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Review Article
Soil and Mangrove: A Review

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Abstract

Mangrove forests dominate the coastlines of tropical and subtropical climates of the world. Mangroves provide protection in coastal areas from storms and erosion to help create sources of income for human being. Research on mangroves received little focus earlier in the 20th century. The current knowledge on physico-chemical properties of soil, soil nutrition, ecological relationship of soil and vegetation and relationship of soil with species composition and structure of mangrove forests in tropical mangrove environment is reviewed and discussed. Large differences occur between mangrove forests with respect to soil pH, salinity, bulk density, CEC, nutrients, carbon and organic matter contents of the mangrove soils. Recent findings suggest that different soil properties influence the vegetation, species composition and structure of mangrove forests. In recent years, a considerable research results on mangrove soils are available to improve our knowledge, but there are still significant gaps and shortcomings. These are, therefore, emphasized and relevant research directions are needed. This study provides a considerable updated knowledge which will help in exploring links for future research among soil properties, vegetation, species composition and structure of mangrove forests.

Key words: Soil properties, nutrients, organic matter, species composition, structure, mangroves

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INTRODUCTION

Mangrove forests cover an area of approximately 160,000 km^2 all over the world, in which the largest forest areas are found in Malaysia, India, Bangladesh, Brazil, Venezuela, Nigeria and Senegal (Giri and Muhlhausen, 2008; Alongi, 2009). Mangrove forests play a very important role in coastal ecosystems located at the interface between land and sea in tropical and subtropical areas of the world. Mangrove plants may grow in different types of soil; therefore, their vegetation, species composition and structure may vary considerably at the global, regional and local scales (Vilarrubia, 2000; Sherman *et al.*, 2003). Mangrove soils are of marine alluvium, transported as sediment and deposited by rivers and the sea. Soils are made up of sand, silt and clay in different combinations and mud actually refers to mixture of silt and clay, both of which are rich in organic matter. Topsoil is loosely formed as sandy or clayey types. The lighter-coloured topsoils are porous and facilitate water percolation and aeration during low tide (Fig. 1a). The darker-coloured clayey topsoils are less well aerated (Fig. 1b).

Soils below the surface i.e., sub-soils are typically waterlogged having little aeration facility which reduces with depth and contain a lot of organic matter. The dark grey or black soil found in mangrove forest produces a strong odour due to the presence of hydrogen sulphide resulting from the anaerobic sulphur-reducing bacteria (e.g., *Desuifovibrio* sp.) which thrive in the anoxic condition (Peter and Sivasothi, 2002). The soils in mangrove forest are characterized by the combination of various physical, chemical and biological factors, which may vary considerably among different forest sites (Sherman *et al.*, 1998; Otero and Macias, 2002; Ferreira *et al.*, 2007a, b).

The soils in mangrove forests are complex systems resulting from various intricate interactions between abiotic (tides and physiography) and biotic (activities of plants and invertebrates) factors, that may alter within short distances. Soil attributes such as salinity, iron sulfide concentrations, soil redox potential, nutrients, organic matter and physiographical position are the key factors in determining mangrove species composition and structure (Sherman *et al.*, 1998; Marchand *et al.*, 2004; Otero *et al.*, 2006, 2009). The accumulation and degradation of toxic compounds (Ke *et al.*, 2002) and the mobilization and availability of trace elements also significantly influence the zonation of mangroves (Machado *et al.*, 2002, 2004). Research results revealed significant variation in the composition of mangrove soils at different depths, clay mineralogy, total organic carbon content and carbon stock (Ferreira *et al.*, 2010).

Fig. 1(a-b): (a) Sandy-type topsoil and (b) Clayey-type topsoil of mangrove forest

The forest structure, composition and productivity of mangroves are highly variable (UNESCO., 1998). Different studies between forest structure and soil conditions suggest a wide variation in tree height and productivity in response to temporal and special variation of soil factors, such as soil salinity, nutrient availability and soil fertility (Koch, 1997; Fromard *et al.*, 1998; Feller *et al.*, 2003). Consequent to low salinity gradient and increasing salt tolerance up-river and freshwater plant species are established in the mangroves (Ukpong, 1991). Forest structure and vegetation is also varied depending on the carbon stocks and organic matter of the mangrove soil (Field *et al.*, 1998; Jennerjahn and Ittekkot, 2002; Chmura *et al.*, 2003). The soil of the mangrove forest acts as a reservoir of carbon that is in interaction with the atmosphere, storing about three times the biomass that makes up the vegetation and structure of mangroves (Sa *et al.*, 2001).

A number of published work deals with the soil, species composition and structure of tropical mangrove forest, but still there is a significant lacking in carrying out extensive research and making findings available to the scientific community. This study is, therefore, aims at providing an overview of soil properties, nutritional and ecological relationship of soil with composition and structure of mangrove species in tropical forests.

PHYSICAL PROPERTIES OF SOIL IN MANGROVE FOREST

Studies on mangrove soil revealed that soil surface is mainly composed of newly sedimented particles. Physical properties of the soil from different studies conducted in different mangrove forests worldwide are presented in Table 1. The soils have less than 35, 40 and 45% of sand, silt and clay particles, respectively in different mangrove forests (Sukardjo, 1994; Ukpong, 1997; Sah *et al*., 1989). The soil texture was clay loam in these soils. From the study of Moreno and Calderon (2011), it is observed that the soil texture was sandy clay loam with 53.17% sand particles. Sah *et al*. (1989) reported 48% sand particle with silt loam soil texture. However, lower sand particles and higher silt and clay particles having silty clay loam soil texture are also reported by other researchers (Sah *et al*., 1989; Khan *et al*., 1993). Variable values of bulk density are found in the mangrove forests of the world ranging from 0.73 g cm^{-3} (Ukpong, 1997) to 1.42 g cm^{-3} (Sah *et al*., 1989).

Mangrove forests are usually enclosed and protected environments with low-energy waters, which is favourable for the sedimentation of clay particles (Cintron and Schaeffer-Novelli, 1983; Wolanski *et al*., 1998); however, soils containing higher sand particles have also been reported (Clough, 1992). In a study by Ferreira *et al*. (2010) it is revealed that the sand particle was dominant over clay and silt particles, except in deeper layers in transect 1, in which clay was the dominant size fraction (Fig. 2).

CHEMICAL PROPERTIES OF SOIL IN MANGROVE FOREST

From various studies of tropical mangrove forests worldwide it is observed that mangrove soils may be either acidic or alkaline (Table 2). Some researchers found soil pH ranging from 2.87-6.40 (Khan *et al*., 1993; Sukardjo, 1994; Ukpong, 1997; Rambok *et al*., 2010; Ferreira *et al*., 2010; Moreno and Calderon, 2011). Some other researchers reported soil pH above 7.0 ranging from 7.4-8.22 (Sah *et al*., 1989;

Table 1: Physical properties of soil of worldwide tropical mangrove forests

Names of forest	Regions	Forest type	Sand (%)	Silt (%)	Clay (%)	Soil texture	Bulk density	References
Avicennia forest in Apar nature reserve	East Kalimantan, Indonesia	Primary	30.04	39.86	30.10	Clay loam	110.5 (g 100 mL^{-1})	Sukardjo (1994)
Ceriops forest in Apar nature reserve	East Kalimantan, Indonesia	Primary	31.18	35.77	32.05	Clay loam	138.5 (g 100 mL^{-1})	Sukardjo (1994)
Calabar mangrove swamp	Nigeria	Primary	34.66	44.20	21.14	Clay loam	0.73 (g cm^{-3})	Ukpong (1997)
Hooker Bay mangrove	San Andres Island, Colombia	Fringe	53.17	27.80	18.98	Sandy clay loam	0.9 (g cm^{-3})	Moreno and Calderon (2011)
Prentice Island mangrove	Sunderbans, India	Primary	8.10	61.90	30.00	Silty clay	1.07 (g cm^{-3})	Sah *et al*. (1989)
Lotihan Island mangrove	Sunderbans, India	Primary	19.90	40.20	39.90	Silty clay	1.07 (g cm^{-3})	Sah *et al*. (1989)
Sagar Island mangrove	Sunderbans, India	Primary	48.00	36.10	15.90	Silt loam	1.42 (g cm^{-3})	Sah *et al*. (1989)
Harinbari Island mangrove	Sunderbans, India	Primary	24.20	45.80	29.90	Silty clay	1.26 (g cm^{-3})	Sah *et al*. (1989)
Cheringa mangrove	Bangladesh	Fringe	9.00	44.00	47.00	Silty clay	1.02 (g cm^{-3})	Khan *et al*. (1993)

Table 2: Chemical properties of soil of worldwide tropical mangrove forests

			pH					
Names of forest	Regions	Forest type	H_2O	KCl	Eh (mV)	Soil salinity (‰)	CEC (me 100 g^{-1})	References
Avicennia forest in Apar nature reserve	East Kalimantan, Indonesia	Primary	4.82	4.52	-125	33.00	23.72	Sukardjo (1994)
Ceriops forest in Apar nature reserve	East Kalimantan, Indonesia	Primary	3.95	3.25	-146	29.00	14.15	Sukardjo (1994)
Calabar mangrove swamp	Nigeria	Primary	4.80	-	-	-	34.75	Ukpong (1997)
Hooker Bay mangrove	San Andres Island, Colombia	Fringe	6.14	-	-	35.00		Moreno and Calderon (2011)
Prentice Island mangrove	Sunderbans, India	Primary	8.0	-	-	-	19.59	Sah *et al*. (1989)
Lotihan Island mangrove	Sunderbans, India	Primary	7.5	-	-	-	20.93	Sah *et al*. (1989)
Sagar Island mangrove	Sunderbans, India	Primary	7.4	-	-	-	10.07	Sah *et al*. (1989)
Harinbari Island mangrove	Sunderbans, India	Primary	7.6	-	-	-	21.50	Sah *et al*. (1989)
Cheringa mangrove	Bangladesh	Fringe	3.20	3.00	-	-	15.1	Khan *et al*. (1993)
Wildlife Sanctuary Sibuti mangrove	Miri, Sarawak, Malaysia	Primary	3.34	2.92	-	-	13.87	Rambok *et al*. (2010)
Awat-Awat Lawas mangrove	Limbang, Sarawak, Malaysia	Primary	3.19	2.87	-	-	10.63	Rambok *et al*. (2010)
Sundarban mangrove	NE coast of Bay of Bengal, India	Fringe	8.22	-	-121	14.99	-	Das *et al*. (2012)
Sundarban mangrove	Bangladesh	Fringe	7.67	-	-	28.82	-	Hossain *et al*. (2012)
Crumahu river mangrove	Sao Paulo, Brazil	Fringe	6.4	-	-99	-	-	Ferreira *et al*. (2010)

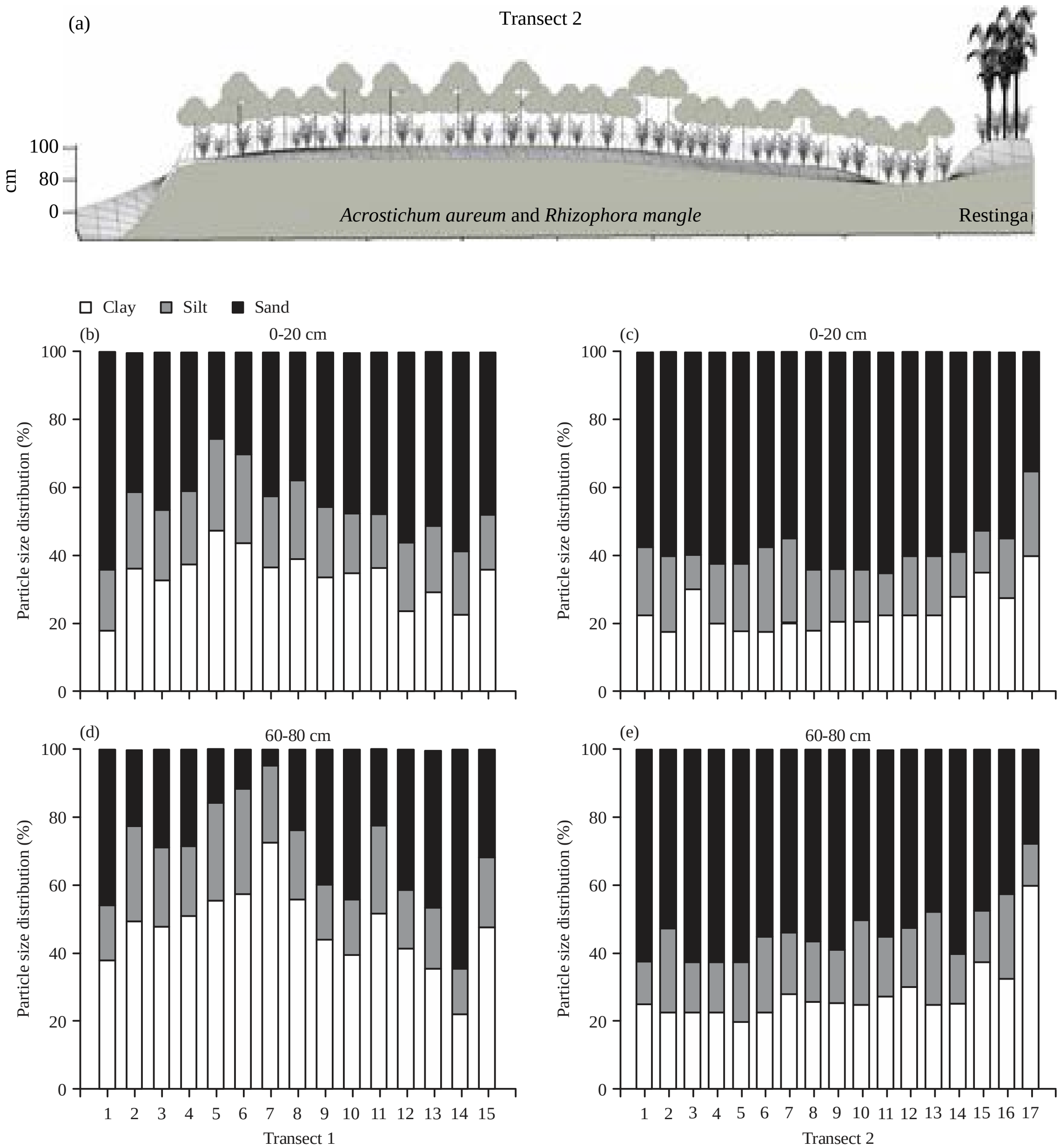

Fig. 2(a-e): Spatial distribution and depth-related distribution of clay, silt and sand particles in soils from two transects (Ferreira *et al*., 2010)

Hossain *et al*., 2012; Das *et al*., 2012). From the values of redox potential (Eh) studied in mangrove soils in different areas of the world it is found that the Eh value is less than 100 mV meaning that the soils are anaerobic. The variability of the mangrove forest in terms of soil salinity is observed all over the world. In some forests the salinity values are obtained more than 30‰ (Sukardjo, 1994; Moreno and Calderon, 2011). However, the salinity value of 14.99‰ is also observed by Das *et al*. (2012). Different studies indicate that the Cation Exchange Capacity (CEC) of soils differ among the mangrove forests worldwide ranging from 10.63-34.75 me 100 g^{-1}. The values of CEC above 20 me 100 g^{-1} are observed in some mangrove forests across the world (Sukardjo, 1994; Ukpong, 1997; Sah *et al*., 1989), indicating the presence of large amount of organic matter and suggesting that the soils represent a potentially large sink for cations.

Several available plant nutrients have been studied in different mangrove forests of the world. Total nitrogen values observed ranged from 0.09-0.97% (Table 3). The element phosphorus is measured in different units in different forest

Table 3: Nutritional properties of soil of worldwide tropical mangrove forests

Names of forest	Regions	Forest type	N (%)	P	K (me 100 g^{-1})	Ca (me 100 g^{-1})	Mg (me 100 g^{-1})	Na (me 100 g^{-1})	Cl (%)	References
Avicennia forest in Apar nature reserve	East Kalimantan, Indonesia	Primary	0.37	8.73 (ppm)	0.29	80.55	40.12	87.88	-	Sukardjo (1994)
Ceriops forest in Apar nature reserve	East Kalimantan, Indonesia	Primary	0.97	26.34 (ppm)	0.17	66.65	25.23	74.94	-	Sukardjo (1994)
Calabar mangrove swamp	Nigeria	Primary	0.09	1.22 (μg mL^{-1})	0.08	12.80	16.73	0.48	2.70	Ukpong (1997)
Hooker Bay mangrove	San Andres Island, Colombia	Fringe								Moreno and Calderon (2011)
Prentice Island mangrove	Sunderbans, India	Primary	-	-	-	10.81	8.02	0.45	-	Sah *et al.* (1989)
Lotihan Island mangrove	Sunderbans, India	Primary	-	-	-	12.16	6.31	0.56	-	Sah *et al.* (1989)
Sagar Island mangrove	Sunderbans, India	Primary	-	-	-	6.72	0.54	1.23	-	Sah *et al.* (1989)
Harinbari Island mangrove	Sunderbans, India	Primary	-	-	-	10.90	3.27	1.53	-	Sah *et al.* (1989)
Cheringa mangrove	Bangladesh	Fringe	0.60	5.2 (mg kg^{-1})	0.79	0.71	1.21	4.53	3.32	Khan *et al.* (1993)
Wildlife Sanctuary Sibuti Mangrove	Miri, Sarawak, Malaysia	Primary	0.22	25.27 (%)	-	-	-	-	-	Rambok *et al.* (2010)
Awat-Awat Lawas Mangrove	Limbang, Sarawak, Malaysia	Primary	0.15	12.32 (%)	-	-	-	-	-	Rambok *et al.* (2010)
Sundarban mangrove	Bangladesh	Fringe	0.09	-	-	-	-	-	-	Hossain *et al.* (2012)

N: Nitrogen, P: phosphorus, K: Potasium, Ca: calcium, Mg, Magnesium, Na: Sodium, Cl: Chlorine

Table 4: Organic carbon and organic matter of soil of worldwide tropical mangrove forests

Namse of forest	Regions	Forest type	Organic carbon (%)	Organic matter (%)	References
Avicennia forest in Apar nature reserve	East Kalimantan, Indonesia	Primary	3.96	6.81	Sukardjo (1994)
Ceriops forest in Apar nature reserve	East Kalimantan, Indonesia	Primary	11.40	19.61	Sukardjo (1994)
Calabar mangrove swamp	Nigeria	Primary	6.43	11.06	Ukpong (1997)
Hooker Bay mangrove	San Andres Island, Colombia	Fringe	13.31	22.89	Moreno and Calderon (2011)
Prentice Island mangrove	Sunderbans, India	Primary	0.55	0.95	Sah *et al.* (1989)
Lotihan Island mangrove	Sunderbans, India	Primary	0.62	1.07	Sah *et al.* (1989)
Sagar Island mangrove	Sunderbans, India	Primary	0.65	1.12	Sah *et al.* (1989)
Harinbari Island mangrove	Sunderbans, India	Primary	0.75	1.29	Sah *et al.* (1989)
Cheringa mangrove	Bangladesh	Fringe	2.92	5.02	Khan *et al.* (1993)
Wildlife Sanctuary Sibuti mangrove	Miri, Sarawak, Malaysia	Primary	12.18	20.96	Rambok *et al.* (2010)
Awat-Awat Lawas mangrove	Limbang, Sarawak, Malaysia	Primary	9.38	16.20	Rambok *et al.* (2010)
Sundarban mangrove	Bangladesh	Fringe	0.38	0.65	Hossain *et al.* (2012)

areas. Rambok *et al.* (2010) reported the highest (25.27%) phosphorus in Sibuti mangrove, Sarawak, Malaysia while Sukardjo (1994) reported 26.34 ppm phosphorus in Apar nature reserve mangrove, Indonesia. From the data shown in Table 3 a considerable variation is observed in the nutrient values of K, Ca, Mg, Na and Cl. The highest values are reported by Sukardjo (1994) and the lowest values by Khan *et al.* (1993).

Organic carbon and organic matter contents of the mangrove soils are widely varied in different mangrove forests of the world (Table 4). The organic carbon and organic matter values ranged from 0.38 and 0.65-13.31 and 22.89%, respectively. In some mangrove forests above 10% organic carbon is reported (Sukardjo, 1994; Rambok *et al.*, 2010; Moreno and Calderon, 2011), reflecting the peaty nature of the soils. However, less than one per cent organic carbon reported by Sah *et al.* (1989) and Hossain *et al.* (2012) indicates the poor nutritional conditions of the soils of some mangrove forests.

ECOLOGICAL RELATIONSHIP OF SOIL AND VEGETATION IN MANGROVE FOREST

It is reported that tidal inundation seemed to affect soil salinity in mangrove forest. Mangroves are salt tolerant and relative tolerance varies among species. Mangrove vegetation is more luxuriant in lower salinities (Kathiresan *et al.*, 1996) and experimental evidence indicates that at high salinity, mangroves spend more energy to maintain water balance and ion concentration rather than for primary production and growth. It is also evident that under high salinity levels mangrove biomass production and retention are adversely affected that influence vegetation in mangrove forest (Lin and Sternberg, 1993; Suwa *et al.*, 2009). Ecological group classification in Sundarbans mangroves indicates that *Avicennia marina* and *A. officinalis* can tolerate wide range of soil salinity while *Aegiceras corniculatum*, *Ceriops decandra*, *Dalbergia spinosa*, *Derris trifoliate* and *Excoecaria agallocha* are restricted to low salinity areas. Most species had an optimum pH range except *Avicennia marina*, which occurred in varied pH conditions. *Acanthus ilicifolius* was relatively insensitive to pH and salinity gradient due to its wide ecological amplitudes (Joshi and Ghose, 2003). In another study, it was observed that *Avicennia marina* was the most salinity tolerant species, followed by *Rhizophora mucronata*, *Ceriops tagal* and *Lumnitzera racemosa*. *Excoecaria agallocha* was the least salt tolerant species (Perera *et al.*, 2013). From an ecological investigation of mangrove forest it is observed that the mangrove-*Rhizophora mangle*, *Rhizophora racemosa*, *Rhizophora harrisonii* and *Avicennia africana* commonly

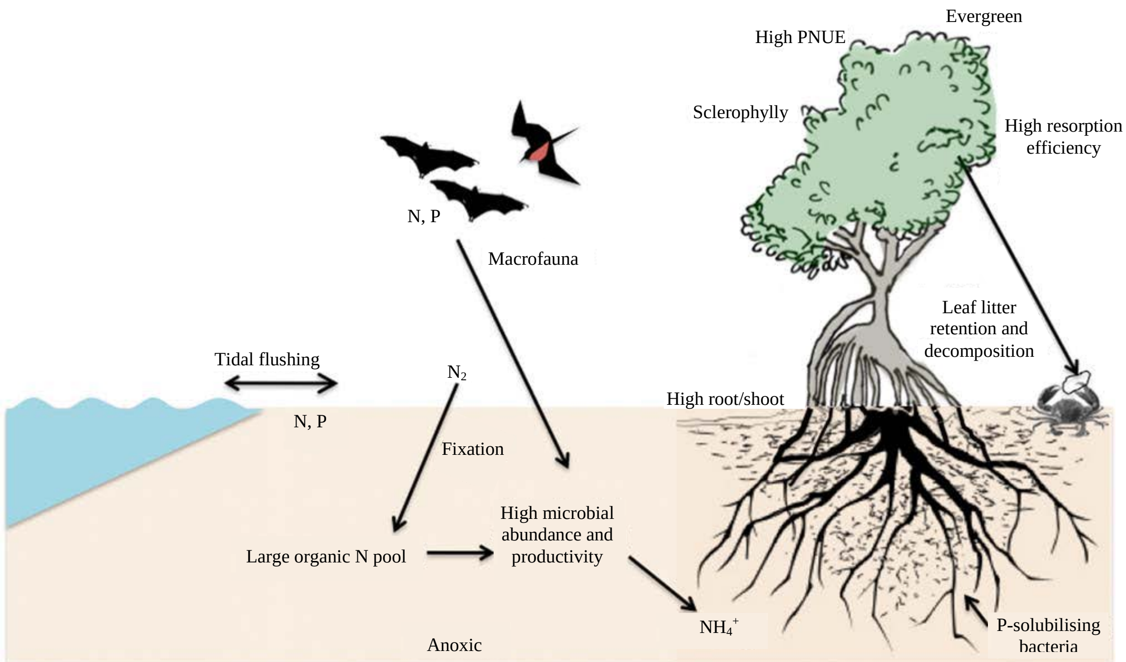

Fig. 3: Schematic diagram for the processes of tidal flushing, nitrogen fixation, microbial activity, leaf litter and abundant macrofauna as well as the nutrient conservation mechanisms characteristic of mangrove forests (Komiyama *et al*., 2008)

occur in mixed stands with the associes-*Nypa fruticans*, *Phoenix reclinata*, *Acrostichum aureum*, *Acutas afer*, *Vossia cuspidate* and *Selaginella* spp. (Ukpong, 1997).

Some studies have underscored that mangrove vegetation is influenced by critical ecological processes such as denitrification, nitrogen fixation (Pelegrai *et al*., 1997, 1998), phosphorus sedimentary processes (Chen and Twilley, 1999) and mangrove-water column nutrient exchange (Childers *et al*., 1999; Davis III *et al*., 2003). Mangroves are a diverse group of plants and are an ecological entity with little phylogenetic association. This may lead to marked differences in soil properties, nutrient uptake, nutrient availability and productivity of mangrove vegetation (Fig. 3).

RELATIONSHIP OF SOIL PROPERTIES WITH SPECIES COMPOSITION AND STRUCTURE OF MANGROVE FOREST

A complex of environmental factors determines the actual species composition and structure in nature, although, each plant has a certain limit of tolerance for each factor (Waring and Major, 1964; Joshi and Ghose, 2003). Since the mangrove habitat is basically saline, several studies have attempted to correlate salinity with the species composition, structure and productivity (Lugo, 1980; Mall *et al*., 1987; Ukpong, 1991; Chen and Twilley, 1998, 1999). Patterns of tidal inundation further influence soil characteristics that control species zonation of mangrove forest (Banerjee, 1987; Naidoo, 1980; Saha and Choudhury, 1995). Patches and zones of forest composition result from complex gradients of hydroperiod and soil conditions, such as nutrient limitation (Feller, 1995; Ukpong, 1998) and abiotic stresses such as salinity and sulfide (Nickerson and Thibodeau, 1985; McKee, 1993). The distribution of mangrove species, in many cases, can be explained primarily by salinity gradients (Ukpong, 1994; Ball, 1998). Spatial differences in soil salinity influence the species composition and distribution of the mangrove forest due to differences in the ability to support high and fluctuating salinity between mangrove trees (Verheyden *et al*., 2005; Robert *et al*., 2009). The pH of a soil significantly affects species composition, primarily due to the change in availability of both essential elements such as Phosphorus (P), as well as non-essential elements such as Aluminium (Al) that can be toxic to plants at elevated concentrations (Black, 1993; Slattery *et al*., 1999). The importance of both salinity and pH for species composition and structure of mangroves has been emphasized by Wakushima *et al*. (1994a, b).

Variation in forest structure emerges due to the complex interactions among soil and plant factors (Lovelock *et al*., 2005). Wide variation in forest structure has been correlated with variation in soil physico-chemical characteristics and particularly with variation in salinity (Joshi and Ghose, 2003);

soil NO_3, especially the nitrate to phosphate ratio, soil moisture content and soil temperature (McDonald *et al*., 2003). It is reported that different soil factors strongly influence the occurrence, growth and structure of mangroves, which include soil erosion, sedimentation rates, salinity, nutrient inputs and soil quality (Perera *et al*., 2013).

Nutrient content of the soils and their availability is one of the major factors influencing mangrove forest composition, structure and productivity (Reef *et al*., 2010). Many mangrove soils have extremely low nutrient availability (Lovelock *et al*., 2005), but nutrient availability varies greatly between mangroves and also within a mangrove stand (Feller *et al*., 2003). Nutrient availability is one of the three dominant components influencing mangrove structure (Ukpong, 1997). Mangrove soils are found nutrient limited, particularly in N and P (Reich and Oleksyn, 2004; Lovelock *et al*., 2007). Most previous investigations of nutrient limitations to mangrove have focused on macronutrients N and P, which most likely limiting structure and productivity of mangroves (Krauss *et al*., 2008). Limitations to structure and productivity imposed by iron are also likely, but not yet to be assessed in the field (Alongi, 2010). In mangrove soils, N was considered the primary nutrient that affects species composition and structure of forest, although more recent analysis found that N and P influence structure and composition in approximately equal proportions (Elser and Hamilton, 2007). Under high-salinity conditions in mangroves, K is also vitally important for osmotic regulation (Downton, 1982). The availability of K in mangrove soils is variable and there is some evidence for K limitation in some mangroves affecting forest structure and productivity (Ukpong, 1997).

Mangrove soils are typically saline, anoxic, acidic and frequently waterlogged. The delivery of nutrients in sediments and water during tidal inundation and sporadically in floodwaters associated with cyclones and hurricanes provides significant sources of nutrients for mangroves (Lugo and Snedaker, 1974; Davis III *et al*., 2003). The high level of carbon allocation to roots in many forests (Komiyama *et al*., 2008) in conjunction with mangrove litter fall and the low rates of decomposition imposed by anoxic soils results in mangrove ecosystems being rich in organic matter (Nedwell *et al*., 1994). Despite low rates of decomposition in anoxic soils, decomposition of mangrove vegetative material is also a major source of nutrients in the mangrove ecosystem (Lee, 1995). Topographic factors such as elevation determine the frequency and duration of tidal inundation, which subsequently affects the salinity, oxidation state and nutrient availability of the soil, resulting in complex patterns of nutrient demand and supply that contribute to the variable structure of mangrove forests.

CONCLUSION

In this study, it is discussed that the research advances in understanding of the variation of soil pH, bulk density, texture, CEC, nutrients, salinity, organic carbon and organic matter among the tropical mangrove forests in the world and have indicated a marked research need for inclusive studies. We took an approach to describing the effects of soil physico-chemical factors on ecophysiology and vegetation in mangroves. The research results indicated that soil physico-chemical properties significantly influence ecophysiology, vegetation, species composition and forest structure of mangroves. What is especially new to this study, however, is that we identified the importance of studying physico-chemical properties and determining the influence of more elements as important drivers not only to mangrove establishment on a global scale, but also to develop technologies for effective growth and persistence of mangroves on local scale. Research should attempt to include more subservient site-specific factors of pH, bulk density, texture, salinity, nutrients, organic carbon and organic matters in future evaluations.

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