Distribution and sources of carbon, nitrogen, phosphorus and biogenic silica in the sediments of Chilika lagoon

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The present study investigated the spatial and vertical distribution of organic carbon (OC), total nitrogen (TN), total phosphorus (TP) and biogenic silica (BSi) in the sedimentary environments of Asia's largest brackish water lagoon. Surface and core sediments were collected from various locations of the Chilika lagoon and were analysed for grain-size distribution and major elements in order to understand their distribution and sources. Sand is the dominant fraction followed by silt+clay. Primary production within the lagoon, terrestrial input from river discharge and anthropogenic activities in the vicinity of the lagoon control the distribution of OC, TN, TP and BSi in the surface as well as in the core sediments. Low C/N ratios in the surface sediments (3.49–3.41) and cores (4–11.86) suggest that phytoplankton and macroalgae may be major contributors of organic matter (OM) in the lagoon. BSi is mainly associated with the mud fraction. Core C5 from Balugaon region shows the highest concentration of OC ranging from 0.58–2.34%, especially in the upper 30 cm, due to direct discharge of large amounts of untreated sewage into the lagoon. The study highlights that Chilika is a dynamic ecosystem with a large contribution of OM by autochthonous sources with some input from anthropogenic sources as well.

1. Introduction

Coastal lagoons play a critical role in the biogeochemical processes by behaving both as source and sink for carbon (C), nitrogen (N), phosphorus (P), silica (Si) and other materials. The organic matter (OM) present in the coastal aquatic bodies are a compound mixture of allochthonous and autochthonous sources, which includes primary production by intrinsic aquatic plants (seagrasses, macroalgae and other angiosperms), contributions from tidal transportation, land-use changes, agricultural runoff and from municipal and industrial discharges (Thornton and McManus 1994; Yamamuro 2000; Liu *et al.* 2007; Wu *et al.* 2013). Decay process of plants produces labile as well as refractory organic matter, which contributes largely to the OM pool of the

sediments, macrophytes detritus acts as a source of carbon to the estuarine water, whereas more decay resistant vascular plants act as nitrogen sinks to the sediments (Rice and Tenore 1969; Flindt *et al.* 1999; Zhou *et al.* 2007). Apart from the dissociation of organic matter, many internal factors like dissolution, flocculation and mixing of fresh and saline contribute to the nutrients in coastal water bodies. Gaining knowledge about the sources of OM in coastal sediments and the factors controlling its distribution is crucial to the understanding of global biogeochemistry, since coastal water bodies are sites for intensive organic carbon production, turn over, and burial (Hu *et al.* 2009; Jennerjahn 2012).

Post-deposition bottom sediments and the constituents associated with them, such as organic matter, are likely to undergo a number of

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diagenetic transformations (Giffin and Corbett 2003; Vandewiele *et al.* 2009; Anawar *et al.* 2010). The C/N ratio of terrestrial OM varies over a wide range of 12–4000 and decreases during diagenesis, whereas C/N ratios of algae and plankton are lower, ranging from 6–14, and less variable (Atkinson and Smith 1983; Jennerjahn *et al.* 2004; Wu *et al.* 2007). Silicon is an essential element in coastal ecosystems essential for the diatoms growth (Struyf *et al.* 2007). Biogenic silica in sediments is considered to be one of the important components to understand the biogeochemical processes and paleo-environmental records in coastal ecosystems (Lijun *et al.* 2008).

Many investigations have been carried out in Chilika lagoon on water quality, ecology, metal pollution, salinity structure and mixing processes (Panda *et al.* 1995, 2006; Nayak and Behera 2004; Panigrahi *et al.* 2007, 2009; Mohanty and Panda 2009; Zachmann *et al.* 2009). Some authors have focussed on carbon and methane emissions and dissolved inorganic carbon distribution (Das *et al.* 2005; Gupta *et al.* 2008; Muduli *et al.* 2012; Kanuri *et al.* 2013; Muduli *et al.* 2013). However, a detailed study focussing on the distribution and sources of C, N, P and BSi in the sedimentary environment of this lagoon has not been carried out to the best of our knowledge. The present study was, therefore, undertaken to investigate the distribution and

sources of organic carbon (OC), total nitrogen (TN), total phosphorus (TP) and biogenic silica (BSi) in the surface and core sediments of the coastal lagoon.

2. Study area

Chilika lagoon is the largest brackish water lagoon in Asia spread between latitude 19°28'–19°54'N and longitude 85°06'–85°35'E (figure 1). It is designated as a wetland of international importance under the Ramsar Convention in 1981. It is a shallow water body with a length of ~65 km and a variable breadth of 20 km. The water spread area is estimated to be 704 km² and 1020 km² during the summer and monsoon seasons, respectively (Gupta *et al.* 2008). The important hydrological influences in Chilika lagoon are:

- silt-laden freshwater discharges from the distributaries of Mahanadi river,
- drainage from degraded catchment basin lying on the western and southern margins of the lagoon, and
- exchange of lagoon water with the Bay of Bengal. Large amounts of silt are added into the lagoon, nearly 1.5 million MT year⁻¹ of silt is added by the distributaries of Mahanadi river, while

Figure 1. Map of Chilika showing sampling locations for surface sediments and cores.

0.3 million MT year⁻¹ of sediment enters from the western catchment (Ghosh *et al.* 2006).

Changes in land use pattern promote erosion in the upstream areas and have increased the sediment load significantly. Chilika lagoon has thick macrophytes vegetation including algae, angiosperms, pteridophytes and seagrasses. The decay of macrophytes contributes to biological sedimentation process. The northern sector has a large area covered by submerged and other macrophytes, while the southern sector has seagrass beds and algae.

3. Materials and methods

A total of 11 surface sediments (S1–S11) and 5 cores (C1–C5) were collected from different regions of the lagoon. The sampling was done in the first week of June, before the onset of monsoon. During the month of June, the water level remains low and the average temperature is around 35°C. Core C1 was collected from the outer channel region, near Satpada village, which witnesses large tourist activities. This region is close to the sea mouth and experiences maximum influence of adjoining sea (Bay of Bengal). Cores C2 and C5 were collected from the central sector, C2 from near Nalabana island, which is a bird sanctuary and a tourist spot, and C5 from near Balugaon township, a major fishing village. Core C3 was collected at the southernmost end of the lagoon, near Rambha village. Core C4 was collected from a relatively pristine region with large algal mats and seagrass meadow in the southern sector. The surface sediment samples were scraped by plastic scoops and cores were collected using hand-held steel auger drilled through exposed sediments at shallow water depths. Coring was carried out at different sections of the lagoon at shallow depths with the help of 1 m long stainless steel casing having an internal diameter of 5 cm. The cores retrieved are of varying lengths, ranging from 60 cm to 1 m. The cores were sectioned at 5 cm intervals, on the boat itself, and stored in polyethene bags. The samples were stored at 4°C until further analysis. The cores were cautiously sliced into 5 cm segments avoiding mixing and stored in zipped polyethene bags. The sediment samples were carefully brought to the laboratory and allowed to dry at room temperature and oven-dried prior to analysis. For the analysis of C, N, P and BSi, sediment samples were crushed to fine powder and stored.

3.1 Grain size analysis

Size separation for the samples was carried out in the laboratory following the standard sieving

method (Ingram 1971). Samples were air-dried for 4–5 days, then oven dried at 60°C for 24 hr. The samples were thoroughly homogenised by conning and quartering technique. The samples were sieved on an electromagnetic sieve shaker into different size fractions as follows: >250, 250–125, 125–63 and <63 µm, grain size fractions.

3.2 Analysis of carbon, nitrogen, phosphorus and biogenic silica

The total carbon (TC) and total nitrogen (TN) in the sediment samples were determined by CHNS analyser (Euro elemental analyser – 3000 series). OC was analysed by Walkley and Black method (Walkley and Black 1934). Total phosphorus analysis was carried out by solution A method (Shapiro 1975). Biogenic silica (BSi) in the sediment were analysed according to the method of Struyf *et al.* (2007). The analytical precision of all the measurements was ±5%.

4. Results

4.1 Grain size and distribution of C, N, P and BSi in surface sediments

The textural and depositional conditions are determined by the grain size data of the sediments. Chilika lagoon surface sediments are dominated by medium-fine sand fraction and a small percentage falls into silt+clay. The >250 µm fraction is dominant followed by the 125–63 µm fraction. The silt+clay content varies between 4 and 16% in the surface sediments. Surface sediment S6 from the northern sector and S8 from the central sector show the maximum amount of particles <63 µm (figure 2). Concentrations of TC, OC, TN, TP and BSi are presented in table 1 and figure 3(a, b). Surface sediments showed distinct variation for all the nutrients studied in the surface sediments. TC value in the surface sediments ranged from 0.34 to 1.97%. Surface sediments from the different sectors contained OC ranging from 0.26 to 1.66%. However, the OC content in the surface sediments is lower in the present study when compared with other studies from similar locations in Chilika lagoon (Das *et al.* 2005). TN in the surface sediments ranged from 0.07 to 0.39%. Lowest value of TN was observed in sediments from the outer channel region, which also had lowest OC value (figure 3b). TP ranged from 0.02 to 0.51%, whereas BSi varied between 0.10 and 1.82%. C/N ratio ranged from 3 to 13. The lowest and highest values for C/N were 3.49 at site S11 and 13.15 at site S7 (table 1 and figure 3a, b).

Figure 2. Grain size distribution in surface sediments.

Table 1. TC%, OC%, TN%, TP%, BSi% and C/N ratios in Chilika lagoon.

		Surface sediments (n = 11)	Core 1 (n = 19)	Core 2 (n = 20)	Core 3 (n = 12)	Core 4 (n = 17)	Core 5 (n = 13)
TC%	Min	0.34	0.62	0.60	0.78	0.98	0.98
	Max	1.97	1.00	1.01	1.45	1.73	2.86
	Average	1.21	0.82	0.81	1.10	1.36	1.81
	SD	0.46	0.11	0.10	0.20	0.20	0.61
OC%	Min	0.26	0.40	0.44	0.69	0.78	0.58
	Max	1.66	0.79	0.89	1.01	1.43	2.34
	Average	0.86	0.59	0.64	0.87	1.01	1.38
	SD	0.34	0.10	0.10	0.09	0.17	0.56
TN%	Min	0.07	0.05	0.08	0.08	0.16	0.11
	Max	0.39	0.10	0.30	0.10	0.23	0.24
	Average	0.17	0.07	0.08	0.09	0.19	0.17
	SD	0.10	0.01	0.01	0.00	0.02	0.04
TP%	Min	0.02	0.00	0.00	0.01	0.06	0.01
	Max	0.51	0.04	0.14	0.10	0.31	0.27
	Average	0.13	0.01	0.05	0.03	0.17	0.07
	SD	0.13	0.01	0.05	0.03	0.08	0.08
BSi%	Min	0.10	0.00	0.001	–	0.00	0.01
	Max	1.82	0.03	0.028	–	0.16	0.21
	Average	0.76	0.01	0.011	–	0.05	0.09
	SD	0.59	0.01	0.009	–	0.04	0.06
C/N	Min	3.49	6.99	6.53	8.21	4.01	4.41
	Max	13.15	11.86	11.27	10.05	7.87	11.58
	Average	7.11	10.25	8.73	9.45	6.06	8.04
	SD	3.18	1.38	1.41	17.15	1.03	2.25

4.2 Grain size and C, N, P and BSi distribution in core sediments

The grain size distribution in the cores has been presented in figures 4–6. The grain size distribution

reveals coarser sediments in cores C1 and C2, collected near the sea mouth and central region of the lagoon, respectively (figure 4). However, core C3 collected from the southernmost region also depicts higher sand content (figure 5). Core C4

Figure 3. (a) Box plot graph showing the distribution of total carbon (TC), organic carbon (OC), total phosphorus (TP) and biogenic silica (BSi) in surface sediments. (b) Distribution of total carbon (TC), organic carbon (OC), total nitrogen (TN), total phosphorus (TP) and biogenic silica (BSi) in surface sediments in different sectors of the lagoon.

from the mid-south region of the lagoon, has higher silt+clay content. Core C5 collected from the south central region near the Balugaon township showed maximum sediment particles, $<63 \mu\text{m}$.

The distributions of nutrients in the vertical profile of the sediments, in the cores C1–C5, have been presented in table 1 and figures 4–6. Sedimentary OC (avg. 0.59%) and TN (avg. 0.07%) varied between a limited range in core C1 (figure 4). A consistent behaviour was observed for TP (avg. 0.01%) throughout the length of the core except at a depth of 85 cm where a large deviation is observed. The mean BSi concentration in core C1

was 0.01%. BSi first decreased up to a depth of 35 cm, then increased to a large amount at the depth of 40 cm and then decreased again. Core C2 showed a similar trend like C1 in OC (avg. 0.64%) and TN (avg. 0.08%) values, whereas TP (avg. 0.05%) values fluctuated up to 60 cm and then showed a consistent decrease through the entire length. BSi showed a consistent value till a depth of 55 cm, then a fluctuation is observed from 60 to 100 cm. In the case of core C3 and C4, values of OC, TN and TP remain almost consistent throughout the length of the core. BSi was below the detection limit in core C3. In core C4, BSi values varied

Figure 4. Distribution of total carbon (TC), organic carbon (OC), total nitrogen (TN), total phosphorus (TP), biogenic silica (BSi) and C/N ratios along the depth in cores C1 and C2.

at different depths of the core. In core C5, the highest value for OC was observed in the first 10 cm, which then gradually decreased along the depth. TN varied along the depth in a limited range (avg. 0.17). Total phosphorus (TP) showed an increasing trend up to a depth of 15 cm and then decreased gradually. An increasing trend for BSi is observed till a depth of 55 cm and then decreased in the last 10 cm. The C/N ratios ranged from 6 and 10 in all the cores (table 1; figures 4–6). The lowest value of 6 is observed in core C4 and highest value of 10 is observed in core C1.

4.3 Statistical analysis

Principal component analysis (PCA) was applied to the data to determine the sources of OM in

the surface as well as in core sediments. Factors were identified using varimax rotation and the ones having eigenvalue >1 are only considered. The PCA for surface sediments reveals two factors. The first factor shows a strong positive correlation between OC, TN and silt+clay ($<63 \mu\text{m}$). The second factor shows positive loadings between BSi and OC (table 2).

In core C1, three factors are formed. The first factor showed a strong positive loading of OC and TN. The second factor revealed a positive loading for silt+clay. The third factor showed a positive loading of TP. In core C2, the first factor showed positive loading of OC, TN and TP. The second factor showed a positive loading of silt+clay and negative loading of BSi. The sources of OC and TN are similar in core C3, whereas TP has a different source as suggested by PCA

Figure 5. Distribution of total carbon (TC), organic carbon (OC), total nitrogen (TN), total phosphorus (TP), biogenic silica (BSi) and C/N ratios along the depth in cores C3 and C4.

results. In core C4, the silt+clay fraction shows slightly positive loading with BSi. The second factor shows a positive loading of TN. In core C5, only a single factor is formed, which showed a strong positive loading of OC, TN and TP, while BSi and silt+clay are negatively correlated (table 2).

5. Discussion

5.1 Sources and distribution of major elements in surface sediments

Most of the surface sediments are dominated by sand, such a trend has also been observed in

sediments from other coastal regions (Prasad and Ramanathan 2008; Ranjan *et al.* 2010; Jia *et al.* 2012; Reotita *et al.* 2014). The sediments from the estuarine region are dominated by sand due to the influence of the sea, therefore, sedimentary organic carbon showed minimum concentration in the outer channel region, while the highest concentration was found in the sediment from the northern sector, as also observed by two extreme values in the box plot diagram for organic carbon (figure 3a). The northern sector sediments have greater mud (silt+clay) content brought by the tributaries of Mahanadi, which holds more OC and TN. The large surface area of fine sediments have a greater sorptive capacity and thus hold more organic carbon (Dunn *et al.* 2008; Magni *et al.*

Figure 6. Distribution of total carbon (TC), organic carbon (OC), total nitrogen (TN), total phosphorus (TP), biogenic silica (BSi) and C/N ratios along the depth in core C5.

2008; Ye *et al.* 2014). A positive loading of OM (OC, TN) with silt+clay in the PCA results also suggests the role of finer particles in OM acquisition (table 2). Comparatively, higher OC in surface sediments S9 from the central sector may be due to greater anthropogenic activities in the vicinity of this location (figure 3b). At site S10 in the southern sector of the lagoon, very clear water might have allowed the growth of phytoplanktons and macroalgae. Subsequently, their death and decay lead to their deposition in bed sediments, adding to the OM content. The southern sector witnesses more phytoplankton growth, which may be contributing to the OM in the sediments (Srichandan *et al.* 2015). The maximum value of TN was found in surface sediment S3, which was collected a little ahead of the Satpada village, which witnesses large boat traffic and direct discharge of domestic waste into the lagoon from many small fishing villages. TP concentration in the sediments shows a spatial variability. Sediments from the regions with sea water dominance showed higher phosphorus content, i.e., surface sediments S2 from the outer channel region, and S9, S10 and S11 from central and southern sectors (figure 3). This trend is possibly associated with the estuarine mixing process and release of phosphorus from the reducing sediments (Baijural *et al.* 2013). A moderately higher concentration of TN and TP in the surface sediments S9, S10 and S11 could also be due to rural domestic run off and diagenetic processes (Zachmann *et al.* 2009). BSi showed a higher concentration in the surface sediments S6, S7 and S8 (figure 3), which may be a result of more fine grains present in these sediments, holding more biogenic silica (Lijun *et al.* 2008; Yang *et al.* 2015). According to the findings of Bernardez *et al.* (2005), there is a general

tendency for higher values of biogenic silica in muddy fractions and lower values in sandy fractions. Sediments with higher OC content also have more BSi which implies that OM reduces the rate of BSi dissolution in sediments; thus resulting in its accumulation in fine-grained sediments; (Lehtimäki *et al.* 2013; Yang *et al.* 2015). This has also been confirmed by PCA, which exhibited the positive loadings of OC and BSi (table 2).

The C/N ratios in surface sediments range from 3.49 and 13.51 with an average of 7.11 (table 1 and figure 7), which indicated that the OM produced by marine algae and other macrophytes could be an important source of sedimentary organic carbon. The autochthonous component, coming from aquatic organisms, has a C/N ratio ranging from 4 to 10, indicative of OM without cellulosic structure, coming from algae and phytoplankton. The allochthonous constituent, mostly coming from terrestrial plants, is more refractory due to their high lignin and cellulose content and has a C/N ratio of >12 (Devesa-Rey and Barral 2012; Yamamuro and Kamiya 2014). The other reason for low C/N ratio could be higher rates of OM matter mineralisation in Chilika lagoon, as have been observed by the other authors (Muduli *et al.* 2012). The labile component of OM decomposes through processes like autolysis, leaching and microbial mineralisation, releasing CO₂, thus causing a decrease in the carbon content of OM in relation to nitrogen (Gao *et al.* 2012).

Higher C/N ratios observed in surface sediment from the northern sector could be due to riverine sediment load, as well as contribution from higher plants like *Potamogeton pectinatus*, *Phragmites karka* and *Eichhornia crassipes*, which dominate this part of the lagoon. These plants have more

Table 2. Principal Component Analysis for different parameters in surface and core sediments of Chilika lagoon.

	Factors		
	1	2	3
Surface sediments			
OC	0.676	0.575	
TN	0.891	−0.314	
TP	−0.044	−0.774	
BSi	−0.011	0.875	
Mud	0.791	0.180	
Core C1			
OC	0.902	−0.235	0.024
TN	0.816	0.398	0.039
TP	0.064	−0.015	0.933
BSi	0.114	−0.766	−0.404
Mud	0.128	0.797	−0.276
Core C2			
OC	0.929	0.028	
TN	0.957	0.024	
TP	0.923	0.059	
BSi	−0.240	−0.715	
Mud	−0.162	0.795	
Core C3			
OC	0.367	0.913	
TN	−0.399	0.897	
TP	0.892	0.017	
Mud	−0.836	0.019	
Core C4			
OC	−0.777	−0.536	
TN	−0.006	0.878	
TP	−0.262	0.486	
BSi	0.492	−0.138	
Mud	0.893	−0.266	
Core C5			
OC	0.911		
TN	0.815		
TP	0.818		
BSi	−0.872		
Mud	−0.971		

cellulosic content, which decays slowly and which may have contributed to a greater amount of C/N ratio. The northern sector also receives large input of terrestrial material through river discharge which may be adding remains of terrestrial plants with higher C/N ratios. The plot of OC *vs.* TN can be used to assess the contribution of different OM sources (Ruttenberg and Goni 1997). There are external sources of TN besides contribution from the *in situ* macro and microflora (Zhou *et al.* 2007; Prasad and Ramanathan 2008). High nutrient runoff from agricultural fields in the drainage basin, effluents from aquaculture ponds, and domestic drainage from the habitable islands

and human settlements around the lagoon are probable sources of external nitrogen into the lagoon system (Jennerjahn 2012; Yang *et al.* 2015). The weak correlation between the two components could also be a result of preferential loss of carbon in relation to nitrogen due to microbial activities (Zhou *et al.* 2007).

5.2 Sources and distribution of major elements in core sediments

Slight nutrient variation is observed among cores collected from different sectors. This may be due to both, the marine and fluvial, influences on the sediments. The proximity of the sampling locations to major human settlements could also be responsible for the higher concentration of OC, TN and TP. Lower values of OC in cores C1 and C2 is due to more sand content in these cores which holds less amount of nutrients since sediment texture plays a key role in controlling the OC content (Hedges and Keil 1995; Goni *et al.* 2003). The absence of fine silt and clay and dominance of medium to fine sand in these cores can be attributed to tidal impacts and hydrodynamic sorting (Ranjan *et al.* 2010; Gao *et al.* 2012; Jia *et al.* 2012; Yang *et al.* 2015). Average values of OC in cores C3 and C4 are 0.87% and 1%, respectively, which is higher than cores C1 and C2 but lesser than C5. Though core C3 has higher sand content, the OC values are slightly higher than core C1 and C2, which could be due to its location near Rambha town. The direct discharge of wastes from the town may be responsible for higher OC and TN concentrations. Higher silt+clay content in core C4 may be due to the entrapment of fine sediments by micro and macrophytes growth, which also provides a more sorptive capacity to hold OC. In core C5 with average value of 1.38% of OC has the highest among the five cores. Especially the OC has a higher value of 2–2.5% in the upper 30 cm of the core which can be attributed to the untreated sewage and the waste from agro-based industry and the prawn processing unit directly discharged into the lagoon from thickly populated Balugaon township (Panigrahi *et al.* 2009). TN values are somewhat comparable in cores C1 and C3 and cores C2 and C4. The OC and TN values in all the five cores are comparable to values reported from other lagoons and coastal areas in tropical regions (Zhou *et al.* 2007; Ranjan *et al.* 2010; Jia *et al.* 2012). The PCA results for cores C1, C2, C3 and C5 revealed that they have a similar source, whereas, in core C4, they may be having different sources (table 2).

The average value of 0.01% for TP in core C1 is quite low. This could be due to phosphorus quenching by free iron oxide (Sundareshwar

Figure 7. Sedimentary organic carbon (OC) vs. total nitrogen (TN) in the surface and core sediments of Chilika lagoon.

and Morris 1999; Sappal *et al.* 2014). Phosphorus concentration in core C2 ranges from 0.0 to 0.2%, up till a depth of 55 cm, and from 0.0 to 0.1%, up to a depth of 25 cm in core C3. The increase in phosphorus could be anthropogenic, as well as from calcium carbonate of the marine organisms since phosphorus binds to Ca besides Fe and Al (Sundareshwar and Morris 1999; Yang *et al.* 2015). The TP values ranged from 0.06 to 0.31% in core C4. Total phosphorus in core C4 shows a decreasing trend up to a length of 40 cm and then increases in the next 15 cm. The increase in concentration could be a result of microbial activities or due to reducing conditions, which release phosphorus back into the pore water, and finally, this gets adsorbed in sediments (Paludan and Morris 1999; Yilmaz and Koc 2012). Saline anoxic environments release back sequestered phosphorus, which can either be reabsorbed or remain available to the biota (Prasad and Ramanathan 2008). TP concentration is higher in the first 15 cm in core C5, which may be added to the sediments through anthropogenic sources. Core C5 was collected near the Balugaon township, which releases domestic and agro-based sewage waste directly into the lagoon (Panigrahi *et al.* 2009).

BSi showed an alternating trend of increase and decrease ranging from 0.01 to 0.09% in the cores (table 1). This variation can be associated with the diatom growth periods when they take up dissolved silica (DSi) and deposit it as BSi in their frustule (Sturmf and Conley 2008). The degradation of OM surrounding the diatom cells causes BSi dissolution into the water column and their decrease in the sediments (Sappal *et al.* 2014). Cores C4 and C5, with higher silt+clay content, also show higher BSi average values of 0.04 and 0.06%, respectively. The results also indicate that sediment texture plays a major role in controlling the nutrient content, which is consistent with studies in other lagoon systems (Zhou *et al.* 2007; Lijun *et al.* 2008; Gao *et al.* 2012).

The cores from different sites show different C/N ratios, but the overall ratios do not vary much (figure 4–6). Slight variation in C/N ratios in all the cores could also be a result of OM mineralisation and preservation (Gonneea *et al.* 2004). Core C1 and C3 have slightly higher C/N ratios, as coarse sediment fractions contain a larger proportion of intact land-plant debris as compared to finer fractions and thereby have elevated C/N ratios

(Meyers 1997). Core C4 has C/N values ranging from 4 to 7 with an average of 6, which could be due to the autochthonous contribution of OM from the algal vegetation in the lagoon (Routh *et al.* 2009; Liu *et al.* 2010). External input of nutrients increases algal productivity which further lowers the C/N ratios (Ranjan *et al.* 2010; Gao *et al.* 2012; Jia *et al.* 2012).

The plots of OC *vs.* TN is used to assess the contribution of different OM sources (Ruttenberg and Goni 1997). Except for cores C2 and C5, the plot OC *vs.* TN yield weak correlations between the two components (figure 7). Cores C1, C3 and C4 show a weak correlation between OC and TN (figure 7). This can be interpreted as sources of nitrogen other than OM contributing to the TN pool in the lagoon sediments. Inorganic nitrogen in the form of NH_4^+ sorbed to the sediments or in the form of NO_3^- added through high nutrient runoff from adjacent agricultural fields, effluents from aquaculture ponds, and domestic drainage from human settlements could be the source of nitrogen other than OM (Subramanian 2004; Prasad and Ramanathan 2008; Raju *et al.* 2011). The nitrogen present in domestic sewage consists of organic nitrogen, bound to carbon-containing compounds like proteins ($\text{R}-\text{NH}_2$). Decomposition of organic nitrogen in the sewage, by a variety of microorganisms present therein, slowly transforms the organic nitrogen to ammonia (NH_3) by a process termed as 'mineralisation'. Ammonia mainly exists as ammonium ion (NH_4^+) in the aqueous medium, which gets geochemically immobilised by getting adsorbed to the soil and sediments (Raju *et al.* 2009).

Chemically, this has been represented as follows:

A slightly good correlation was observed between OC and TN in cores C2 and C5 (figure 7). This suggests that nitrogen may be present in the organic forms besides inorganic forms in these cores (Liu *et al.* 2010). On the other hand, selective degradation of OM also alters the correlation between OC and TN. The release of CO_2 or CH_4 as degradation products, ammonia preservation and addition of microbial-associated nitrogen alters the relation between OC and TN (Gao *et al.* 2012).

6. Conclusions

This study investigated the spatial distribution of OC, TN, TP and BSi in the surface and core sediments of Chilika lagoon. Sediment texture, terrestrial inputs through river discharge, saline water influence, anthropogenic impacts and algal growth play key roles in variable concentrations of OC,

TN, TP and BSi in sediments from different sectors. Low OC concentration is observed in surface and core sediments from the outer channel region, which has more coarse sand grains. Vertical distribution of nutrients is lower in cores C1, C2 and C3 from the outer channel, central and southern sectors, respectively, with higher sand content. Cores C4 and C5 from the southern and central sectors, respectively, with higher silt+clay content, seagrass beds and algal presence, have a greater concentration of OC, TN and BSi. Core C5 collected near the Balugaon township in the central sector shows the maximum concentration of OC, especially in the upper 30 cm, probably due to untreated sewage discharged directly into the lagoon from Balugaon township. Besides the anthropogenic input into the lagoon, lagoon vegetation plays a major role in OM production. The low C/N ratio indicates the labile nature of OM matter in the sediments.

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