, Tănăselia C. 2016. Geochemical hunting of lithogenic and anthropogenic impacts on polymetallic distribution (Bregalnica river basin, Republic of Macedonia). J Environ Sci Health, Part A 51(13):1180-1194.

• Banerjee K, Selvam PA, Purvaja R, Ramesh R. 2016. Heavy metal distribution and pollution assessment using environmental indices in the surface sediments of Sundarbans Delta, India. J Appl Geochem. 18(4):369-385.

• Behera SK, Shukla AK. 2013. Depth-wise distribution of zinc, copper, manganese and iron in acid soils of India and their relationship with some soil properties. J Indian Soc Soil Sci. 61:244 -252

• Bhagabati AK. 2001. Biodiversity and associated problems in the islands of the Brahmaputra, Assam. Geogr Rev India 63:330-343.

• Bhaskar BP, Baruah U, Vadivelu S, Raja P, Sarkar D. 2009. Pedogenesis in some subaqueous soils of Brahmaputra valley, Assam, India. J Indian Soc Soil Sci. 57:237-244.

• Bhaskar BP, Baruah U, Vadivelu S, Sarkar D. 2008. Characterization of depositional soils in dynamic fluvial landforms of Majuli Island for land use related issues. Agropedology 18:33-43.

• Bhaskar BP, Sarkar D. 2013. Capability and quality assessment of rice growing hydric soils in Majuli river Island, Assam, India. J Agric Environ Int Dev. 107:13-32.

• Bhuyan N, Barur NG, Borah DK, Bhattacharyya D, Basumatari A. 2014. Georeferenced micronutrient status in soils of Lakhimpur district of Assam. J Indian Soc Soil Sci. 62:102-107.

• Bhuyan SK. 1968. Tungkhungia Buranji. History and Antiquarian studies in Assam. Dept. of History and Antiquarian Studies, Gauhati University, Gauhati.

• Borkakati K, Takkar PN. 2000. Forms of boron in acid alluvial and lateritic soils in relation to ecosystem and rainfall distribution. In: Proceedings of the International Conference on Managing Resources for Sustainable Agricultural Production in the 21st century. Better Crops. Vol. 2; 2000 Feb 14-18; New Delhi, India; p. 127-128.

• Bradford GR, Arkley RJ, Pratt PF, Bair FL. 1967. Total content of nine mineral elements in fifty selected benchmark soil profiles of California. Hilgradia 38: 541-556.

• Chakravarthy SK, Sinha H, Mathur BS. 1984. Morphological and physico-chemical characteristics of some alluvial soils of Assam. J Indian Soc Soil Sci. 32:128-136.

• Committee of Soil Standard Methods for Analyses and Measurements. 1986. Soil Standard Methods for Analyses and Measurements. Hakuyusha, Tokyo, Japan.

• Domingo LE, Kyuma K. 1983. Trace elements in tropical Asian paddy soils. I. Total trace element status. Soil Sci Plant Nutr. 29:439-452.

• Eisenmann V. 2002. Die Bedeutung der Böden für das Renaturierungs potential von Rückdeichungs gebieten an der mittleren Elbe, Hamburg: Verein zur Förderung der Bodenkunde in Hamburg.

• Evans CV, Franzmeier DP. 1988. Colour index values to represent wetness and aeration in some Indiana soils. Geoderma 41:353-368.

• Gee GW, Bauder JW. 1986. Particle size analysis. In: Klute A, editor. Methods of soil analysis. 2nd ed. Agron. Monogr. 9. Madison, Wisconsin: ASA and SSSA.

• Geological Survey of India. 1989. Recent advances in the study of Tertiary stratigraphy of north east India–A critical resume. Key papers presented in Group Discussion on Tertiary Stratigraphyof north east India. Special Publication No 23:1-21.

• Gotoh S. 1976. Distribution of total and extractable forms of iron, manganese, and aluminum in development of rice soils of saga polder lands. Soil Sci Plant Nutr. 22:335-344.

• Hakanson L. 1980. An ecological risk index for aquatic pollution control. A sedimentological approach. Water Research14(8):975-1001.

• Harikuma, Nasir UP, Mujeebu Rahma MP. 2009. Distribution of heavy metals in the core sediments of a tropical wetland system. Int J Environ Sci Technol. 6:225-232.

• Jackson ML. 1973. Soil chemical analysis. New Delhi: Prentice Hall of India Pvt. Ltd.

• Jackson ML. 1979. Soil chemical analysis. Advance course. Madison, WI, USA: University of Wisconsin.

• Jensen JR. 1986. Introductory digital image processing. Englewood Cliffs, New Jersey: Simon and Schuster Inc.

• Jien SH, Hseu ZY, Chen ZS. 2004. Relations between morphological color index and soil wetness condition of anthraquic soils in Taiwan. Soil Sci. 169:871-882.

• Junk WJ. 2004. The flood pulse concept: new aspects, approaches, and applications — an update. In: Welcome RL, Petr T, editors. Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries. Bangkok, Thailand: FAO Regional Office for Asia and the Pacific. p. 117-149.

• Kabata-Pendias A. 2010. Trace Elements in Soils and Plants. Third Edition. Boca Raton: CRC Press. 432 p.

• Karmakar KM. 1985. Genesis and classification of soils in the northern Brahmaputra valley of Assam. Ph. D. Thesis. New Delhi: I.A.R.I.

• Katyal JC, Sharma BD. 1991. DTPA extractable and total Zinc, Copper, Manganese and Iron in Indian soils and their association with some soil properties. Geoderma 49:165-79.

• Katyal JC, Vlek PLG. 1985. Micronutrient problems in tropical Asia. Fert Res. 7:69-94.

• Kawaguchi K, Kyuma K. 1975. Paddy Soils in Tropical Asia: Part 4. Soil Material Classification. Tonan Ajia Kenkyu 13:215-227.

• Kawaguchi K, Matsuo Y. 1955. Distribution of free oxides along soil profiles in time series of dry rice fields in polder lands of Kojima-Basin. Soil Plant Food I:67-70.

• Khan AW, Ahmad SKA. 1997. Arsenic in Drinking Water: Health Effects and Management. A Training Manual. Dhaka: Department of Occupational and Public Health, National Institute of Preventive and Social Medicine (NIPSOM).

• Lahiri SK, Sinha R. 2014. Morphotectonic evolution of the Majuli Island in the Brahmaputra valley of Assam, India inferred from geomorphic and geophysical analysis. Geomorphol. 227:101-111.

• Latrubesse E. 2008. Patterns of anabranching channels: The ultimate end-member adjustment of mega rivers. Geomorphol. 101:130-145.

• Li GR, Mahler RJ. 1992. Micronutrients in the Kootenai River Valley of northern Idaho. Effect of soil chemical properties on micronutrient availability. Commun Soil Sci Plant Anal. 23:1161-1178.

• Lindsay WL, Norvell WL. 1978. Development of DTPA soil test for zinc, iron, manganese and copper. Soil Sci Soc Am J. 42:421-428.

• Loska K, Wiechulła D, Korus I. 2004. Metal contamination of farming soils affected by industry. Environ Intl. 30(2):159-165.

• Lu X, Wang l, Lei K, Huaing J, Zhai Y. 2009. Contamination assessment of Copper, Lead, Zinc, Manganese and Nickel in street dust of Boaji, NW China. J Hazard Mater. 161:1058-1062.

• Mahajan A, Sharma SK, Gupta RD, Sharma R. 2007. Morphological, Physical and Chemical Properties of Soils from North West Himalayas. Bulg J Agric Sci. 13:607-618.

• Manno E, Varrica D, Dongarrá G. 2006. Metal distribution in road dust samples collected in an urban area close to a petrochemical plant at Gela, Sicily. Atmos Environ. 40:5929-5941

• Milligan GW, Cooper MC. 1988. A study of standardization of variables in cluster analysis. J Class. 5:181-204.

• Minakshi TNS, Nayyar VK, Sharma PK, Sood AK. 2005. Spatial distribution of micronutrients in soils of Patiala district – a GIS approach. J Indian Soc Soil Sci. 53:324-329.

• Moslehuddin AZM, Egashira K. 1996. Mineralogical composition of some important paddy soils of Bangladesh. Bull Inst Trap Agric Kyushu Univ. 19:33-54.

• Moslehuddin AZM, Laizoo S, Egashira K. 1999. Trace Elements in Bangladesh Paddy Soils. Commun Soil Sci Plant Anal. 30:1975-1996.

• Muller G. 1969. Index of geoaccumulation in sediments of the Rhine River. Geol J. 2:109-118.

• Nanson GC, Croke JC. 1992. A genetic classification of floodplains. Geomorphol. 4:459-486.

• Nene YL. 1966. Symptoms, cause and control of Khaira disease of paddy. Bull Indian Phytopathol Soc. 3:97-191.

• Ntekim EE, Ekwere SJ, Ukpong EE.1993. Heavy metal distribution in sediments from Calabar River, southeastern Nigeria. Environ Geol. 21:237-241.

• Patrick WH, Mikkelsen DS, Wells BR. 1985. Plant Nutrient Behaviour in Flooded Soils. In: Engelstad OP, editor. Fertilizer Technology and Use. 3rd edition. Madison, WI: Soil Sci Soc Am. p. 197-228.

• Pegoraro RF, Silva IR, Novais RF, Mendonça ES, Gebrim, FO, Moreira FF. 2006. Diffusive flux and bioavailability of micronutrients in soils: influence of liming, soil texture and green manure. Rev Bras Ciênc Solo 30(5):859-868.

• Rezapour S, Golmohammad H, Ramezanpour H. 2014. Impact of parent rock and topography aspect on the distribution of soil trace metals in natural ecosystems. Intl J Environ Sci Technol. 11:2075-2086.

• Salomons W, de Rooij NM, Kerdijk H, Bril J. 1987. Sediments as a source for contaminants? Hydrobiol. 149:13-30.

• Sangwan BS, Singh K. 1993. Vertical distribution of Zn, Mn, Cu and Fe in some Aridisols of Haryana and their relationship with soil properties. J Indian Soc Soil Sci. 41:463-467.

• Sarma JN. 2005. Fluvial processes and morphology of Brahmaputra river in Assam, India. Geomorphol. 70:226-256.

• Sarma JN, Phukan MK. 2004. Origin and some geo-morphological changes of Majuli island of the Brahmaputra River in Assam, India. Geomorphol. 60:1-19

• Schoeneberger PJ, Wysocki DA, Benham EC, Soil Survey Staff. 2012. Field book for describing and sampling soils, Version 3.0. Lincoln, NE: Natural Resources Conservation Service, National Soil Survey Center.

• Schulz-Zunkel C, Krueger F. 2009. Trace metal dynamics in floodplain soils of the River Elbe: a review. J Environ Qual. 38:1349-1362.

• Sharma BD, Kumar R, Singh B, Sethi M. 2009. Micronutrients distribution in salt-affected soils of the Punjab in relation to soil properties. Archives of Agronomy and Soil Science 55(4):367-377.

• Sharma BD, Mukhopadhyay SS, Sidhu PS, Katyal JC. 2000. Pedospheric attributes in distribution of total and DTPA-extractable Zn, Cu, Mn and Fe in Indo-Gangetic plains. Geoderma 56:31-55.

• Shukla AK, Babu PS, Tiwari PK, Prakash C, Patra AK, Patnaik MC. 2015. Mapping and frequency distribution of current micronutrient deficiencies in soils of Telangana for their precise management. Indian J Fert. 11(8):33-43.

• Shukla AK, Behera SK, Lenka NK, Tiwari PK, Prakash C, Malik RS, Sinha NK, Singh VK, Patra AK, Chaudhary SK. 2016b. Spatial variability of soil micronutrients in the intensively cultivated Trans-Gangetic Plains of India. Soil & Tillage Research 163:282-289.

• Shukla AK, Sinha NK, Tiwari PK, Prakash C, Behera SK, Lenka NK, Singh VK, Dwivedi BS, Majumdar K, Kumar A, Srivastava PC, Pachauri SP, Meena MC, Lakaria BL, Siddiqui S. 2016a. Spatial distribution and management zones for sulfur and micronutrients in Shiwalik Himalayan region of India. Land Degrad Dev. DOI: 10.1002/ldr.2673.

• Shukla AK, Tiwari PK, Prakash C. 2014. Micronutrient deficiencies Vis- a- Vis Food and Nutritional security of India. Indian J Fert. 10(12):94-112.

• Sidhu GS, Sharma BD. 2010. Diethylenetriaminepenta-acetic acid–extractable micronutrients status in soil under a rice–wheat system and their relationship with soil properties in different agroclimatic zones of indo-gangetic plains of India. Commun Soil Sci Plant Anal. 41:29-51.

• Singh MV. 2008. Micronutrient deficiencies in crops and soils in India. In: Alloway B, editor. Micronutrient deficiencies in Global crop production. Netherlands: Springer. p. 93-125.

• Soil Survey Division Staff. 1995. Soil Survey Manual. Agric. Handb. U.S. Dept. Agric. 18. Jodhpur: Indian Print. 437 p.

• Soil Survey Staff. 2014. Keys to Soil Taxonomy. 12th Edition. Washinton, D.C.: U. S. Dept. of Agriculture and Natural Resources Conservation Service.

• Takagi T, Oguchi T, Matsumoto J, Grossman MJ, Sarker MH, Matin MA. 2007. Channel braiding and stability of the Brahmaputra river, Bangladesh, since 1967: GIS and remote sensing analyses. Geomorphol. 85:294-305.

• Takkar PN, Nayyar VK. 1979. Iron deficiency affects rice yield in Punjab. Indian Farming 29:9-12.

• Takkar PN, Nayyar VK. 1981. Preliminary field observations of manganese deficiency in wheat and berseem. Fert News 26:22-23.

• Thorp JH, Thoms MC, Delong MD. 2006. The riverine ecosystem synthesis: biocomplexity in river networks across space and time. River Res Appl. 22:123-147.

• Tockner K, Lorang MS, Stanford JA. 2010. River floodplains are model ecosystems to test general hydro geomorphic and ecological concepts. River Res Appl. 26:76-86.

• Tockner K, Malard F, Ward JV. 2000. An extension of the flood pulse concept. Hydrol Process. 14:2861-2883.

• Tomlinson DL, Wilson JG, Harris CR, Jeffney DW. 1980. Problems in the assessment of heavy metal levels in estuaries and the formation of a pollution index. Helgol Wiss Meeresunter. 33:566-572.

• Torrent J, Schwertmann U, Fetcher H, Alfeve F. 1983. Quantitative relationship between soil colour and hematite content. Soil Sci.136:351-358.

• Valdiya KS. 1987. Environmental Geology in Indian Context. New Delhi: Tata McGraw-Hill Publications.

• Verma VK, Setia RK, Sharm PK, Charanjit S, Kumar AA. 2005. Pedospheric variations in distribution of DTPA-extractable micronutrients in soils developed on different physiographic units in central parts of Punjab, India. Int J Agric Biol. 7:243-246.

• Vinogradov AP. 1966. Chemistry of the Earth´s Crust. Volume 1. Corvallis, USA: The Book Bin, Inc.

• Walkey A, Black IA. 1934. An examination of the digestion method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37:29-38.

• Zhang GL, Gong ZT. 2003. Pedogenic evolution of paddy soils in different soil landscapes. Geoderma 115:15-29.