Ecological Indicators 32 (2013) 253–258

Contents lists available at SciVerse ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Soil biochemical/microbial indices as ecological indicators of land use change in mangrove forests

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ARTICLE INFO

Article history:
Received 1 February 2013
Received in revised form 19 February 2013
Accepted 30 March 2013

Keywords:
ATP
Deforestation
Ergosterol
Metabolic quotient
Soil microbial biomass
Soil respiration

ABSTRACT

The objective of the study was to examine the long-term changes in biochemical/microbial indicators of soil quality due to clear felling of mangroves for establishment of plantations. The biochemical/microbial parameters included dissolved organic-C (DOC) and -N (DON), soil microbial biomass-C (SMBC), -N (SMBN) and -P (SMBP), soil respiration (SR), metabolic quotient (qCO_2), adenylates (ATP, AMP and ADP), adenylate energy charge (AEC), ergosterol and their ratios. Results revealed that the undisturbed mangroves possessed considerably greater amounts of soil organic C, DOC and DON. Consequently, SMBC, SMBN and SMBP showed marked reductions in the plantations suggesting an average loss of 66%, 49% and 75%, respectively due to changed land use. Likewise, SR decreased by 46.4% in the plantations. Enhanced qCO_2 levels in the plantations indicated a microbial community under stress with a high maintenance carbon demand, while lower qCO_2 levels in the mangroves indicated an efficient microbial community and a better use of available organic substrates. The levels of ATP, AMP and ADP followed a trend identical to that of SMB and SR. Greater ergosterol concentration led to greater ergosterol/SMBC ratio suggesting a shift in the microbial community structure from a primarily fungi dominated SMB in the mangroves to a fungi recessive SMB in the plantations.

1. Introduction

Mangroves are one of the most productive and bio diverse wetlands on earth. They are recognized as being an important component of the global C cycle and account for 11% of the total input of terrestrial carbon into the ocean (Jennerjahn and Ittekkot, 2002) and 10% of the terrestrial dissolved organic carbon (DOC) exported to the ocean (Dittmar et al., 2006). But these unique coastal tropical forests are among the most threatened habitats in the world and presently, less than 50% remain, and of this, over 50% is degraded (http://mangroveactionproject.org; accessed on 19/2/2013). These forests cover an area of around 137,760 km^2 m ha in 118 countries and territories and approximately 75% of mangroves are concentrated in just 15 countries (Giri et al., 2011). They have also reported that the largest extent of mangroves is in Asia (42%) followed by Africa (20%), North and Central America (15%), Oceania (12%) and South America (11%). Among these, the insular mangroves of the Andaman Islands (India) are considered to be the most luxuriant covering an area of 615 km^2 (Saxena et al., 2013). Certain areas of these forests were clear-felled for fire-wood, agriculture and allied activities involving plantations of coconut, arecanut, rubber, padauk and teak. Though extensive research has been carried out on the ecology, structure and functioning of the mangrove ecosystem, very little information is available concerning an array of soil biochemical/microbial indices that are sensitive indicators of soil quality. Such information would provide valuable insight into the extent of soil deterioration and improve the scientific basis of management decisions that contribute to the recovery of soil quality.

The microbial indices and their relationships in the temperate (Díaz-Raviña et al., 2005; Priha et al., 2001; Zheng et al., 2010) and tropical (Dinesh et al., 2003, 2004b; Joergensen, 2010; Salamanca. et al., 2002) forests have been extensively studied. However, there are no reports that have used biochemical/microbial indicators for studying long-term changes in soil quality in the mangroves and adjacent plantations establishment by clearing these mangrove forests. Earlier studies on soil microbial parameters in undisturbed and disturbed mangrove forest sites included either the dead mangrove sites (Dinesh et al., 2004a) or those hit by Tsunami (Ghoshal Chaudhuri et al., 2009).

The major objective of the study was to examine the long-term changes in biochemical/microbial indicators of soil quality due to clear felling of mangroves for establishment of plantations. Besides, soil microbial biomass-C, -N and -P and soil respiration, we also

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http://dx.doi.org/10.1016/j.ecolind.2013.03.035

determined the levels of ergosterol (a fungal biomarker), adenylates (ATP, AMP and AMP) and the ratios of these parameters in these soils. We hypothesized that such land use change in the mangroves forests would markedly influence soil organic substrate and nutrient levels, which would subsequently alter the soil microbial biomass, respiration rates and microbial community in the long-term.

2. Materials and methods

2.1. Site details

The study sites were located in South Andaman Islands, India (10°30′–13°42′ N latitude and 92°14′–94°16′ E longitude). The site details and the dominant tree species in the mangroves are mentioned in Table 1. The soils of all the sites are Entisols derived from fluvio-marine deposits, possessed a peraquic moisture regime and are classified as Typic Sulfaquent. The soil at 0–12 cm is dark grayish brown, clay loam, weak subangular blocky with moderate permeability and many fibrous roots. At 12–30 cm it is light brown gray, clay loam, medium subangular blocky, firm and sticky with moderate permeability and many fine fibrous roots (Ganeshamurthy et al., 2002).

For the study, five luxurious mangrove sites and adjacent plantations of (*Cocos nucifera* L.), arecanut (*Areca catechu* L.), teak (*Tectona grandis* L.f.), rubber (*Hevea brasiliensis* Müll. Arg.) and padauk (*Pterocarpus dalbergioides* Roxb. ex DC.) were chosen. The plantations were developed by clearing the mangrove areas during varying periods of time. The site details and age of the plantations are given in Table 1. The interspaces of the plantations were mostly barren with sparse vegetation. No organic or inorganic fertilizers have been applied to the plantations for the past 5 years and when previously applied were confined only to the base of the respective trees.

2.2. Soil sampling

From each site encompassing an area of 10 ha, 6 random soil cores (0–30 cm, 7 cm Ø) were taken, cleared of any organic debris and transferred for storage in sealed plastic bags. Care was taken to ensure that the sampling points in the mangroves included only those that were not permanently inundated by sea water. Sea water incursion occurred only during periods of high tide (once or twice per day). Once in the laboratory, the uppermost cm, which frequently includes debris and freshly fallen litter was excluded and the soils were sieved (<2 mm), analyzed for moisture content and stored at 4 °C for not more than 10 days before analyses. Subsamples for the determination of SOC and mineral N were sieved to pass a 0.5 mm mesh.

2.3. Soil physico-chemical properties

Soil analyses were done on all the samples from each site. The relevant properties of the soil samples studied are given in Table 2. The soil pH was determined in 1:2.5 soil:water suspension. Total N was determined by the micro-Kjeldahl digestion procedure (Bremner and Mulvaney, 1982), soil organic C (SOC) by the Walkley–Black wet combustion method (Nelson and Sommers, 1982), available P using the dilute acid-fluoride (Bray) extractant (Olsen and Sommers, 1982) and soil Al and Fe using the methods of Barnhisel and Bertsch (1982) and Olson and Ellis (1982) respectively.

2.4. Soil biochemical/microbial properties

Dissolved organic C and N (DOC and DON respectively) were determined by incubating soil samples at constant temperature (20 °C) and moisture (55% water holding capacity-determined by the Pressure Plate method of Klute, 1986) for 3 weeks (Smolander and Kitunen, 2002). Water extractions were made from the samples before and after incubation. The soil samples were shaken in 1.5 L ultra-pure water for 2 h (200 rpm) and the suspensions were centrifuged (20 min at 10,000 rpm) and the supernatants filtered through a series of filters (GF/D and Schleicher and Schuell GF 52 glass fiber filter and 0.45 μm membrane filter) using a vacuum system. The extracts were analyzed for total N using the alkaline persulfate oxidation method (Cabrera and Beare, 1993) and organic C as described earlier. Soil respiration was measured as the CO_2 evolved from moist soil, adjusted to 55% water holding capacity, and pre-incubated for 7 days at 20 °C in the dark. The CO_2 production was then measured for the next 7 days using NaOH traps and titration with HCl (Salamanca. et al., 2002). The soil microbial biomass-C (SMBC), -N (SMBN) and -P (SMBP) were estimated by fumigation-extraction (Vance et al., 1987) using k_{EC} of 0.45 (Joergensen, 1996), k_{EN} of 0.54 (Joergensen and Mueller, 1996) and k_{EP} of 0.40 (Brookes et al., 1982) respectively.

For determination of ergosterol, the soil samples were extracted with 100 mL ethanol for 30 min by oscillating shaking at 250 revolutions min^{-1} (Djajakirana et al., 1996). Ergosterol contents in the extracts were then quantitatively determined by reversed-phase HPLC analysis as described by Joergensen and Castillo (2001). Determination of adenine nucleotides and calculation of adenylate energy charge (AEC = [ATP] + 1/2[ADP]/[ATP] + [ADP] + [AMP]) were done according to the procedure of Bai et al. (1989) as described by

Table 1
Site characteristics of mangrove forest sites and adjacent plantation.

Mangrove forest sites	Dominant vegetation	Adjacent plantation
M1	*Rhizophora apiculata* Blume, *Avicennia marina* (Forssk.) Vierh., *R. mucronata* Lam., *Bruguiera cylindrica* (L.) Blume, *Aegiceras corniculatum* (L.) Blanco, *Sonneratia alba* L.f. *Excoecaria agallocha*	Coconut (*Cocos nucifera* L.) (15–17 years)[a]
M2	*Rhizophora apiculata* Blume, *Avicennia marina* (Forssk.) Vierh., *R. mucronata* Lam., *Bruguiera cylindrica* (L.) Blume, *Aegiceras corniculatum* (L.) Blanco, *Sonneratia alba* L.f. *Excoecaria agallocha*	Arecanut (*Areca catechu* L.) (15–17 years)[a]
M3	*Rhizophora apiculata* Blume, *Avicennia marina* (Forssk.) Vierh., *R. mucronata* Lam., *Bruguiera cylindrica* (L.) Blume, *Aegiceras corniculatum* (L.) Blanco, *Sonneratia alba* L.f. *Excoecaria agallocha*	Teak (*Tectona grandis* L.f.) (21–23 years)[a]
M4	*Rhizophora apiculata* Blume, *Avicennia marina* (Forssk.) Vierh., *R. mucronata* Lam., *Bruguiera cylindrica* (L.) Blume, *Aegiceras corniculatum* (L.) Blanco, *Sonneratia alba* L.f. *Excoecaria agallocha*	Rubber (*Hevea brasiliensis* Müll. Arg.) (19–21 years)[a]
M5	*Rhizophora apiculata* Blume, *Avicennia marina* (Forssk.) Vierh., *R. mucronata* Lam., *Bruguiera cylindrica* (L.) Blume, *Aegiceras corniculatum* (L.) Blanco, *Sonneratia alba* L.f. *Excoecaria agallocha*	Padauk (*Pterocarpus dalbergioides* Roxb. ex DC.) (21–24 years)[a]

[a] Stand age.

Table 2
Physicochemical properties and levels of dissolved organic-C (DOC) and -N (DON) in the undisturbed mangroves and adjacent plantations (mean ± SEM).

Site	pH (1:2.5 H_2O)	Organic C ($g\,kg^{-1}$)	Total N	Bray P ($mg\,kg^{-1}$)	Fe_2O_3 (%)	Al_2O_3	DOC ($mg\,kg^{-1}$)	DON
Mangrove sites								
M1	6.76 ± 0.27	17.2 ± 2.3	1.48 ± 0.32	14.1 ± 2.1	0.29 ± 0.12	0.36 ± 0.12	402 ± 112	42 ± 12
M2	6.72 ± 0.22	18.2 ± 1.7	1.85 ± 0.26	12.0 ± 2.3	0.35 ± 0.11	0.24 ± 0.09	467 ± 96	51 ± 09
M3	6.63 ± 0.34	17.2 ± 1.3	1.64 ± 0.31	21.5 ± 3.2	0.38 ± 0.13	0.44 ± 0.09	422 ± 123	54 ± 11
M4	6.67 ± 0.36	16.6 ± 2.1	1.52 ± 0.42	12.6 ± 1.9	0.44 ± 0.09	0.56 ± 0.11	424 ± 116	47 ± 13
M5	7.15 ± 0.25	16.4 ± 2.2	1.49 ± 0.19	15.6 ± 2.3	0.43 ± 0.11	0.44 ± 0.13	427 ± 89	42 ± 12
Plantation sites								
Coconut	4.70 ± 0.30	7.0 ± 1.1	0.84 ± 0.13	5.6 ± 1.1	0.84 ± 0.19	0.82 ± 0.22	226 ± 72	24 ± 08
Arecanut	4.74 ± 0.27	7.4 ± 1.4	0.84 ± 0.15	4.2 ± 0.9	0.80 ± 0.21	0.79 ± 0.16	216 ± 69	27 ± 08
Rubber	4.62 ± 0.26	8.9 ± 1.1	1.12 ± 0.15	6.3 ± 0.8	0.78 ± 0.21	0.84 ± 0.14	250 ± 75	34 ± 09
Teak	4.83 ± 0.22	6.9 ± 0.9	0.83 ± 0.10	5.1 ± 1.2	0.89 ± 0.23	0.91 ± 0.24	233 ± 69	33 ± 11
Padauk	4.76 ± 0.31	7.9 ± 1.3	0.81 ± 0.17	4.6 ± 0.9	0.81 ± 0.20	0.89 ± 0.22	256 ± 63	30 ± 07
lsd (0.05)	ND	5.4	0.43	3.9	0.23	0.27	74	6

Dyckmans and Raubuch (1997). The adenylates were determined in a 4 g moist soil taken from the 100 g soil sample used for measuring basal respiration. Dimethylsulphoxide (DMSO), Na_3PO_4 (10 mM) buffer + EDTA (20 mM) at pH 12 and nucleotide releasing buffer for microbial ATP (NRB, Celsis) were used as extractants. After derivatisation with chloracetaldehyde, the adenine nucleotides were determined by HPLC as described by Joergensen and Castillo (2001).

2.5. Statistics

Analyses for various properties were performed on all soil samples, mean values determined, and the values are expressed on an oven dry soil basis (24 h at 105 °C). The significance of treatment effects was determined by one-way analysis of variance (ANOVA). Where the *F* values were significant, post hoc comparisons were made using the least significant (LSD) difference test at the 0.05 probability level.

3. Results and discussion

3.1. Soil physico-chemical properties

Soil pH differed markedly among the sites (Table 2) and the mean level across the plantations (4.7) was lower than that in the mangroves (6.8). Conversely, both Fe_2O_3 and Al_2O_3 were appreciably higher in the plantations (mean 0.82 and 0.85%, respectively) than in the mangroves (mean 0.38 and 0.41%, respectively). Organic substrates *viz*., SOC, DOC and DON were lower by 49%, 45% and 37%, respectively in the plantations compared to the mangroves (Table 3). Likewise, the total N and Bray P levels were on an average lower by 44% and 66%, respectively in the plantations. This is consistent with several reports in tropical forest ecosystems that suggest notable losses in total soil N and SOC due to deforestation (Joergensen, 2010; Singh et al., 2010). It is, however, apparent that the mangrove soils contained considerably greater amounts of organic substrates and nutrients which are due in large part to nutrient regeneration from fallen tree litter, decaying roots, etc. (Lacerda et al., 1995), preponderance of dense fibrous roots of the mangrove tree species and the pneumatophores (Upkong, 1997).

3.2. Soil microbial biomass-C, -N and -P

The SMBC, SMBN and SMBP levels were significantly reduced from an average of 472.6, 34.6 and 14.8 $\mu g\,g^{-1}$, respectively in the mangroves to 161, 17.8 and 3.6 $\mu g\,g^{-1}$, respectively in the plantations. This accounted for a loss of 66%, 49% and 75%, respectively in SMBC, SMBN and SMBP levels in the plantations (Table 3). Such reductions can be attributed to reduced input of plant residues due to absence of fresh overstory litter. Plants add energy to the soil system in the form of litter and root exudates which eventually are turned into SMB, which is a major pool responsible for nutrient cycling and for controlling amounts of nutrients available to plants (Ohtonen et al., 1999). Positive linear relationship between SOC and SMBC (Fig. 1) indicated that SMB followed a trend parallel to that of SOC when mangroves are converted to cropland. Numerous reports on SMBC reduction due to forest clearance exist. Reductions as high as 80% (Pfenning et al., 1992), 63–73% (Dinesh et al., 2003, 2004b) and significant decreases in SMBC, SMBN and SMBP levels to the tune of 34.8%, 41.5% and 30.8%, respectively (Singh et al., 2010) have been reported.

Similar to DOC, the availability of labile C in the soil can also be evaluated by Q_{MIC} (percentage of SMBC to SOC), values below 2% being a signal of SOM depletion (Anderson, 2003). In our study, mean Q_{MIC} decreased from 2.8% in the mangroves to 1.8% in the plantations (Table 4). Greater Q_{MIC} in the mangroves resulted from the diversity of organic matter input and/or through a more efficient microbial community, which suggested better availability of SOM than in the plantations. Besides, the reduction of Q_{MIC} in the plantation soils was associated with a marked decline in SMBC/SMBN ratio (Table 4). It declined from an average of 14.0 in the mangroves to 9.0 in the plantations. Large SMBC/SMBN ratios in the mangroves possibly suggested fungal dominance of the microbial community (Joergensen and Emmerling, 2006).

Unlike SMBC/SMBN ratio, SMBC/SMBP ratios in the mangroves (mean 32) were consistently lower than the corresponding ratios in

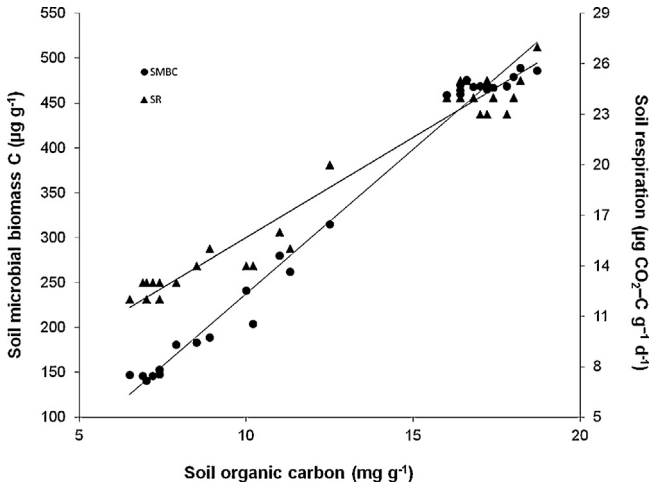

Fig. 1. Relationship of soil organic C with soil microbial biomass C and soil respiration in the mangroves and adjacent plantations ($r = 0.82$ and 0.81 respectively; $p < 0.005$).

Table 3
Soil microbial biomass-C, -N, -P, soil respiration, levels of adenylates and ergosterol in soils under undisturbed mangroves and adjacent plantations (mean ± SEM).

	SMBC[a] ($\mu g\,g^{-1}$)	SMBN[b]	SMBP[c]	SR[d] ($\mu g\ CO_2$—C $g^{-1}\,d^{-1}$)	Adenylates				Ergosterol ($\mu g\,g^{-1}$)
					ATP ($nmol\,g^{-1}$)	ADP	AMP	Sum	
Mangrove sites									
M1	465 ± 104	32 ± 8	14.6 ± 4.7	25 ± 7	2.76 ± 0.63	0.23 ± 0.09	0.43 ± 0.14	3.83	2.47 ± 0.48
M2	489 ± 98	38 ± 8	14.3 ± 4.5	25 ± 6	3.17 ± 0.68	0.24 ± 0.10	0.41 ± 0.12	3.82	3.34 ± 0.67
M3	469 ± 89	34 ± 10	15.4 ± 5.2	23 ± 6	2.96 ± 0.57	0.21 ± 0.08	0.45 ± 0.13	3.62	3.41 ± 0.61
M4	476 ± 98	34 ± 6	14.5 ± 4.4	25 ± 8	2.95 ± 0.87	0.21 ± 0.06	0.43 ± 0.15	3.59	3.16 ± 0.57
M5	464 ± 108	35 ± 6	15.4 ± 4.3	25 ± 4	2.79 ± 0.54	0.25 ± 0.07	0.41 ± 0.13	3.45	2.93 ± 0.67
Plantation sites									
Coconut	141 ± 65	18 ± 4	3.8 ± 0.9	13 ± 3	0.72 ± 0.14	0.14 ± 0.06	0.24 ± 0.11	1.10	0.44 ± 0.13
Arecanut	148 ± 72	16 ± 6	3.4 ± 1.1	12 ± 3	0.75 ± 0.15	0.15 ± 0.07	0.24 ± 0.09	1.14	0.56 ± 0.12
Rubber	189 ± 68	22 ± 6	4.1 ± 1.1	15 ± 4	0.78 ± 0.17	0.18 ± 0.07	0.22 ± 0.08	1.24	0.63 ± 0.15
Teak	146 ± 78	14 ± 3	3.3 ± 1.1	13 ± 3	0.66 ± 0.12	0.15 ± 0.08	0.21 ± 0.09	1.02	0.56 ± 0.15
Padauk	181 ± 61	19 ± 5	3.6 ± 1.4	13 ± 2	0.76 ± 0.13	0.16 ± 0.07	0.23 ± 0.10	1.15	0.49 ± 0.13
lsd (0.05)	93	9	6	3	0.36	0.07	0.09		0.82

[a] SMBC – soil microbial biomass C.
[b] SMBN – soil microbial biomass N.
[c] SMBP – soil microbial biomass P.
[d] SR – soil respiration.

the plantations (mean 44) indicating wide variation due to changed land use (Table 4). This result indicated that the SMBC/SMBP ratio showed considerably more variation than the SMBC/SMBN ratio as observed by Joergensen (2010) in soils under forest, pasture, plantations and agriculture. This is due to relatively wide variation in SMBP levels compared to SMBN levels among the mangrove and plantation sites. Though our results contradict the report of Cleveland and Liptzin (2007) that rather uniform SMBC/SMBP ratios exist in soil, variability in this ratio is supposed to be caused by the capacity of bacteria and fungi to store excess P in the form of cell internal polyphosphates and cell wall components, e.g., teichoic acids and use this stored P at times of P limitation (Oberson and Joner, 2005). It is also possible that the return of inorganic P and organic P components to soil through litter fall significantly decreased the SMBC/SMBP ratios (Muhammad et al., 2007) in the mangroves.

3.3. Soil respiration and metabolic quotient

Consistent with the results on SMB, soil respiration (SR) rates decreased due to changed land use from an average of 24.6 $\mu g\ CO_2$—C g^{-1} per day in the mangroves to 13.2 $\mu g\ CO_2$—C g^{-1} per day in the plantations, indicating a reduction of 46.4% (Table 3). SR is a useful parameter for measuring the biological activity of the soil and enhanced rates in the mangroves is reflective of the greater levels of labile organic substrates especially DOC. Contrarily, lower SR rates under the plantations were due to severe depletion of readily decomposable substrates, suppression of the decomposition of native SOC (Ding et al., 2010) and due to decrease in SMB and activity (Lee and Jose, 2003). The relationship between SR and SOC (Fig. 1) indicated that besides SMB, the levels of organic substrates also controlled the dynamics of CO_2 emission from the soil.

The metabolic quotient, qCO_2 (SR per unit of microbial biomass) is considered as the most straightforward index widely used to evaluate ecosystem development, disturbance or system maturity (Bastida et al., 2008) and has a great potential for improving our understanding of the development of microbial communities in the ecosystem that they inhabit (Anderson and Domsch, 2010). It reflects the maintenance energy requirement of soil microbes; level above 2 g C—$CO_2\ h^{-1}$ kg $C_{MIC}{}^{-1}$ being the critical threshold for the base line performance of microbial communities (Anderson, 2003). In the present study, qCO_2 levels were consistently lower in the mangroves (Table 4) and the mean levels indicated a 60% increase in the plantations. The levels of qCO_2 is related to availability of organic substrates i.e., the total maintenance demand of growing cells with carbon limitations is higher than organisms without carbon-limitations (Anderson and Domsch, 2010). In ecological terms, however, a high qCO_2 reflects a high maintenance carbon demand, and if the soil system cannot replenish the carbon which is lost through respiration, microbial biomass will decline (Anderson and Domsch, 2010). Enhanced qCO_2 levels in the plantations, therefore, suggested greater maintenance demand suggesting that the conversion of total carbon into microbial carbon is less efficient leading to lower SMBC. Conversely, in the mangroves, lower qCO_2 levels indicated a decrease in the microbial community maintenance energy requirement.

3.4. Adenylates and adenylates energy charge

The levels of soil ATP, ADP and AMP in the mangroves were markedly higher compared to the corresponding levels in the plantations (Table 3). Consequently, the sum of the adenylates and AEC were also greater in the mangroves (mean 3.7 $nmol\,g^{-1}$ and 0.86 respectively) compared to the corresponding levels in the plantations (mean 1.1 $nmol\,g^{-1}$ and 0.73 respectively; Table 4). Soils with greater ATP levels registered greater ATP/SMBC ratios

Table 4
Ratios of various soil microbial indices in soils under mangroves and adjacent plantations.

	SMBC/SOC (%)	SMBC/SMBN	SMBC/SMBP	qCO_2 (mg CO_2—C g^{-1} SMBC d^{-1})	AEC	ATP/SMBC (μmol g^{-1})	Ergosterol/SMBC (%)
Mangrove sites							
M1	2.7	14.5	31.8	53.8	0.87	5.94	0.53
M2	2.7	12.9	34.2	51.1	0.86	6.05	0.68
M3	2.7	13.8	30.4	49.0	0.85	6.63	0.73
M4	2.9	14.0	32.8	52.5	0.85	5.90	0.66
M5	2.8	13.3	30.1	53.9	0.84	6.83	0.63
Plantation sites							
Coconut	2.0	7.8	37.1	92.2	0.72	5.11	0.31
Arecanut	2.0	9.3	43.5	81.1	0.72	4.53	0.38
Rubber	2.1	8.6	46.1	79.4	0.74	4.13	0.33
Teak	2.1	10.4	44.2	89.0	0.72	4.52	0.38
Padauk	2.3	9.5	50.3	71.8	0.73	3.53	0.27
lsd (0.05)	0.4	1.2	7.4	9.4	0.06	0.65	0.14

(Table 4) and the values across mangroves (mean 6.4 μmol g^{-1}) were consistently greater than those encountered in the corresponding plantations (mean 4.7 μmol g^{-1}). Apparently, the supply of energy and nutrients by litter fall increased the metabolic activity of soil microorganisms and consequently the ATP-to-SMBC ratio. However, in the plantation soils where ATP/SMBC ratios were low, it is possible that the microbial biomass was metabolically less active and hence the access to organic N was lower leading to decreased N mineralization and consequently wider SMBC/SMBN ratios.

3.5. Ergosterol

Ergosterol is considered as a reliable, robust and relatively inexpensive bioindicator for fungal biomass in soils (Joergensen and Wichern, 2008; Montgomery et al., 2000) and to date, the measurement of the ergosterol concentration in natural substrates is arguably the most efficient method for estimating their fungal biomass (Buesing and Gessner, 2006). Similar to SMB, SR and ATP, ergosterol concentration (Table 3) in the mangroves (mean 3.1 μg g^{-1}) far exceeded the corresponding levels in the adjacent plantation (mean 0.51 μg g^{-1}). The ergosterol/SMBC ratio, which is an indicator for living saprotrophic fungi (Powlson et al., 1987) also followed an identical trend (Table 4) and the mean level in the mangroves was almost double (0.65%) than that in the plantations (0.34%).

The fungal biomass in our soils was estimated from ergosterol content using a factor of 90, the conversion factor from micrograms ergosterol to micrograms fungal biomass C proposed by Djajakirana et al. (1996). By this conversion, we found that fungi were the dominant microbial community in the mangroves constituting 58% of total SMBC, while it constituted only 30% in the plantations. This indicated a shift in microbial community structure due to changed land use with fungi dominating the microbial community in these mangrove soils. Conversely, in our earlier study on disturbed and undisturbed mangroves (Dinesh et al., 2004a) we found that fungi represented only 24–37% of the SMB. However, the soils in the referred study were sampled under permanent anoxic conditions unlike the present study wherein the soils were not permanently saturated by sea water. Mangrove sites are home to a group of fungi called 'manglicolous fungi' (Sahoo and Dhal, 2009) and these fungi and thraustochytrids (fungi-like unicellular protists) are the first colonizers of fallen mangrove leaves which initiate the decomposition of organic litter, thereby allowing secondary colonization by bacteria and yeasts (Raghukumar et al., 1995). Earlier report on the distribution of microorganisms in mangrove soils and waters from the southern region along the coast of the Andaman Sea and the Gulf of Thailand also indicated that fungi dominated bacteria and algae (Chalermpongse and Thappipidh, 1985).

4. Conclusions

The results suggested that the measured biochemical/microbial indicators did show perceptible deterioration in soil quality due to changed land use. Clear felling of mangroves led to marked reductions in the levels of soil nutrients and organic substrates. As a consequence, significant reductions in SMBC, SMBN, SMBP, SR and adenylate levels were observed in the plantations. The observed variations in biochemical/microbial indicators of soil quality can be attributed to differences in the quantity and quality of the present and past substrates and labile soil organic matter, especially DOC and DON. Greater ergosterol concentration led to greater ergosterol/SMBC ratio with fungi dominating the microbial community in the mangroves. Higher qCO_2 levels in the plantations indicated decreased substrate use efficiency and lower rates of conversion of total carbon into microbial carbon. The study also suggested that microbial biomass, soil respiration and metabolic quotient are robust and sensitive indicators that can be used to measure long-term variations in soil quality due to changed land use.

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