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Stable carbon and nitrogen isotopic signatures of organic matter sources in near-shore areas of Lake Victoria, East Africa

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ABSTRACT

Stable isotope ratios of organic carbon and nitrogen ($\delta^{13}C$ and $\delta^{15}N$) were measured in suspended particulate matter (SPM) and sediment in the near-shore areas of Tanzanian waters of Lake Victoria (LV) to identify the various sources of organic matter in different areas of the lake. Spatial variations in $\delta^{13}C$, $\delta^{15}N$, and C/N ratios in SPM and sediments in inshore areas were due to differences in the proportions and sources of autochthonous or allochthonous matter. Watershed characteristics, such as urbanization, and lake characteristics, such as algal blooms, also immensely influenced the stable isotope signal of the organic matter in sediments. Stable C and N ratios showed that inshore areas in bays without pronounced fluvial input were dominated by autochthonous planktonic organic matter; conversely, for bays receiving significant fluvial inflows, the composition of organic matter depended on the extent of preservation of shoreline vegetation. Signals resulting from input of anthropogenic organic waste as a result of urbanization were distinguishable from natural sources. This work demonstrates the potential to discriminate between input sources of organic material into lakes using stable isotope signals in sediment and suspended particulate matter.

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Introduction

Lake Victoria is the world's second largest lake, with surface area of 69,500 km^2 and a catchment area of 263,000 km^2 (Akiyama et al., 1997; LVEMP, 2002). The lake undergoes four hydrodynamic seasons which are characterized by cooling and complete mixing of the water column during June–August, gradual warming of the water column with the onset of stratification in September–December, complete stratification of the lake with development of the deep (30 m–60 m) thermocline in January–March, and cooling with the development of temperature gradient from the lake bottom to the surface in April–May (Talling and Talling, 1965; LVEMP, 2006). The lake is threatened by unsustainable development activities in the watershed which has lead to undesirable inputs to the lake. The situation is particularly worrisome because of the increasing population and industrial activities in the Lake Victoria Basin (LVB).

The rural areas of LVB are characterized by cultivated fields and large numbers of livestock and wildlife, which influence the quantity and composition of suspended particulate matter (SPM) exported from the catchment. Potential sources of organic matter from the urban watersheds include municipal storm water drainage and domestic and industrial wastewater. SPM from urbanized catchments are characteristically distinct because they include waste water discharges from anthropogenic modified surfaces such as tarmac roads, pavements, roof tops, construction sites, etc. (Bibby and Webster-Brown, 2005). The forest cover of a major portion of the southern LVB has tremendously diminished in size during the past three decades, mainly because of charcoal making, fuel wood collection, agricultural land expansion, human settlement, and animal grazing. This has resulted in the transport of excessive quantities of SPM by runoff into the inshore areas of the Lake Victoria (Machiwa, 2003).

The near-shore areas of Lake Victoria are largely characterized by bays with convoluted shorelines. Poorly flushed bays which receive large amounts of riverine discharge have anoxic sediments as a consequence of the rapid accumulation of sediments in these areas (Talbot and Lærdal, 2000; Muzuka et al., 2005). Lake areas close to shorelines receiving significant runoff have turbid waters, especially during the rainy season and are low in productivity; the sediment isotopic signature is characteristic of terrigenous C_4 plant material (Muzuka et al., 2005). Conversely, planktonic signatures are preserved mainly in sediments deposited in areas where fluvial inputs are weak, i.e., in the more offshore and/or exposed areas of the lake.

Suspended particulate matter (SPM) in runoff is comprised of soil, vegetation, detritus, etc., and is dependent on the characteristics of the catchment, e.g., whether it is dominated by grasslands, forests, agricultural fields, or urban areas. The use of stable isotope ratios of carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$) denoted as $\delta^{13}C$ and $\delta^{15}N$, respectively, can provide important information on the sources of organic matter in sediments and SPM as has been shown in several studies, especially in the marine environment (Saino and Hattori,

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1980; Machiwa, 2000; Lepoint et al., 2004; Smit et al., 2005; Muzuka and Shunula, 2006; Cornelisen et al., 2007).

Carbon isotope is useful in distinguishing sources of organic carbon based on the photosynthetic characteristics of plants. Trees are C_3 plants, i.e., they use ribulosodiphosphatcarboxylase enzyme to fix CO_2, forming a three-carbon compound during the initial steps of CO_2 assimilation; their characteristic $\delta^{13}C$ is approximately −26‰ (Muzuka, 1999). Conversely, grasses are C_4 plants, i.e., they use phosphoenolpyruvate carboxylase enzyme to fix CO_2, with oxalacetic acid, a four-carbon compound is formed during the first steps of CO_2 assimilation. Grasses have $\delta^{13}C$ signatures between −14‰ and −10‰ (Fry and Sherr, 1984). In addition to grasses, wetland macrophytes and food crops such as maize and rice are C_4 plants.

Terrestrial vegetation can be a major source of organic carbon to aquatic ecosystems and can be identified from the $\delta^{13}C$ signatures of sedimentary and SPM pools of aquatic systems (Peters et al., 1978; Middelburg and Nieuwenhuize, 1998; Machiwa, 2000; Augley et al., 2007). In the other cases, it may be difficult to ascertain the source where there is oil pollution and because of the similarity with planktonic signatures. The $\delta^{13}C$ values of organic C from unaltered petroleum range from −34‰ to −18‰, the average being −28‰ (Hoefs, 1987) and freshwater plankton is −20‰ to −17‰ (Campbell et al., 2003).

Stable nitrogen isotope analysis of SPM and sediments also allows for the identification of the sources of organic matter. $\delta^{15}N$ of SPM is strongly dependent on the $\delta^{15}N$ of the source nitrogen (e.g. N_2, NO_3^-, or NH_4^+). According to Heaton (1986), water influenced only by atmospheric deposition of NO_3^-; $\delta^{15}N$ values range from +2‰ to +8‰, while $\delta^{15}N$ values for NO_3^- from animal wastes range from +10‰ to +20‰. NO_3^- from synthetic fertilizers is depleted in ^{15}N; the values range from −3‰ to +3‰. $\delta^{15}N$ values of nitrogen-fixing plants ($\delta^{15}N$ for atmospheric N_2 = 0‰ by definition) range from −2‰ to +2‰ and for non-N_2-fixing plants, from −8‰ to +10‰ (Shearer and Kohl, 1986; Grice et al., 1996; Hemminga and Mateo, 1996; Raven et al., 2002; Yamamuro et al., 2003). It also is possible to trace wastewater input to aquatic systems traced using stable N isotopes. According to Thomton and McManus (1994) and Liu et al. (2007), sewage has $\delta^{15}N$ ranging from −3.0‰ to +2.3‰; $\delta^{13}C$ from −26.7‰ to −22.9‰; and C/N from 6.6 to 12. 6. In river samples SPM containing about 25% sewage organic C, Wayland and Hobson (2001) reported $\delta^{15}N$ values between 2.7‰ and 4.6‰ and $\delta^{13}C$ values between −22.0‰ and −22.2‰. The authors also noted that sewage impacted algae had isotopic signature ($\delta^{13}C = -19.8 \pm 1.8$‰; $\delta^{15}N = +29.0 \pm 0.9$‰) which was different from nonimpacted ones ($\delta^{13}C = -31.9 \pm 3.5$‰; $\delta^{15}N = +5.2 \pm 3.6$. Elevated $\delta^{15}N$ values in water contaminated with human and animal wastes are a result of volatilization of ^{14}N-rich NH_3 due to microbial processes (Horrigan et al., 1990; Macko and Ostrom 1994; MacClelland et al., 1997). In some cases, therefore, it is difficult to distinguish ^{15}N enrichment in sediment due to denitrification in the water and manure application in the watershed.

In a study of organic matter in Magu Bay, Lake Victoria, Muzuka et al. (2005) reported $\delta^{13}C$ of particulate organic carbon and $\delta^{15}N$ in surface sediments as ranging from −19.6‰ to −13.7‰ and from −2.0‰ to +5.6‰, respectively; they tried with some success to link the stable isotope signals to the sources of organic matter. This study builds on this earlier work. The objective of this study was to establish the origins and fate of suspended particulate organic matter in the inshore areas of southern LV using stable isotopes of carbon and nitrogen. The questions asked were as follows: (i) Does N isotope support detecting a fertilizer and wastewater signature in sediments and SPM? (ii) What is the contribution of plankton versus littoral zone vegetation in contribution to organic matter in sediments and SPM? What is the role of terrestrial matter? Can organic wastes be detected? (iii) How does the lake geomorphology influence SPM transport?

Materials and methods

Study area

Five areas in the southern portion of Lake Victoria were studied (Fig. 1). Two areas were embayments which receive major river

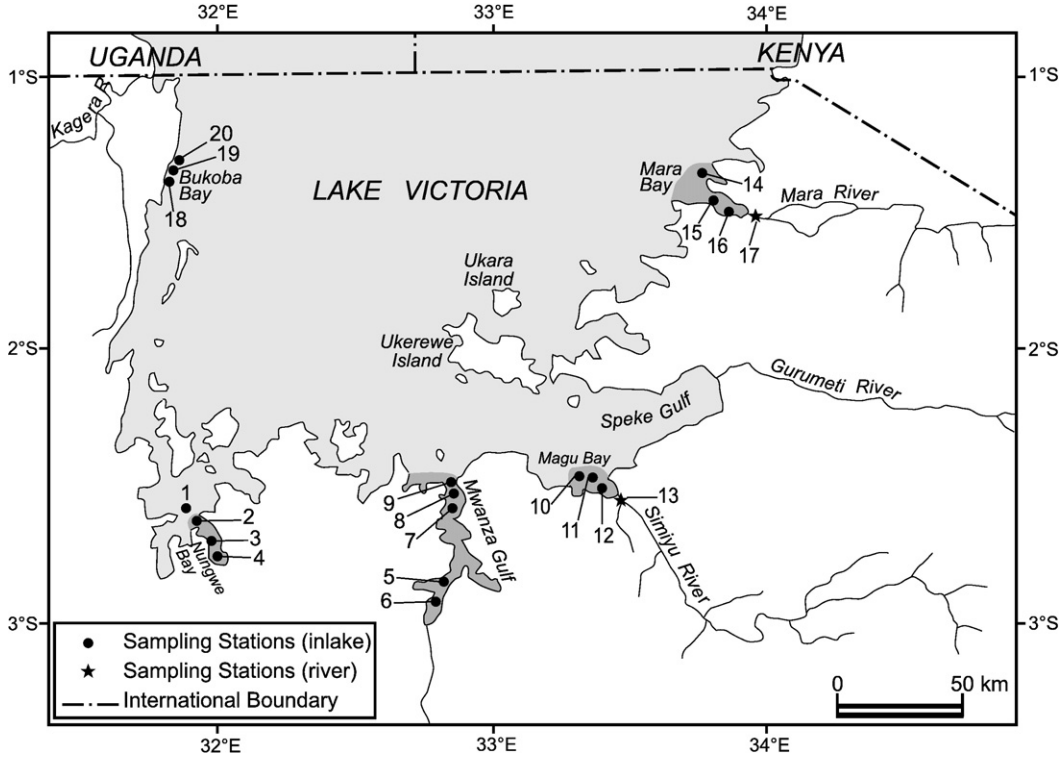


Fig. 1. Map of Lake Victoria (Tanzania waters) showing the sampling stations in Nungwe Bay (1, 2, 3, and 4), Mwanza Gulf, southern part (5 and 6), Mwanza Gulf, northern part/Mwanza North Bay (7, 8, and 9), Magu Bay (10, 11, and 12), Mara Bay (14, 15, and 16), and the Bukoba inshore area (18, 19, and 20) for sediment and suspended particulate matter.

inputs, i.e., Mara Bay fed by the Mara River and Magu Bay fed by the Simiyu River. The northern part of Mwanza Gulf receives substantial wastewater input via the Mirongo drainage. Another area, Nungwe Bay, has no major river input, while the fifth area, the Bukoba inshore area, is a relatively straight shoreline without a distinct embayment; moreover, the Bukoba shoreline is exposed to strong wave action in most part of the year. Sediments in bays with insufficient fluvial discharge were mostly fine grained with high organic matter content; conversely, sediments in Magu bay closer to the Simiyu River mouth had a higher proportion of silt, while sediments at the Mara River mouth had a high organic matter content in addition to silts; the Mara River watershed is vegetated compared with the Simiyu River watershed. Sediments of Bukoba littoral zone were characteristically sandy with low organic content, thus, the sediments are scoured. The urban catchments were the Northern part of Mwanza Gulf, Mara Bay, and the exposed shore of Bukoba. The agricultural catchments were Magu Bay and Nungwe Bay.

Sample collection

Sampling was conducted in the Tanzanian waters of Lake Victoria from May to July 2006. This period was at the end of the rainy season and corresponded with the onset of cooling in the deeper parts the lake (>30 m) which lead to complete mixing of the water column. Sediment and SPM samples were collected from 20 stations (Fig. 1), which were located in five sites as shown in Table 1. The five areas are referred to throughout the text for ease of data analysis and interpretation of the results.

Sediments were collected with a box corer aboard a fiberglass boat from water depths ranging from 1.3 to 11.4 m as determined using a portable echo sounder; water transparency was between 0.3 and 2.0 m as determined with a Secchi disc (Table 1). The top 2 cm of the sediment was scooped with a spoon and kept cool in plastic bags. Sediment samples were air-dried in an air-conditioned, clean room at 25 °C until they attained a constant weight and were sieved on a 1-mm mesh plastic sieve.

Water samples were collected at the surface (0.5 m depth) using a 2-L Kemmerer (acrylic) water sampler, and SPM was obtained by centrifugation (Middelburg and Nieuwenhuize, 1998; Machiwa, 1999; Machiwa and Hallberg, 2002). Water samples were centrifuged at 4000 rpm in 250-mL centrifuge bottles for 30 minutes, then the settled materials were quantitatively washed into 10-mL centrifuge tubes and recentrifuged. The settled materials were collected in 1.5-mL Eppendorf tubes, freeze-dried, and kept in a freezer at −20 °C until they were submitted for analysis.

Sample analysis

Air-dried sediment and freeze-dried SPM samples for stable carbon and nitrogen isotopic composition as well as organic carbon and nitrogen contents analyses were washed with 1 M HCl and freeze-dried. The samples were accurately weighed into tin cups, squashed to enclose the sample, and combusted using a Flash EA 1112 series elemental analyzer (Thermo Finnigan, Italy). The gases were passed to a Delta Plus XP Isotope ratio mass spectrometer (Thermo electron, Germany), via a Conflo III gas control unit (Thermo Finnigan, Germany). The in-house standards used were sucrose, valine, and lentil, all have been previously calibrated against IAEA standards. Working standards were run at intervals for each analytical run to correct final isotope values. Stable carbon and nitrogen isotope ratios are expressed in standard delta notation ($\delta^{13}C$ and $\delta^{15}N$) according to the following formula:

$$\delta^{k}X = \left[\left(R_{sample} / R_{\text{standard}}\right) - 1\right] \times 1000$$

where ${}^{k}X$ is ^{13}C or ^{15}N and R is the corresponding ratio, $^{13}C/^{12}C$ or $^{15}N/^{14}N$.

The carbon and nitrogen ratios are expressed relative to Vienna Pee Dee Belemnite (VPDB) and atmospheric nitrogen (N_2), respectively. Average reproducibilities based on replicate measurements of

Table 1
Locations and names of sampling stations indicating water depth and transparency.

Station no. and location	Latitude/longitude	Depth (m)	Secchi depth (m)
Nungwe Bay (NUB)			
1. Outer Nungwe Bay	S 02°36.911′/E 031°53.753′	10.3	0.85
2. Mid Nungwe Bay	S 02°38.183′/E 031°56.881′	6.5	0.65
3. Inner Nungwe Bay	S 02°42.244′/E 031°58.847′	4.2	0.65
4. Nugwe Port	S 02°46.078′/E 032°00.547′	2.9	0.65
Mwanza Gulf (MZG)			
5. Buyagu (rural catchment)	S 02°51.041′/E 032°49.874′	3.5	0.75
6. Mtalamba (rural catchment)	S 02°54.765′/E 032°48.895′	3.0	0.60
7. Butimba (urban catchment)	S 02°33.945′/E 032°53.278′	7.5	1.25
8. Capripoint (urban catchment)	S 02°30.974′/E 032°53.250′	10.8	1.5
9. Mirongo River entrance (urban catchment)	S 02°30.746′/E 032°53.647′	6.1	1.25
Magu Bay (MGB)			
10. Outer Magu Bay	S 02°29.265′/E 033°21.140′	9.5	1.85
11. Shinebo	S 02°30.875′/E 033°23.780′	5.4	0.8
12. Simiyu River entrance	S 02°31.568′/E 033°25.256′	1.3	0.3
13. [a]Simiyu River Bridge	S 02°34.487′/E 033°27.683′	0.65	-
Mara Bay (MRB)			
14. Busweta	S 01°23.813′/E 033°46.296′	11.4	1.5
15. Mwigobero (urban)	S 01°29.253′/E 033°49.028′	3.7	0.75
16. Mara River entrance	S 01°31.222′/E 033°54.621′	2.6	0.7
17. [a]Mara River Bridge	S 01°31.765′/E 033°58.598′	4.2	0.7
Bukoba near-shore area (BKB)			
18. Colping Hotel	S 01°21.614′/E 031°49.329′	10.2	2.0
19. Bukoba port	S 01°20.522′/E 031°49.473′	7.0	1.6
20. Kifungu	S 01°19.694′/E 031°50.513′	2.8	1.9

[a] Stations located within rivers.

the working standard valine for $\delta^{13}C$ and $\delta^{15}N$ determinations are about 0.02‰ and 0.09‰, respectively.

Results and discussion

Organic carbon in SPM and the sediment samples ranged from 2.7% to 35.7% and from 0.2% to 25.8%, respectively (Table 2). The differences in organic carbon content between sites were statistically significant for SPM ($p = 0.005$, KW = 14.896) and sediment ($p = 0.005$, KW = 14.925) samples. The C/N ratios in SPM ranged from 3.5 to 10.1 and, for sediments, from 7.5 to 19.1. Differences in C/N ratios between sites (Fig. 2) were statistically significant for SPM ($p = 0.049$, KW = 9.491) and sediment ($p = 0.025$, KW = 11.129). Inshore locations close to river mouths had higher C/N ratios than inshore locations not affected by river discharge and more offshore stations.

The $\delta^{13}C$ and $\delta^{15}N$ values of SPM samples ranged from −24.53‰ to −14.68‰ for $\delta^{13}C$ and from −1.88‰ to 6.09‰ for $\delta^{15}N$, while sediment samples ranged from −22.39‰ to −14.98‰ and from −1.30‰ to 6.01‰, respectively (Table 3). These values are compared with the isotopic values of some end-member samples from LV catchment including phytoplankton and macrophytes from the lake and fringing wetlands (Table 4). The riverine end member SPM samples were from Mara River and Simiyu River. These are then used to infer carbon and nitrogen sources. The relationship between SPM $\delta^{13}C$ and $\delta^{15}N$ ratios in sediment and SPM, as shown in Fig. 3, shows two main sources of organic material to and in Lake Victoria.

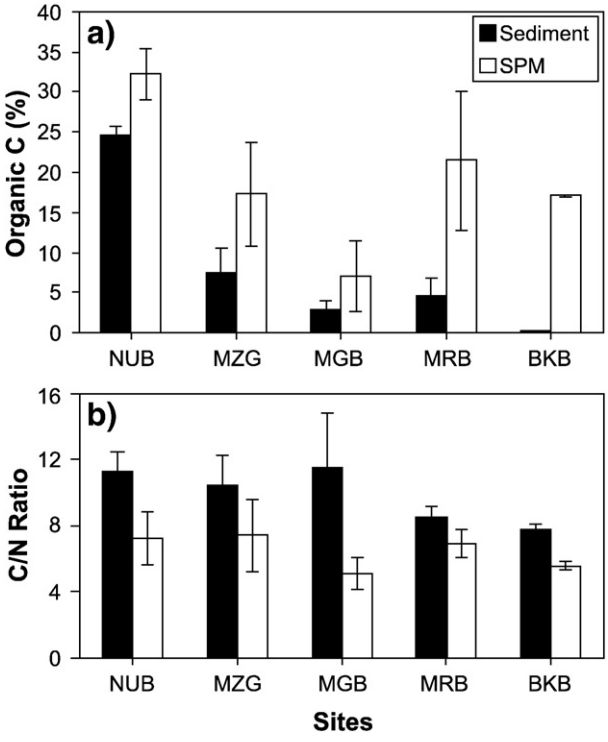


Fig. 2. (a) Organic carbon content and (b) C/N ratios in sediment and SPM samples from the sampling sites.

Mara and Magu bays (strong river inputs, poorly flushed)

Considering first the SPM samples, the $\delta^{13}C$ and C/N ratios of SPM samples collected at the Mara and Simiyu rivers' (in Magu Bay) mouths suggest that they were derived from detritus of aquatic rather than terrestrial origin; $\delta^{13}C$ was depleted (−24.5‰) and the C/N ratios ranged from 4.8 to 19.1. Similarly, for the sediments, about 90% of the sites were dominated by ^{13}C ($\delta^{13}C > -21$‰) characteristic of detritus of phytoplankton origin (Table 4). The organic matter in the sediment samples was more characteristic of *Cyperus papyrus* and *Phragmites* than in SPM, which was more similar to plankton. It is noteworthy that even in these lake areas where there was significant fluvial discharge, sediments were characterized by organic matter of shoreline wetland vegetation origin indicating entrapment of allochthonous materials in the wetlands fringing the lake. This indicates that the wetlands

Table 2
Suspended particulate matter load and organic carbon and nitrogen contents of the suspended particulate matter (SPM) and sediment (Sed.) samples.

Location	SPM (mg/L)	SPM organic C (%)	SPM C/N ratio	Sed. organic C (%)	Sed. C/N ratio
Nungwe Bay (weak river input, poor flushing)					
2.9 (4)	208.0 ± 1.4	32.3 ± 3.4	9.0 ± 1.2	23.0 ± 0.1	10.1 ± 0.1
4.2 (3)	113.1 ± 16.2	35.7 ± 0.02	7.0 ± 0.02	24.8 ± 0.1	12.7 ± 0.1
6.5 (2)	27.7 ± 4.8	32.8 ± 0.1	6.7 ± 0.1	24.6 ± 0.1	10.7 ± 0.1
10.3 (1)	4.7 ± 0.2	28.0 ± 0.2	5.8 ± 0.1	25.8 ± 0.2	11.8 ± 0.1
Mwanza Gulf (weak river input, poor flushing)					
3.0 (6)	294.8 ± 10.8	21.2 ± 1.3	9.0 ± 0.3	8.0 ± 0.3	9.2 ± 0.1
3.5 (5)	421.9 ± 48.0	24.6 ± 0.4	10.1 ± 0.03	8.0 ± 0.2	9.7 ± 0.1
6.1(9)	17.4 ± 2.4	10.0 ± 1.2	4.8 ± 0.1	3.4 ± 0.3	13.8 ± 0.2
7.5 (7)	37.6 ± 10.6	19.1 ± 1.01	6.6 ± 0.1	11.8 ± 0.1	9.8 ± 0.1
10.8 (8)	15.5 ± 0.8	16.2 ± 3.1	6.2 ± 0.3	5.9 ± 0.4	9.6 ± 0.2
Magu Bay (strong river input, poor flushing)					
1.3 (12)	23.3 ± 6.1	2.2 ± 0.3	3.5 ± 0.02	2.0 ± 0.2	14.7 ± 0.1
5.4 (11)	10.8 ± 4.6	5.4 ± 2.6	5.3 ± 0.7	2.2 ± 0.03	11.7 ± 0.02
9.5 (10)	6.7 ± 2.3	10.9 ± 3.4	5.7 ± 0.1	4.1 ± 0.1	8.2 ± 0.1
Simiyu River (13)	46.3 ± 8.2	2.7 ± 0.2	7.1 ± 0.4	0.7 ± 0.1	7.8 ± 0.1
Mara Bay (strong river input, poor flushing)					
2.6 (16)	3.9 ± 0.6	25.0 ± 3.1	7.6 ± 0.1	2.7 ± 0.1	9.0 ± 0.1
3.7 (15)	25.6 ± 9.9	23.8 ± 3.2	5.7 ± 0.2	7.1 ± 0.2	7.8 ± 0.2
11.4 (14)	1.1 ± 0.2	9.4 ± 0.9	6.3 ± 0.3	4.2 ± 0.2	8.7 ± 0.1
Mara River (17)	2.8 ± 0.9	16.5 ± 0.2	10.1 ± 0.8	7.7 ± 0.2	19.1 ± 0.1
Bukoba littoral zone (exposed to strong wave activity)					
2.8 (20)	23.6 ± 1.3	17.1 ± 0.3	5.8 ± 0.2	0.3 ± 0.1	8.1 ± 0.1
7.0 (19)	16.6 ± 1.3	17.0 ± 0.2	5.6 ± 0.2	0.3 ± 0.03	7.5 ± 0.02
10.2 (18)	17.5 ± 3.7	17.2 ± 0.3	5.3 ± 0.2	0.2 ± 0.1	7.9 ± 0.03

The station numbers are shown in parentheses against water depth (m).

Table 3
Mean (±SD) stable organic carbon and nitrogen isotope values in sediment and suspended particulate matter.

Location	$\delta^{13}C$ (‰)		$\delta^{15}N$ (‰)	
	Sediment	SPM	Sediment	SPM
Nungwe Bay (weak river input, poor flushing)				
2.9 (4)	−19.97 ± 0.14	−18.41 ± 0.16	−0.49 ± 0.04	−1.92 ± 0.58
4.2 (3)	−20.82 ± 0.05	−19.24 ± 0.22	−0.53 ± 0.06	−0.48 ± 0.03
6.5 (2)	−20.93 ± 0.11	−19.20 ± 0.27	0.12 ± 0.01	0.71 ± 0.23
10.3 (1)	−20.05 ± 0.08	−18.09 ± 0.21	0.39 ± 0.03	0.48 ± 0.11
Mwanza Gulf (weak river input, poor flushing)				
3.0 (6)	−17.73 ± 0.16	−14.68 ± 0.30	−0.16 ± 0.01	−1.88 ± 0.44
3.5 (5)	−17.42 ± 0.21	−14.10 ± 0.01	−0.71 ± 0.13	−1.25 ± 0.23
6.1 (9)	−22.39 ± 0.22	−21.52 ± 0.04	6.01 ± 0.14	3.38 ± 0.48
7.5 (7)	−20.49 ± 0.07	−20.31 ± 0.23	−1.03 ± 0.03	4.23 ± 0.01
10.8 (8)	−21.65 ± 0.13	−20.71 ± 0.52	2.44 ± 0.17	3.86 ± 1.51
Magu Bay (strong river input, poor flushing)				
1.3 (12)	15.52 ± 0.10	−20.17 ± 0.19	0.98 ± 0.08	1.67 ± 0.14
5.4 (11)	−15.90 ± 0.44	−20.17 ± 0.35	4.66 ± 0.18	2.54 ± 0.63
9.5 (10)	−19.93 ± 0.12	−20.49 ± 0.27	0.67 ± 0.11	2.50 ± 1.37
Simiyu River (13)	−15.85 ± 0.14	−24.50 ± 0.31	2.80 ± 0.15	6.09 ± 0.33
Mara Bay (strong river input, poor flushing)				
2.6 (16)	−16.54 ± 0.18	−17.46 ± 1.28	−1.30 ± 0.06	6.05 ± 0.76
3.7 (15)	−19.12 ± 0.13	−20.48 ± 1.27	−1.18 ± 0.02	1.92 ± 0.21
11.4 (14)	−20.65 ± 0.04	−20.38 ± 0.40	2.13 ± 0.12	2.17 ± 0.11
Mara River (17)	−14.98 ± 0.27	−24.53 ± 1.55	−0.07 ± 0.01	−0.56 ± 0.02
Bukoba littoral zone (exposed to strong wave activity)				
2.8 (20)	−14.95 ± 0.14	−20.36 ± 0.11	4.03 ± 0.15	2.05 ± 0.02
7.0 (19)	−18.96 ± 0.07	−19.94 ± 0.26	4.62 ± 0.07	2.82 ± 0.06
10.2 (18)	−18.47 ± 0.05	−20.55 ± 0.31	1.79 ± 0.04	2.07 ± 0.04

The station numbers are shown in parentheses against water depth (m).

fringing the lake are natural filters for N and P (Bavor and Waters, 2008), hence the need for their conservation.

Differences in $\delta^{13}C$ and $\delta^{15}N$ characteristics of organic matter in sediment and SPM in river samples indicate that organic matter in sediment and SPM was rather uncoupled. Sediment samples from riverine stations had enriched ^{13}C values compared to the corresponding SPM samples suggesting that the organic matter was chiefly derived from adjacent soils where grasses and reeds were the predominant vegetation. Simiyu River (station 13) transported SPM of terrestrial C_3 plant origin as characterized by depleted ^{13}C values. The Simiyu River sediment had enriched ^{13}C values characteristic of the abundant *Phragmite* sp. in the river. In addition, the river also mobilized a significant amount of nitrogenous compounds likely from animal wastes in the watershed, as indicated by low C/N ratio and enriched ^{15}N values (Tables 2 and 3). The $\delta^{15}N$ value and the low C/N ratio (7.8) suggest also the presence of animal waste. Similarly, in Mara River (station 17), the organic C in SPM was depleted in ^{13}C, suggesting C_3 plants origin, while the sediment was enriched in ^{13}C and had high C/N ratio likely from the abundant *C. papyrus* (Tables 2 and 3).

In Mara Bay (MRB), station 15 was within an urban catchment and had a limited growth of shoreline vegetation. Like in urban Mwanza stations (see below), the depleted ^{13}C values in the sediment are likely from domestic wastewater from Musoma town. Although station 14 also has depleted ^{13}C values, the low $\delta^{13}C$ signature of sediment at the station suggests input of planktonic organic C as well as animal and human wastes.

In Magu Bay (MGB), there is a slight offshore transport of organic matter. With the exception of the open lake (station 10), the organic sediment in the inshore area (stations 11 and 12) was enriched with ^{13}C from the luxuriant growth of the extensive fringing *C. papyrus*. The

Table 4
Indicative values (‰) of stable carbon and nitrogen isotope signatures and C/N ratios of some biological and environmental samples from Lake Victoria.

Type of material	*n*	$\delta^{13}C$	$\delta^{15}N$	C/N	Reference
Aquatic plants					
Sedges (*Cyperus papyrus*)	6	−12.7 to −11.9	0.2 to 2.7	66.3	Present study; Campbell et al., 2003
Reeds (*Phragmites* spp.)	4	−11.9 to −11.7	5.2 to 5.3	33.7	Present study
Water hyacinth (*Eichhornia crasspes*)	6	−27.8 to −27.2	2.7 to 3.4	21.5	Present study; Campbell et al., 2003
Bulrush (*Typha* spp.)	4	−28.3 to −27.9	4.21 ± 0.04	22.8	Present study
Vossia spp.	2	−12.8 to −12.4	0.5 to 0.8		Campbell et al., 2003
Plankton and SPM					
Phytoplankton (near-shore)	3	−19.9 ± 0.7	4.3 ± 0.8		Campbell et al., 2003
Zooplankton (near-shore)	3	−17.6 ± 0.8	7.1 ± 0.3		Campbell et al., 2003
Zooplankton (offshore)	2	−20.6 to −20.4	7.7 to 7.7		Campbell et al., 2003
Suspended particulate matter	20	−21.5 to −14.1	4.2 to −1.9 4.7 to10.1	4.7 to 10.1	Present study; Campbell et al., 2003
Invertebrates					
Caridina nilotica	23	−22.8 to −19.0	4.4 to 7.2		Campbell et al., 2003
Mussels (small)	2	−24.1 to −23.4	7.1 to 7.8		Campbell et al., 2003
Prosobranch snail	1	−18.9	5.6		Campbell et al., 2003

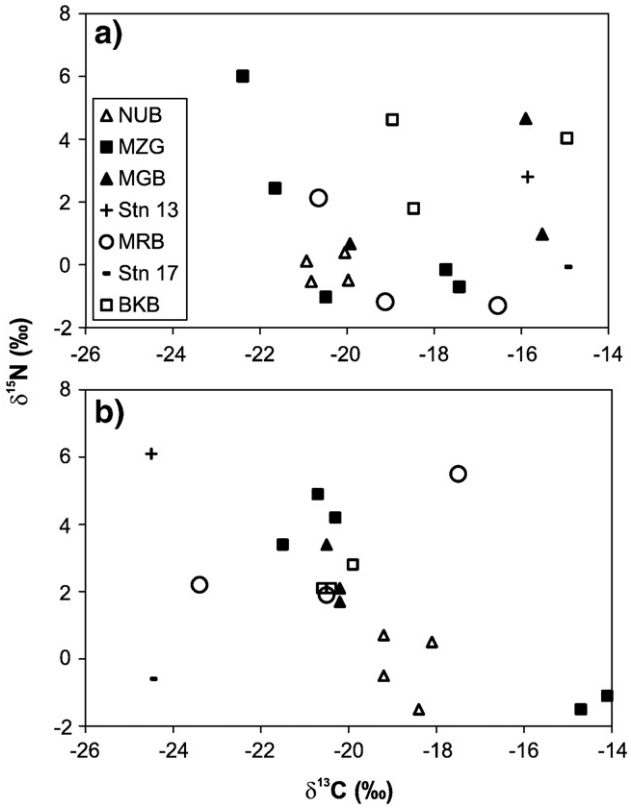


Fig. 3. Characteristic $\delta^{13}C$ (‰) and $\delta^{15}N$ (‰) isotopic fingerprints of (a) sediment and (b) SPM from the five main sampling sites in Lake Victoria.

open lake SPM was mainly phytoplankton ($\delta^{13}C$ −20.5‰ to −20.2‰). The major source of organic matter in the inshore areas of Magu Bay were C_4 plants. Organic matter in the inshore areas of Magu Bay has higher C/N ratios and enriched ^{13}C values characteristic of macrophytes fringing the lake shoreline. Similar observations were reported by Muzuka et al. (2005) who suggested that the organic matter in sediment was mainly from grasses in the watershed.

Mwanza Gulf (poorly flushed)

The northern part of Mwanza Gulf showed interesting results. The area is within the most urbanized catchment, receives higher wastewater input via Mirongo stream and other channels. The depleted ^{13}C values of the sediment and SPM in the inshore areas of the urban part of the lake (stations 7, 8, and 9) indicated input of organic matter from sources other than plankton or shoreline wetland plants. Unfortunately, the shoreline plants in urban areas have been seriously degraded. The obtained $\delta^{13}C$ (≈−22‰), $\delta^{15}N$ (>+3‰) and low C/N ratios in sediment and SPM at stations 7, 8, and 9 are indicative of a mixture of autochthonous organic matter and waste material. The likely sources of organic wastes include industrial (fish processing, dairy, soap factories, etc.), domestic wastewater, and urban runoff, which may contain animal waste including sewage and petroleum hydrocarbons. Solid waste open dumps containing wood shavings and other organic wastes are common in the Mwanza City. The enrichment of ^{15}N in the inshore part of the lake certainly indicates sewage input via pathways such as drainage, subsurface infiltration, or storm water runoff. It is difficult to evaluate the contribution of municipal wastewater as a source of organic matter in the inshore area of Mwanza because SPM in domestic wastewater varies widely in isotopic signals (Thomton and McManus, 1994; Liu et al., 2007). The $\delta^{13}C$ values of sedimentary organic C demonstrated a small gradient from the station closest to the shoreline towards the station outside the bay. Station 7, located outside the bay in the northern part of Mwanza Gulf, was characterized by SPM with ^{13}C-depleted organic C of planktonic origin, low C/N, high organic C content, and enriched ^{15}N; this indicates an attenuation of allochthonous influence and an increase in the contribution of autochthonous organic matter. Muzuka (2001) observed a similar trend of increase in dominance of autochthonous sources of organic matter away from the shore in the coastal waters off Dar es Salaam.

Waters in the south of the Mwanza Gulf (MZG, stations 5 and 6) are poorly flushed, and like in Nungwe Bay (see below), there was also a strong sediment–SPM coupling. The southern part of the Mwanza Gulf, with rural settlements in the catchment, was characterized by ^{13}C-enriched SPM from C_4 plants, most likely *C. papyrus* and *Phragmite* sp. from lakeshore as well as grasses from the catchment.

Nungwe Bay (no major river input, poorly flushed)

In Nungwe Bay (NUB, stations 1, 2, 3, and 4), there was a strong sediment–SPM coupling suggestive of a slow or ineffectual lateral transport of material due to the weak riverine input and a low flushing rate (Fig. 3). The similarity of $\delta^{13}C$ signatures in sediment and SPM indicated that SPM was comprised of a significant proportion of autochthonous material, resuspended sediment and probably a limited allochthonous input. Given the occurrence of high algal biomass in the bay (Mbonde et al., 2004), it is likely that a large proportion of the organic sediment was phytoplankton detritus. The $\delta^{13}C$ (−21.0‰ to 18.1‰) and $\delta^{15}N$ (−1.5‰ to+ 0.7‰) values in Nungwe Bay suggest a relatively enriched ^{13}C source characteristic of LV phytoplankton (Campbell et al., 2003). The near-zero $\delta^{15}N$ values suggest predominance of N_2-fixing microalgae in Nugwe Bay.

Bukoba littoral zone (wave exposed area)

In Bukoba area (BKB), the sediment organic C was low (0.3 %) indicating input of mainly siliciclastic material and/or flushing of fine organics. The $\delta^{13}C$ values suggest organic matter is of phytoplankton origin as well as input from aquatic macrophytes as suggested by the low C/N ratio. There is no indication that Bukoba area is dominated by nitrogen-fixing phytoplankton. The low amount of organic matter in sediment is derived chiefly from autochthonous labile algal material deposited from the water column. Differences in $\delta^{13}C$ and $\delta^{15}N$ characteristics of organic matter in sediment and SPM showed that the organic matter in sediment and SPM is rather uncoupled. The $\delta^{13}C$ in the SPM in Bukoba area was more negative than observed in the sediment. SPM in Bukoba area was chiefly of plankton material. Sediment in station 20 was isotopically heavier in terms of $\delta^{13}C$ and $\delta^{15}N$ values, suggesting input of C_4 organic matter as well as presence of animal waste.

Broad patterns

About 89% of the near-shore stations had SPM that was composed of autochthonous organic carbon derived from phytoplankton and zooplankton. The $\delta^{15}N$ values of SPM suggest that in one third of the near-shore stations, nitrogen is derived from N_2 fixation ($\delta^{15}N$ = −1‰ to +1‰) by Cyanobacteria (Machiwa et al., 2004). In the stations that had high autochthonous organic matter input from aquatic macrophytes and plankton, the sediments were enriched with ^{15}N ($\delta^{15}N$>1‰). This enrichment of ^{15}N values was most likely mainly due to denitrification. The denitrification of SMP following deposition on the sediments suggests suboxic conditions in the surface sediment.

The observed $\delta^{13}C$ values ranging from −24.5‰ to −14.1‰ lie in the higher end for organic C isotope composition, indicating scarcity of C_3 plants in the catchment. Considering that organic C of terrigenous origin has depleted ^{13}C values (Gearing et al., 1991; Peterson and Fry

1987), the observed $\delta^{13}C$ signal in open lake SPM is largely from *in situ* algal production. The dominance of autochthonous SPM in open lake locations was also confirmed by lower C/N ratios in the sediment milieu. The differences in carbon isotope ratios between locations are interpreted to represent the different sources of organic matter that is deposited in the sediment. In particular, the higher values indicate that aquatic macrophytes such as sedges and reeds significantly contribute to the organic matter in the sediment. The $\delta^{15}N$ values in most of the stations were in the normal range, except few samples that had $\delta^{15}N > 3‰$, indicative of animal waste input. Based on the $\delta^{13}C$ and $\delta^{15}N$ data, water hyacinth does not appear to be a significant source of detritus in the bays and the open lake (Tables 3 and 4).

Conclusions

In agreement with studies elsewhere (e.g., Bouillon et al., 2002), spatial variation in stable C and N isotopes and C/N ratios in SPM and sediments in the inshore areas of southern Lake Victoria are caused by the differences in the relative proportions of organic matter sources. Stable isotope and C/N ratios are characteristics of lacustrine plankton and their detritus ($\delta^{13}C \approx -20‰$ and $C/N < 10$) and indicate that these sources dominate the SPM and sediment organic matter of the larger part of the near-shore areas of the lake suggesting high productivity. The organic C isotope ratios in sediment decreased towards the bay mouths and into the lake, indicating the increasing input of planktonic matter and/or decreasing amount of allochthonous material. The results show that human activity in the urban catchment influences to a certain extent the stable isotope signatures of the organic sediment in the near-shore areas of the lake. Watershed characteristics, such as urbanization, also immensely influence the stable isotope signal of organic sediment in near-shore samples with the data, suggesting that organic matter introduced in the bays was not efficiently flushed out. There was some horizontal mobilization of SPM in areas with significant riverine input, such as Magu and Mara bays. The ineffectual lateral transport of SPM from some bays results into concomitant deposition of allochthonous matter within the inshore areas. No attempt has been made to evaluate the extent of lateral transport of allochthonous dissolved organic matter towards outside the bays.

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