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Physico-chemical, biochemical and microbial characteristics of soils of mangroves of the Andamans: a post-tsunami analysis

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The mangroves of the Bay Islands accounting for 18% (383 km^2) of the total Indian mangroves were adversely affected by the December 2004 tsunami. Changes in topography, salinity and massive water inflow have led to extensive soil degradation and associated nutrient losses in these mangroves. The major aim of the study was to determine whether the December 2004 tsunami had any effects on soil physico-chemical (pH, electrical conductivity of saturation extract (EC), clay, cation exchange capacity (CEC), organic carbon (OC), total N (TN), Bray phosphorus (P), exchangeable cations (Ca, Mg, K and Na)) and biochemical/microbial parameters (Microbial biomass–C (C_{MIC}), –N (N_{MIC}), N-flush, basal respiration and hydrolytic enzyme activities). The post-tsunami soil samples (disturbed sites) were characterized by higher levels of EC, Na and Mg, while the pre-tsunami soils samples (undisturbed sites) had higher levels of OC, P, K and CEC. The study also revealed marked reductions in microbial biomass and activity in the disturbed sites. C_{MIC}, N_{MIC}, N-flush, basal respiration, and activities of hydrolytic enzymes like BAA-protease, casein-protease, phosphomonoesterase, β-glucosidase, arylsuphatase, invertase, carboxy methyl cellulase and dehydrogenase were considerably lower in the disturbed sites. Higher levels of metabolic quotient (qCO_2) in the disturbed soils indicated comparatively more stressed soil microbial community with reduced substrate utilization efficiency. Apparently, microbial activity was limited by the supply of biologically available substrates like OC in the disturbed sites. Contrarily, the more direct supply of nutrients from decomposing plant litter and the indirect supply of nutrients from the mineralization of organic matter led to significantly higher microbial activity in the undisturbed sites.

Keywords: Biochemical properties, mangrove forests, microbial biomass carbon, soil enzymes, soil microbial activity.

MANGROVES cover an area of around 15 mha (or 1,50,000 km^2) worldwide, with close to 40% of this area found in the countries affected by the December 2004 tsunami. Presently, less than 50% of the area remains, and of this over 50% is degraded due mainly to anthropogenic factors like conversion to fish ponds, agricultural land, etc.[1]. Of the country's total area under mangrove vegetation, 70% is recorded on the east coast and 12% on the west coast. The Bay Islands (Andaman and Nicobar) account for 18% of the country's total mangrove area[2,3]. The insular mangroves exist in the Bay Islands on many tidal estuaries, small rivers, neritic islets and lagoons, accounting for 18% (383 km^2) of the total Indian mangroves. As would be expected, the mangroves along the Andamans coast were adversely affected by the 2004 tsunami.

However, the extent of damage is still not clear and it may take sometime before the final impacts are known, since the deposit of silt may clog the pores of the aerial roots of mangroves, and thus suffocate them. Changes in topography, soil salinity and freshwater inflow from upstream may also adversely affect the mangroves and other coastal forests in the longer term (http://www.fao.org/newsroom/en/news/2005/89119/index.html accessed on 01/02/2008). One of the major consequences of the tsunami is the extensive soil degradation and associated nutrient losses.

In order to minimize soil degradation and to adopt management techniques that contribute to the maintenance or recovery of soil fertility, the soil quality should be ascertained in order to understand the limits that can be set to its use and treatment. Of all the parameters that determine soil quality, biological and biochemical variables are the most sensitive to changes occurring in a soil[4,5] and provide rapid and accurate information on changes in soil quality due to their sensitivity to environment stress[6], role in degradation[7] and strong influence on microbially mediated processes like nutrient cycling,

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nutrient capacity and aggregate stability[8]. Sufficient data on these parameters will, therefore, be immensely useful for detecting possible degradation and estimating the degree of recovery of degraded mangrove soils during rehabilitation.

This study reports the results of post-tsunami analysis on soil biochemical/microbial properties of mangrove forests of the Bay Islands. The aim was to determine the effect of the tsunami on soil physico-chemical and biochemical/microbial properties of the mangrove forests in the region. For the study, soil cores (0–30 cm) were taken from ten randomly selected spots from within the intertidal zone of ten mangrove forest sites in March 2006. All core samples were collected at low tide. The tsunami hit (disturbed) mangrove sites selected for the study are Manjeery, Burmanalha, Kodiyaghat, Sippighat, Wandoor, Shole Bay, Kalataung, Yerata, Barataung and Potataung. The soils were then sieved (<2 mm), analysed for moisture content and stored at 4°C for not more than one week before analyses. Sub-samples for the determination of organic C and total N were sieved to pass a 0.5 mm mesh. Electrical conductivity (EC) was measured in saturated extracts using a conductivity meter. A combined glass–calomel electrode was used to determine the pH of aqueous suspensions (1 : 2.5 solid/liquid ratio).

Before chemical analysis, samples were washed with 60% (v/v) aqueous ethanol to remove salts. Total N and organic C were determined using standard methods[9]. Clay content was determined by the pipette method[10] and cation exchange capacity (CEC) by the method of Gillman[11]. Exchangeable cations (Ca, Mg, K and Na) were extracted in ammonium acetate[12], followed by determination of Ca, Mg and K by atomic absorption and Na by flame photometry. Bray P was measured using the dilute-acid fluoride extractant[13] and soil Al and Fe using the spectrophotometric methods described by Barnhisel and Bertsch[14] and Olson and Ellis[15] respectively.

Microbial biomass C (C_{MIC}) and N (N_{MIC}) were determined using the chloroform fumigation technique[16], utilizing a factor of 0.45 (refs 17 and 18) and 0.54 (refs 19 and 20) respectively. Nitrogen flush was calculated from the difference between ninhydrin-reactive N in fumigated and non-fumigated samples[21]. Basal respiration (CO_2 evolution) was determined by adjusting the moisture content to 55% of water-holding capacity and pre-incubating the soil samples, as described by Salamanca *et al.*[22]. Dehydrogenase was assayed using 2,3-5 triphenyl tetrazolium chloride as the substrate[23], urease using urea as the substrate[24], BAA-protease and casein-protease using α-benzoyl-*N*-argininamide (BAA) and casein respectively, as substrates[25], acid phosphomonoesterase using *p*-nitrophenol phosphate as the substrate[26], β-glucosidase using *p*-nitrophenyl-β-D-glucopyranoside as the substrate[27], phosphodiesterase using *bis-p*-nitrophenyl phosphate as the substrate[28], arylsulphatase using *p*-nitrophenyl sulphate as the substrate[29], invertase using saccharose as the substrate[30], and carboxy methyl cellulase using carboxymethyl cellulose as the substrate[30].

Maxima, minima, means and standard deviations (SD) of the soil variables are expressed on an oven-dry soil basis (105°C). The results were then compared with our earlier unpublished data on soils collected from the same mangrove sites in March 2004. The relationships between the different parameters were determined by the Pearson's correlation test and the interdependence of the soils variables was determined by principal component analysis (PCA).

For convenience, in the subsequent sections the tsunami-hit mangrove forest sites will hitherto be referred to as disturbed sites. Soil pH was acidic and exhibited little variation among the sites (Table 1). Electrical conductivity (EC of the saturation extract) was considerably higher at the disturbed sites (33.8 ± 1.5 dS m^{-1}), indicating accumulation of salts. In contrast, Al_2O_3 and Fe_2O_3 showed very little variation compared to CEC, which declined marginally from 236 ± 31 to 225 ± 23 mmol kg^{-1} due to disturbance. On the contrary, the clay content was lower by 35%, Bray P by 31%, and organic C by 25% at

Table 1. Relevant properties of soils at the undisturbed and tsunami-hit mangrove sites

	Undisturbed sites			Tsunami-hit sites		
	Minimum	Maximum	Mean ± SD	Minimum	Maximum	Mean ± SD
pH	4.1	6.7	5.3 ± 1.00	3.6	6.2	4.8 ± 0.95
EC (dS m^{-1})	20.3	25.6	23.2 ± 1.70	31.3	36.2	33.8 ± 1.5
Total N (mg g^{-1})	2.01	2.81	2.34 ± 0.24	2.0	2.85	2.36 ± 0.31
Organic C (mg g^{-1})	14.1	24.6	19.1 ± 3.4	9.9	22.4	14.3 ± 4.3
CEC (mmol kg^{-1})	202	286	236 ± 31	189	275	225 ± 23
Bray P (mg 100 g^{-1})	19.2	37.4	25.6 ± 6.1	14.7	20.9	17.7 ± 2.3
Exchangeable K ($Cmol_c$ kg^{-1})	1.12	1.35	1.25 ± 0.08	0.81	1.06	0.90 ± 0.07
Exchangeable Ca ($Cmol_c$ kg^{-1})	6.7	7.9	7.0 ± 0.6	6.1	7.4	6.7 ± 0.4
Exchangeable Mg ($Cmol_c$ kg^{-1})	3.2	3.8	3.4 ± 0.2	4.1	4.9	4.5 ± 0.2
Exchangeable Na ($Cmol_c$ kg^{-1})	8.2	12.7	10.9 ± 1.5	10.3	15.8	13.8 ± 1.7
Al_2O_3 (%)	0.31	1.55	1.12 ± 0.36	0.33	1.45	1.14 ± 0.24
Fe_2O_3 (%)	0.21	1.63	1.14 ± 0.29	0.15	1.34	1.10 ± 0.14
Clay (%)	19	27	23 ± 3	11	19	15 ± 3

Table 2. Values of soil microbial and biochemical parameters at the undisturbed and tsunami-hit mangrove sites

	Undisturbed sites			Tsunami-hit sites		
	Minimum	Maximum	Mean ± SD	Minimum	Maximum	Mean ± SD
Microbial biomass C (μg g^{-1})	370	504	426 ± 50	242	352	286 ± 36
Microbial biomass N (μg g^{-1})	33.2	48.8	39.6 ± 4.6	23.0	30.0	27.3 ± 2.6
N flush (μg g^{-1})	7.6	14.9	11.9 ± 2.8	5.6	12.8	9.8 ± 1.6
Basal respiration (μg CO_2–C g^{-1} per day)	11.6	16.2	13.2 ± 2.3	8.9	13.5	10.9 ± 1.7
qCO_2 (mg CO_2–C g^{-1} biomass C per day)	23.9	47.6	31.0 ± 5.2	23.4	44.6	38.0 ± 3.2
Dehydrogenase (nmol TPF g^{-1} h^{-1})	253	513	412 ± 86	121	278	212 ± 42
Catalase (mmol H_2O_2 consumed g^{-1} h^{-1})	1.76	4.51	3.53 ± 0.87	0.81	1.46	1.21 ± 0.19
Phosphomonoesterase (μmol *p*-nitrophenol g^{-1} h^{-1})	11.5	20.4	15.48 ± 2.90	5.2	9.4	7.34 ± 1.43
Phosphodiesterase (μmol *p*-nitrophenol g^{-1} h^{-1})	3.5	6.2	5.03 ± 1.02	3.1	5.7	4.54 ± 0.95
Arylsulphatase (μmol *p*-nitrophenol g^{-1} h^{-1})	0.51	1.00	0.73 ± 0.18	0.46	1.23	0.68 ± 0.11
Urease (μmol NH_3–N g^{-1} h^{-1})	6.0	17.0	12.8 ± 3.0	5.8	15.7	11.7 ± 3.1
BAA-protease (μmol NH_3–Ng^{-1} h^{-1})	6.33	8.74	7.39 ± 0.90	4.66	8.18	6.35 ± 1.09
Casein-protease (μmol tyrosine g^{-1} h^{-1})	2.3	4.6	3.6 ± 0.4	1.2	2.5	2.0 ± 0.4
β-Glucosidase (μmol *p*-nitrophenol g^{-1} h^{-1})	3.4	6.7	5.5 ± 1.1	2.1	5.2	3.7 ± 0.9
CM cellulase (μmol glucose g^{-1} h^{-1})	0.61	0.94	0.78 ± 0.11	0.25	0.76	0.43 ± 0.10
Invertase (μmol glucose g^{-1} h^{-1})	7.8	15.7	12.4 ± 2.7	5.4	13.7	9.8 ± 2.1

the disturbed sites. Gomez and Fortes[31] also observed greater organic matter levels in the surface soils of undisturbed mangrove forests of Pagbilao, Quezon. Lower clay and organic C levels at the disturbed sites indicated washing away of finer soil particles, organic fractions and litter by the flood. On the contrary, greater levels of organic C and nutrients like P and K at the undisturbed sites are due in large part to nutrient regeneration from fallen leaves, twigs, buds, flowers, decaying roots, etc[32]. Among the exchangeable cations, Ca did not show much variation among the sites, while K was greater at the undisturbed sites. On the contrary, Mg and Na levels were markedly higher at the disturbed sites. This finding is consistent with the possibility that overflowings during tsunami were relatively high in Na and Mg ions, which then accumulated near or on the soil surface.

Among the biochemical parameters, C_{MIC} level at the undisturbed sites was on an average 426 ± 50, which decreased to 286 ± 36 μg g^{-1}, indicating a 33% decline (Table 2), possibly due to decreased microbial activity in response to lower levels of organic C and nutrients in the disturbed sites. Earlier studies on total litter productivity at various mangrove sites of the Andamans indicate considerably lower annual litter fall at the disturbed mangrove sites (472 g dry wt m^{-2}) compared to the undisturbed sites (830 g dry wt m^{-2})[33]. Since microbial biomass in forest soils is largely governed by litter fall[34], greater microbial biomass at the undisturbed sites reflects greater accumulation of plant residues and organic C, which are substrates for soil microbes[35]. This is reflected in the extistence of a strong correlation between microbial biomass and organic C ($r = 0.76$ at $P < 0.05$; $n = 200$). This is expected since both are part of the organic matter pool[36] and microbial biomass is influenced more quickly by organic inputs than by changes in organic matter[37].

Similar to C_{MIC}, the average levels of N_{MIC} and N flush at the disturbed sites (27.3 ± 2.6 and 9.8 ± 1.6 μg g^{-1} respectively) were lower by 31 and 18% compared to the undisturbed sites (39.6 ± 4.6 and 11.9 ± 2.8 μg g^{-1} respectively; Table 2). Since N flush is a measure of the microbial biomass, a small biomass would have a low N flush[38]. Therefore, greater N flush values at the undisturbed sites indicate greater microbial activity and microbial biomass as reflected by the high correlation between C_{MIC} and N flush ($r = 0.78$; $P < 0.01$). Lower levels of C_{MIC} and microbial activity led to lower basal respiration rates in the disturbed soils. Average CO_2 evolution rates declined by 17% (10.9 ± 1.7 μg CO_2–C g^{-1} per day) in the disturbed sites compared to the undisturbed sites (13.2 ± 2.3 μg CO_2–C g^{-1} per day). On the contrary, metabolic quotient (qCO_2) was higher by 23% in the disturbed sites (38.0 ± 3.2) compared to the undisturbed sites (31.0 ± 5.2). Higher qCO_2 in the disturbed soils indicated microbial community with less catabolic activity[39] and reduced efficiency of substrate utilization or high energy requirements and comparatively more stressed microbial community which was less metabolically efficient[40].

The results pertaining to soil enzyme activities were also identical to those of microbial biomass. The activities of these enzymes were reduced to varying degrees at the disturbed sites (Table 2). Accumulation/stabilization of organic matter[41] coupled with greater microbial activity[42] might explain the greater levels of enzyme activities at the undisturbed sites. On the contrary, loss in nutrients, organic matter and dissolved organic substrates due to forced water flow would have reduced microbial activity and therefore decreased enzyme activity in the disturbed sites. Numerous studies have shown that soil microbial community is influenced by organic C, which

is the principal factor influencing growth and activity of microbial community[43]. Also, in soils under fluvial systems, the sediments are transported in suspension and in bed-load together with bacteria adhering to the transported particles[44] leading to reduced microbial load and enzyme activity. Besides, reduced microbial/enzyme activity at the disturbed sites would also be due to excess salt accumulation (as evidenced by markedly higher EC levels) and osmotic desiccation leading to microbial cell lysis, and a salting-out effect modifying the ionic conformation of the active site of the enzyme protein[45].

In order to clarify the structure of interdependence of various biochemical parameters and soil variables, a joint principal components analysis was done (Table 3). The first factor was loaded by C_{MIC}, N_{MIC}, basal respiration, N flush, dehydrogenase, catalase, β-glucosidase, invertase, casein-protease, OC, Bray P and K, indicating the size and activity of the microbial community and the logical dependence of soil microbes on nutrient content. The high loadings of invertase and casein-protease also suggest that the activities of both these enzymes depend on the microbial community than on their extracellular accumulation in soil. Phosphomonoesterase CM-cellulose, organic C and total N were combined as the second factor characterizing accumulation of hydrolytic enzymes and organic matter in mangrove soils. The third factor was defined by qCO_2 reflecting specific metabolic activity of soil microbes. The high loadings of urease and BAA-protease in the third factor confirmed the independence of the degradation of low molecular weight nitrogen compounds in these soils.

Table 3. Oblique solution primary pattern matrix of the principal components analysis (orthotran/varimax transformation; $n = 200$) for the different physico-chemical and biochemical and microbial properties of the mangrove soils

	Factor 1	Factor 2	Factor 3
C_{MIC}	0.72	n.s.	n.s.
N_{MIC}	0.74	n.s.	n.s.
Basal respiration	0.64	n.s.	n.s.
N flush	0.69	n.s.	n.s.
qCO_2	n.s.	n.s.	0.74
Dehydrogenase	0.75	n.s.	n.s.
Catalase	0.66	n.s.	n.s.
Phosphomonoesterase	n.s.	0.71	n.s.
Phosphodiesterase	n.s.	n.s.	n.s.
Arylsulphatase	n.s.	n.s.	n.s.
Urease	n.s.	n.s.	0.64
BAA-protease	n.s.	n.s.	0.68
β-Glucosidase	0.65	n.s.	n.s.
CM cellulase	n.s.	0.71	n.s.
Invertase	0.66	n.s.	n.s.
Casein -protease	0.62	n.s.	n.s.
PH	n.s.	n.s.	n.s.
CEC	n.s.	n.s.	n.s.
Clay	n.s.	n.s.	n.s.
Organic C	0.64	0.55	n.s.
Total N	n.s.	0.70	n.s.
Bray P	0.64	n.s.	n.s.
Exchangeable K	0.75	n.s.	n.s.
Al_2O_3	n.s.	n.s.	n.s.
Fe_2O_3	n.s.	n.s.	n.s.
Explained variance (%)	41.9	24.2	18.3

n.s., Not significant.

Overall, it is apparent that microbial biomass and activity were markedly higher at the undisturbed sites possibly due to greater levels of labile soil organic matter[45]. Apparently destruction of mangrove vegetation by the tsunami led to decreased litter additions to the soil in the disturbed sites. Consequently, clay content, nutrient (Bray P, exchangeable K) and organic C levels in the soils decreased at the disturbed sites. Besides, the levels of soil C_{MIC}, N_{MIC}, N flush, CO_2 evolution rates and enzyme activities were also reduced by varying degrees. Decreased litter addition/accumulation coupled with loss in organic matter and therefore, microbial activity seems to be the likely reason for lower levels of microbial biomass and enzyme activities in the sites ravaged by the tsunami. The study reveals a clear cause-and-effect mechanism between tsunami and soil quality deterioration at these mangrove sites. This would mean a decrease in microbial-mediated processes like nutrient cycling, nutrient capacity and aggregate stability in the disturbed soils. While the results are important in detecting the extent of soil degradation and could be used for post-tsunami reconstruction of the mangrove ecosystem in the Bay islands, such degradation could be transient in regions where mangrove forest restoration is considered imperative. However, in regions where little effort is made for post-tsunami reconstruction the consequences could be serious, leading to long-term damage to the mangrove ecosystem.

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