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A century of human-induced environmental changes and the combined roles of nutrients and land use in Lake Victoria catchment on eutrophication

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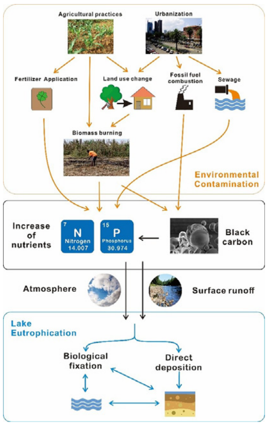
HIGHLIGHTS

- Multi-proxy data trace changes in catchment-derived nutrients into Lake Victoria.
- Input of nutrients (organic C, black C, N and P) and land-use changed after 1960.
- Land-use shifts include decline in forests and rise in farmland and urban development.
- Spatiotemporal changes in nutrients and land-use correspond with diatom communities.
- Anthropogenic changes ushered cultural eutrophication of the lake.

GRAPHICAL ABSTRACT



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ABSTRACT

Lake Victoria, a lifeline for millions of people in East Africa, is affected by anthropogenic activities resulting in eutrophication and impacting the aquatic life and water quality. Therefore, understanding the ongoing changes in the catchment is critical for its restoration. In this context, catchment and lake sediments are important archives in tracing nutrient inputs and their dominant sources to establish causality with human activities and productivity shifts. In this study, we determine the 1) changes in concentrations of total organic carbon (TOC), black carbon (BC), total nitrogen (TN), C/N ratio, and phosphorous (P) fractions in catchment sediments and the open lake, 2) distribution of diatom population in the lake, and 3) land use and land cover changes in the catchment. The distribution of TOC, BC, TN, C/N, and P correlate while showing spatial and temporal variations. In particular, the steady increase in BC confirms atmospheric inputs from anthropogenic activities in the catchment. However, lake sediments show more variations than catchment-derived sediments in geochemical trends. Notably, the catchment has undergone dramatic land use changes since the 1960s (post-independence). This change is most evident in satellite records from 1985 to 2014, which indicate accelerated human activities. For example, urban growth (666–1022%) and agricultural expansion (23–48%) increased sharply at the expense of a decline in forest cover, grassland, and woodlands in the catchment. Cities like Kisumu and Homa Bay expanded, coinciding with rapid population growth and urbanization. Consequently, nutrient inputs have increased since the 1960s, and this change corresponds with the divergence of diatom

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communities in the lake. In addition, the transition to *Nitzschia* and cyanobacteria mark increasing cultural eutrophication in the lake. The geochemical trends and statistical data support our inference(s) and provide insights into urban development and agriculture practices, which propelled increased nutrients from the catchment and productivity shifts in the lake.

1. Introduction

The Lake Victoria Basin (LVB) is one of the most densely populated regions in east Africa that has undergone rapid population growth and urbanization in the last 50 years (Güereña et al., 2015a, b). Rich in various minerals and natural resources, LVB experienced environmental stress from increasing human activities and land use changes. A gradual shift in land-use patterns occurred in the early 1900s due to colonization, resettlement, animal husbandry, and missionary work, ensuing a steady increase in population in East Africa (Swynnerton, 1955; Maitima et al., 2010; Owiyo et al., 2014). The colonial regime oversaw clearing the forests and surrounding wetlands for human settlements, and agriculture and urban development started increasing in the catchment (Shilaro, 2008). Soon after the independence of Kenya, Uganda, and Tanzania in the mid-1960s, the newly formed African governments focused on urban development plans extending beyond the borders of large cities into rural areas.

In recent years, the fundamental challenges faced in Lake Victoria arise from increasing siltation, the input of various nutrients and toxic pollutants from the catchment, agriculture and sewage wastes, pharmaceutical products, and urbanization (UNEP, 2004; Gikuma-Njuru et al., 2005; Stager et al., 2009; Hecky et al., 2010; Nantaba et al., 2020, 2021). Consequently, there have been notable changes in the biological, chemical, and physical properties of the water body (Odada et al., 2009; Stager et al., 2009; Hecky et al., 2010; Nyamweya et al., 2020; Opere et al., 2021). As a result, local people who live around the lake and depend on it for their daily livelihoods face higher risks of food and water safety, economic pressures, and health-related challenges that have been increasing steadily over the last few decades (Gikuma-Njuru et al., 2005; Okungu et al., 2005; Kabenge et al., 2017; Nantaba et al., 2020).

The oversupply of nutrients in the lake causes eutrophication, leading to various changes that have impacted its economic, social, and ecological functions (Okungu et al., 2005; Stager et al., 2009). For example, the rapid proliferation of the invasive water hyacinth population in Lake Victoria has made parts of the lake hard to access (Albright et al., 2004; Güereña et al., 2015). In addition, water hyacinth has multiplied near the lake's border, restricting the economic and social activities pursued by the local communities for their livelihood, e.g., fishing, water transport, and recreational activities (Gikuma-Njuru et al., 2005; Kolding et al., 2008; Heisler et al., 2008; Güereña et al., 2015a, b). The input of nutrients (including carbon, nitrogen, and phosphorous) into the lakes is driven by both terrestrial (Kansiime et al., 2007) and atmospheric deposition (Tamatamah et al., 2005; Zhou et al., 2014). The terrestrial inputs derived from agriculture, sewage, and industrial effluents from the catchment are introduced into the lake by weathering processes, rainfall, and fluvial discharge (Burton, 2002; Kishe-Machumu and Machiwa, 2003; Okungu et al., 2005). In contrast, atmospheric inputs comprise combustion-derived byproducts of P, N, and black carbon (BC) arising from slash and burn practices in fields, biomass burning, and industrial emissions (Hecky, 1993; Tamatamah et al., 2005). While nutrients from the catchment are deposited close to the source (Gikuma-Njuru et al., 2005, 2013), those from atmospheric deposition have a lake-wide footprint (Tamatamah et al., 2005) and source apportionment is more challenging.

Biomass and fossil fuel combustion account for a large percentage of BC emissions found in the upper atmosphere, soils, and sediments (Hammes et al., 2007; Bond et al., 2013). BC forms by condensation and aggregation of small aromatic moieties in the gaseous state during incomplete combustion of carbonaceous material at elevated temperatures (Gustafsson et al., 2001; Hammes et al., 2008). The affinity of different elements to attach to BC is due to its large surface area and the presence of carboxylic and hydroxyl groups in its structure that form covalent bonds (Brodowski et al., 2005; Nguyen and Lehmann, 2009). Therefore, BC correlates positively with nutrients, oxidative metals, and organic compounds (Han et al., 2016; Kappenberg et al., 2019; Polyakov et al., 2020). Researchers have focused on the spatio-temporal distribution of BC and its relationship to combustion processes and ongoing land use changes in lake and fluvial catchments to establish causality with anthropogenic activities (Routh et al., 2004, 2007; Forbes et al., 2006; Nelson et al., 2012; Ruppel et al., 2015).

Researchers have linked changes in Lake Victoria to the input of various nutrients (N, P, and biogenic Si), industrial pollutants (Okungu et al., 2005; Nantaba et al., 2020), biomass combustion products, and BC (Verschuren et al., 2002; Arinaitwe et al., 2018; Odhiambo and Routh, 2016) arising from varied human activities in the catchment (Gikuma-Njuru et al., 2005; Olokotum et al., 2020). While there is a lot of data on C, N, and P levels in the open lake itself, there is little information about the spatiotemporal distribution/input of these elements from the catchment, which is likely one of their dominant sources. Likewise, very little is known regarding the distribution and concentrations of BC in the LVB, even though biomass burning is a common practice in East Africa. Hence, the objective of this study is to quantify the total organic carbon (TOC), BC, total N, C/N, and concentration of P fractions in Lake Victoria and its catchment, with a focus on the Winam Gulf (Fig. 1). Thus, intact sediment cores were recovered from lakeshore/open lake sites representing different land use patterns in the catchment. The sediment cores retrieved from the open lake and in a shallow channel were selected to represent the contrasting trophic conditions (meso/oligotrophic to eutrophic status, respectively) in this large water body. We used geochemical trends in conjunction with land use changes in the catchment to establish causality with eutrophication based on diatom assemblages. This approach of paleoenvironmental reconstruction using multiple proxies helps establish the timing of these changes to implement mitigation options and tackle eutrophication changes in aquatic bodies worldwide.

2. Study area

Lake Victoria developed from a river flow reversal and back ponding process that was caused by the uplift of the western arm of the East African Rift System (EARS) and contemporaneous down warping of the land between the eastern and western arms of the EARS, ca. 400,000 years ago (Johnson et al., 2000). Before the uplift, the rivers in the region flowed westwards. Kenya, Uganda, Tanzania, Rwanda, and Burundi form part of the riparian nations that share the 250,000 km^2 catchment of LVB (Onyango et al., 2021). While the largest portion (44%) of LVB belongs to Tanzania, Kenya covers 22% of the basin. LVB has an equatorial climate affected by the high elevation of the basin and surrounding mountainous terrain (including Mt. Elgon). As a result, the temperature is low (20–35 °C) compared to equatorial regimes, and precipitation is 1000–1500 mm with no distinct dry season (Okungu et al., 2005). Furthermore, the wind regime is a bi-modal pattern; the SW-S-SE direction prevails from January to March, whereas the N-NE-E direction dominates from August to September. Thus, natural processes such as wind and precipitation affect the input of nutrients into the lake (Tamatamah et al., 2005). The basin includes Precambrian volcanic rocks (e.g., basalts, andesites, tuff, dacites, and rhyolite) and Quaternary sediments (e.g., clays, shales, diatomites, and carbonatites). The common soil types are cambisols, vertisols, regosols, and ferralsols (Okungu et al., 2005).

Although Lake Victoria is the largest of the African Great Lakes, it is relatively shallow (average depth of 41 m compared to Lakes Malawi (292 m),

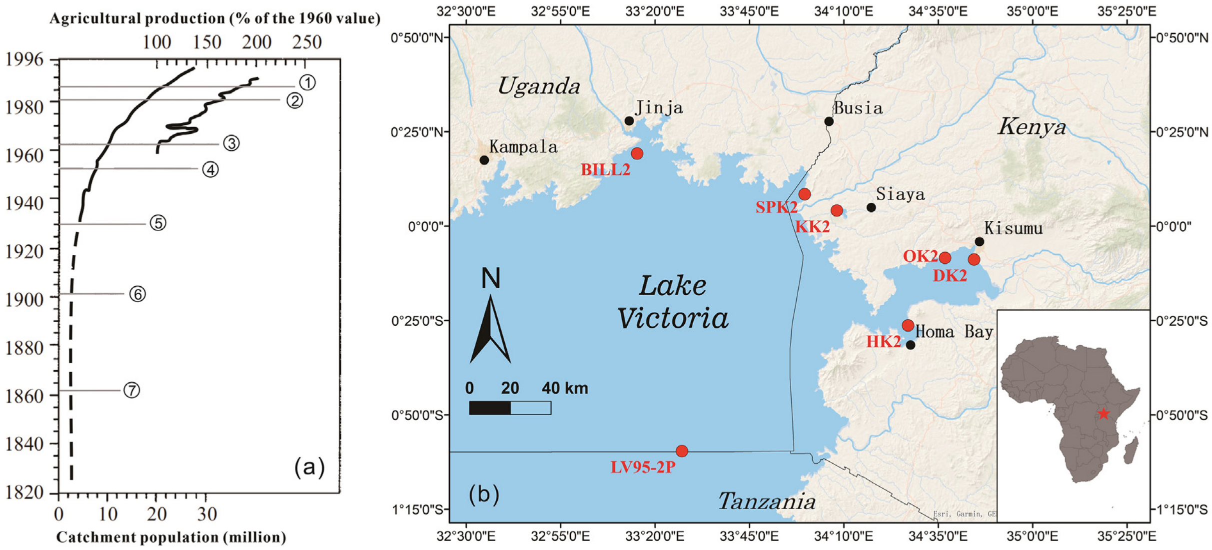

Fig. 1. Location map of the study area. a) Historical changes in the Lake Victoria catchment since the early 1800s. The changes are marked as 1–7; 1 — Pelagic cyanobacteria bloom; 2 — Nile perch population surges, indigenous fish stocks collapse; 3 — Lake-level rise floods riparian wetlands; 4 – Nile perch introduced; 5 — Railroad arrives in Kampala, Uganda; 6 — Railroad arrives in Kisumu, Kenya; 7 — Discovered by European explorers. b) Sampling of sediment cores from the Lake Victoria Basin (Kenya) and the lake. (Modified from Verschuren et al., 2002).

Kivu (240 m), and Tanganyika (570 m)) and sensitive to anthropogenic changes in its surroundings. Because of its large surface area and extensive catchment, the lake receives high organic carbon input compared to other large lake systems globally (Scholz et al., 1998) besides N and P (Gikuma-Njuru et al., 2005; Tamatamah et al., 2005). The coastline is dotted with papyrus swamps and rocky and sandy beaches. According to Okungu et al. (2005), the main rivers and their discharge percentages are Nzoia — 39%, Gucha-Migori — 20%, Sondu — 14%, Yala — 13%, Nyando — 6%, and Sio — 4%. These rivers originate in the highlands, and pollution increases downstream as they meander through the lowlands, including farms and urban settlements. The lake itself is physicochemically heterogeneous due to LVB's diverse topography, climate, hydrology, and land use practices in its catchment. Precipitation and evaporation are the dominant factors controlling the changes in water budget; only ~15% of the input and output of water are regulated by fluvial discharge (Hecky et al., 2006). The circulation pattern in the lake varies, affecting water quality and biota (Crul, 1995). Simulations made by Nyamweya et al. (2016) show that the water column displays thermal stratification between September and May and mixing between June and August. The lake is anoxic in the deeper parts, whereas the surface water is saturated in oxygen. Lake Victoria has high spatial variability in its trophic status. The inland gulfs and waterways in the lake, areas adjacent to large human settlements, and river mouths are relatively turbid and eutrophic. In contrast, the open lake is mesotrophic (Gikuma-Njuru et al., 2013; Okely et al., 2010), whereas the deeper waters are mostly oligotrophic (Simiyu and Kurmayer, 2022).

Since the colonial era, rapid urbanization in the lowlands has seen the development of large urban hubs such as Kisumu, Homa Bay, Mwanza, Jinja, and Kampala along the lake's shoreline. Nearly half of Kenya's population lives in the LVB, endowed with abundant fresh water and natural resources. Kisumu has a major ship-loading facility making it one of the major ports in East Africa (Okungu et al., 2005). The lake basin has about 40 million people (~3% growth rate; Bremner et al., 2013). Many people in the LVB are impoverished and dependent on fishing, agriculture, small-scale industries, tourism, and farming. These practices are mainly unregulated, resulting in overfishing, deforestation, and the increasing use of fertilizers and fossil fuels in the catchment (Cornelissen et al., 2014). In addition, vegetation changes from combustion, deforestation, and other land use practices affected the input of N and P into the lake as early as the 1920s (Hecky, 1993; Hecky et al., 1996; Verschuren et al., 2002). Consequently, eutrophication has steadily increased in recent years, and the overall effects are dramatic (Hecky, 1993; Stager et al., 2009). For example, the invasive overgrowth of water hyacinth and phytoplankton has risen sharply since the 1990s affecting the water quality by creating anoxic conditions that raised toxicity and disease levels (Albright et al., 2004; Güereña et al., 2015a, b). Furthermore, the contiguous floating mats impede access to fishing, transportation, hydroelectric power generation and disrupt native plant communities (Albright et al., 2004). Other ecosystem changes include the virtual decimation of the native cichlid population due to the introduction of the Nile perch (*Lates niloticus*) during the 1950s (Kishe-Machumu et al., 2013), which simplified the food web (Hecky, 1993; Verschuren et al., 2002; Stager et al., 2009; Njiru et al., 2014).

3. Methods

3.1. Sediment sampling

Five sediment cores from the LVB catchment (OK2, DK2, HK2, KK2, and SPK2) were retrieved in 2015, and two from within the lake, i.e., BILL-2 in 2000 and LV95-2P in 1995 (Fig. 1). Table 1 summarizes the specific details of the sampling sites. The catchment sites in LVB represented the four administrative counties, Siaya, Busia, Kisumu, and Homa Bay (Onyango et al., 2021). The sampling sites themselves were located near rivers flowing close by, namely, Sio (SPK2), Nzoia (KK2), Yala (OK2), and Nyando (DK2).

We collected the cores OK2, DK2, HK2, KK2, and SPK2 from the catchment using a percussion corer (Atlas Copco AB, Sweden) equipped with a 100 cm long and 5.5 cm diameter PVC liner. The lake core from the Buvuma Channel (BILL-2) was collected using a UWITEC™ gravity corer (Stager et al., 2009), and a Kullenberg corer was used to retrieve the core from the middle of the lake (LV95-2P; Johnson et al., 1996). On request, samples were provided from LV95-2P cores stored in the core repository in USA. The catchment cores retrieved in 2015 were packed and transported to Sweden and kept at −20 °C until further analyses. The cores were thawed, sliced at 1-cm intervals, and freeze-dried. We crushed the dried samples lightly using a mortar and pestle and thoroughly mixed them.

3.2. Lead dating

The sediment chronology for cores OK2 (Kisumu), DK2 (Kisumu), HK2 (Homa Bay), KK2 (Siaya), and SPK2 (Busia) was determined using the ^{210}Pb-dating methodology at the University of Wisconsin, Milwaukee

Table 1
Sampling details of the cores retrieved from the catchment (in Kenya) and Lake Victoria.

Core	GPS location	Site	Depth and sampling	Drilling method
OK2	0°8′ S 34°37′ E	Kisumu, Kenya, lies in the Yala River basin River fed by precipitation around Mt. Elgon and its surroundings. Altitude — 1197 m asl, 63 m above lake level. Rainfall — 1250 mm; temperature — 23 °C Population density — 460 people/km^2	100 cm June 2015	Percussion corer
DK2	0°7′ S 34°44′ E	Kisumu, Kenya, lies in the Nyando River basin River fed by precipitation from the Kericho Highlands Similar elevation and metrological conditions as OK2	100 cm June 2015	Percussion corer
HK2	0°7′ S 34°26′ E	Homa Bay, Kenya Altitude — 1202 m asl, 68 m above the lake level Rainfall — 1600 mm; temperature — 22.5 °C Population density — 360 people/km^2	100 cm June 2015	Percussion corer
KK2	0°4′ N 34°8′ E	Siaya, Kenya, lies in the Nzoia River basin Altitude — 1152 m asl, 18 m above lake level Rainfall — 2150 mm; temperature — 21 °C Population density — 393 people/km^2	100 cm June 2015	Percussion corer
SPK2	0°10′ N 34° 0′ E	Busia, Kenya, lies in the Sio River basin Altitude — 1188 m asl, 68 m above lake level Rainfall — 1600 mm; temperature — 22.5 °C Population density — 360 people/km^2	100 cm June 2015	Percussion corer
BILL 2	0°20′ N 33° 16′ E	Buvuma Channel, Uganda. Drains into River Nile Water depth — 40 m Hypoxic, thermal stratification between Aug and Dec	50 cm June 2000	Gravity corer
LV95-2P	0°58′ S, 33°27′ E	Middle of Lake Victoria, Tanzania Water depth — 67 m Well oxygenated, stratified	753 cm April 1995	Kullenberg corer

(Goldberg, 1963; Robbins and Edgington, 1975). The procedure involved using 0.5 g of each sample spiked with 1 ml of Polonium (^{209}Po) as an internal standard. We digested the samples using 50 ml of 6 N HCl at 95 °C for 4 h. In addition, we added 1 ml of 30% H_2O_2 and a drop of octanol during the first four 30 min to oxidize the organic matter in the samples. After 4 h, the samples were left to sit overnight and filtered using Whatman filter paper (Quantitative Ashless grade 42) into 125 ml Erlenmeyer flasks. The flasks were heated to evaporate the solution to about 5 ml and then brought up again to 50 ml using E-pure water while maintaining the pH between 0.5 and 1.0 by adding HCl or NaOH. After that, 0.1 g of ascorbic acid was added to each sample to prevent interference of iron during the plating of ^{209}Po. Polished copper discs were labeled and placed into a plastic bottle, and each sample was heated overnight at 95 °C in an oven. The copper discs were then removed from the solution and counted using an alpha spectrometer for 60,000 s under vacuum. ^{210}Po is a daughter of ^{210}Pb, and it is assumed to be in secular equilibrium with its parent nuclide. Therefore, the calculation of ^{210}Pb was the activity of ^{210}Po found in each sample (MacKenzie et al., 2011). Stager et al. (2009) determined the ^{210}Pb and ^{137}Cs profiles in the BILL-2 core. Verschuren et al. (1998) did the ^{210}Pb dating in core LV96-3MC from the same site as LV95-2P, but collected in 1996.

3.3. Elemental measurements

We decarbonated the sediment samples using the fumigation method, which involved placing the samples in porcelain crucibles inside a desiccator with 12 M HCl for 10 h. The samples were kept in the oven at 40 °C for 6 h. Total organic carbon (TOC) and total nitrogen (TN) concentrations were determined using a Perkin Elmer 2400 CHN elemental analyzer (Perkin Elmer Corp., Norwalk, CT). For calibration, acetanilide (C_8H_9NO) was weighed in a tin capsule and run alternately with the blanks.

Black carbon was measured using the chemo-thermal oxidation method (Gustafsson et al., 1997). In brief, we weighed 50 mg of dried sediment into pre-combusted porcelain crucibles covered with aluminum foil and placed them in a muffle furnace (Nabertherm, B150). The samples were heated at 375 °C for 24 h in the presence of excess air. Next, we removed the inorganic carbon in the samples. During this step, 30 mg of the combusted sediment was moistened with 50 μl deionized water and placed in a 5 l vacuum desiccator containing 100 ml of 12 M HCl for 6 h and dried in an oven at 50 °C for 4 h. Finally, we measured the samples on a Perkin Elmer elemental analyzer (EA 2500) at 1030 °C in a quartz column in the presence of oxygen. In addition, we measured reference materials SRM 1944 and SRM 2975 (from NIST, Gaithersburg, MD) and blanks in between the samples.

We determined the phosphorus (P) concentrations based on two different procedures: the sequential extraction procedure (Standards Measurements and Testing (SMT) extraction) and the spectrophotometry detection method (Blue Method). Ruban et al. (1999) modified the SMT extraction method. This procedure involves fractionating P into three forms — inorganic phosphorus (IP), organic phosphorus (OP), and total phosphorus (TP). The Blue Method consists of the production and degradation of phosphomolybdic acid as detailed by (Murphy and Riley, 1962). We measured the intensity of the blue color complex on a spectrophotometer at 882 nm.

3.4. Land use changes

Land use cover and land use change in the fluvial basins, namely Nzoia-Sio, and Yala-Nyando, from 1985 to 2014 by Mugo et al. (2020) were modified and quantified using ArcGis (v. 10.7.1). Land cover in the LVB was classified into the indigenous forest, wetland, woodland, grassland, and farmland to account for the overall vegetation cover in the catchment. To generalize the output, the different types of grassland and woodland (open and close varieties) in Mugo et al. (2020) were broadly classified into two categories. Land use in the catchment was divided into two broad categories, namely farmland and urban areas. The ArcMap software was used to prepare shapefiles, modify the maps, and calculate the changes in land use cover. We considered three rivers, Nzoia, Sio, and Yala, corresponding with our sampling sites (SPK2, KK2, and OK2). We had the complete data for different geochemical proxies and reliable ^{210}Pb chronology to infer the relationship between land use and geochemical proxies in these sites. The land use cover from each year available was clipped with the shapefiles of the basins. The area (km^2) for each land use cover was calculated by multiplying the number of pixels and its value. The percentage of each land use was then calculated by dividing the area of respective land use or land cover by the whole area covered in the basin. Pixels within the sub-basins with no data were represented with white color on the map and were not included in the calculation.

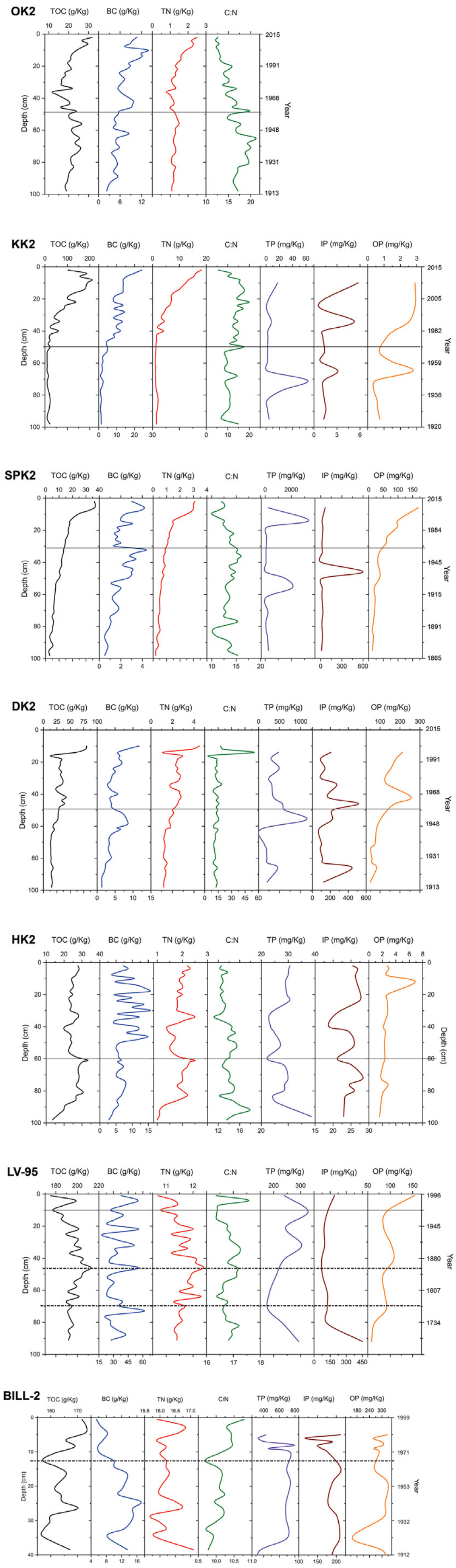

Fig. 2. Geochemical trends showing the distribution of total organic carbon (TOC), black carbon (BC), total nitrogen (TN), carbon/nitrogen (C/N) ratio, total phosphorous (TP), inorganic phosphorous (IP), and organic phosphorous (OP) in Lake Victoria and its catchment. Note the different scales on the x-axis for proxies. Breakpoint (firm or hashed line) shows the transition in the geochemical trend.

3.5. Statistical analyses

Principal Component Analysis (PCA) was conducted using the IBM's SPSS Statistics software to understand the association between nutrients and diatoms. Different components described the score-based correlation from PCA in Buvuma Channel, whereby higher values indicated greater significance; the lowest level for significant factor score was chosen as ±0.5. PCA was also used to identify the factors that impact land use and land cover changes in the catchment from which cores KK2, SPK2, and OK2 were recovered. These three sites had the complete data available for geochemical proxies and corresponding reliable chronology to correlate land use changes with human activities in the catchment. Geochemical proxies and land use cover were interpolated for doing the PCA. PCA was rotated using the varimax method; significant loading was chosen for values over 0.7 and below −0.7.

4. Results

4.1. Sediment chronology

The ^{210}Pb profile of cores SPK2, KK2, and BILL-2 showed a moderate decline of ^{210}Pb activity with depth (Fig. 2). Therefore, we estimated the sedimentation rate from the slope of the resulting curve as per the Constant Rate of Supply (CRS) method using linear regression (Evans, 1984; see Supplementary data Fig. F1). We extrapolated the ages beyond 30 cm depth after determining the mass depths. Between 9 and 12 cm, there was an exponential decrease of ^{210}Pb in SPK2, KK2, and BILL-2 cores corresponding to 1987, 1985, and 1990, respectively. Cores OK2, DK2, and HK2 indicated a more irregular ^{210}Pb activity and did not reach the background level. The mixing of topsoil from tilling in the fields resulted in the uneven distribution of ^{210}Pb activity at these sites. The sedimentation rates for cores SPK2, KK2, and BILL-2 were calculated as 0.35 g/cm^2/yr, 0.09 g/cm^2/yr, and 0.09 g/cm^2/yr, respectively. Sediment chronology data for the cores BILL-2 and LV-95 were from Stager et al. (2009) and Verschuren et al. (2002).

4.2. Geochemical trends in catchment and lake sediments

Table 2 and Fig. 2 summarize the geochemical trends showing the range and average of TOC, BC, TN, C/N, TP, IP, and OP concentrations in Lake Victoria and its cores from the catchment sites. Table 3 summarizes the correlation between TOC, BC, and TN ($p < 0.05$).

4.2.1. Site OK2 (Kisumu)

TOC concentration in OK2 (Fig. 2) increased steadily from the bottom to the mid-core (20.1 g/kg; 42 cm; 1965) before dipping slightly and then increasing near the top. BC concentration started low (2.3 g/kg; 98 cm; 1913) then increased gradually up the core, with the values tripling near the top of the core (13.8 g/kg; 10 cm; 2002) and then dipping slightly. TN concentrations rose gradually except for a dip at 36 cm (0.8 g/kg; 2002). C/N ratio started at 17.2 (98 cm; 1913) and rose gradually to 21.2 (65 cm; 1944) before declining to 12.7 (2 cm; 2012) near the top. Due to insufficient sample material, P was not analyzed in this core.

4.2.2. Site KK2 (Siaya)

The TOC concentration in KK2 (Fig. 2) started relatively low at 22.3 g/kg (98 cm; 1920) and rose gradually until 40 cm (60.5 g/kg; 1982) before increasing rapidly. BC values started low (1.4 g/kg; 98 cm; 1920) and remained steady up to the middle of the core, after which BC increased slowly at first and then rapidly towards the top. TN concentration

Table 2

Geochemical trends showing the range and average concentration of total organic carbon (TOC), black carbon (BC), total nitrogen (TN), carbon/nitrogen (C/N) ratio), total phosphorous (TP), inorganic phosphorous (IP), and organic phosphorous (OP) in Lake Victoria and its catchment.

Location	TOC (g/kg)	BC (g/kg)	TN (g/kg)	C/N	TP (mg/kg)	IP (mg/kg)	OP (mg/kg)
OK2	21.2 (12.0–31.7)	6.93 (2.30–10.7)	1.37 (0.80–2.50)	15.9 (12.1–21.2)	–	–	–
KK2	57.9 (9.80–210)	7.41 (1.00–24.0)	4.44 (1.00–18.1)	12.5 (5.68–20.0)	10.3 (0.75–62.7)	2.00 (0.57–5.73)	1.45 (0.38–2.91)
SPK2	13.3 (2.60–37.0)	2.07 (0.50–4.30)	1.05 (0.20–3.10)	13.1 (9.70–15.8)	537 (42–3326)	61.0 (7.00–600)	46.9 (12.0–169)
DK2	28.4 (13.1–80.3)	4.67 (1.30–11.7)	2.04 (1.10–4.50)	14.1 (4.79–55.3)	370 (51–1142)	188 (73–514)	121 (51.0–256)
HK2	24.9 (13.6–33.3)	7.84 (2.80–15.6)	1.85 (1.00–2.50)	13. 7 (11.2–17.9)	27.9 (22.2–38.6)	24.7 (18.6–28.4)	2.62 (1.60–6.90)
LV-95	194 (175–173)	34.4 (18.9–61.5)	11.6 (10.7–12.4)	16.8 (16.4–17.6)	245 (179–328)	148 (71.3–449)	92.8 (58. 6–153)
BILL-2	164 (156–173)	10.7 (5.40–17.0)	16.2 (15.7–17.1)	10.1 (6.69–10.8)	584 (329–794)	182 (117–213)	284 (157–328)

started low at 1.5 g/kg (98 cm; 1920) and remained low until about the middle of the core, where they gradually increased. C/N values generally decreased up the core. TP concentration increase up the core with a slight dip at 24 cm (0.75 mg/kg; 2002). IP values remained stable up the core except of spikes at 65 cm (3.1 mg/kg; 1952), 34 cm (5.3 mg/kg; 1990), and 10 cm (5.7 mg/kg; 2008). OP concentration increased gently up the core.

4.2.3. Site SPK2 (Busia)

TOC concentration in SPK2 (Fig. 2) started low and rose steadily up the core before doubling near the top. BC in SPK2 was the lowest in all the catchment sites. BC values generally increased up the core. TN values followed the same trend as TOC. C/N values started at 15.0 (98 cm; 1865) and decreased to 9.80 (83 cm; 1887) before irregularly increasing the rest of the way up the core. TP concentration started relatively low and remained steady except for the abrupt increases at 56 cm (2058 mg/kg; 1917) and 14 cm (3326 mg/kg; 1995). IP concentration also varied, starting low and increasing steadily to the top of the core; there was a spike at 46 cm (600 mg/kg; 1933). The concentration of OP increased steadily up the core before increasing five-fold to 169 mg/kg near the top (2 cm; 2012).

4.2.4. Site DK2 (Kisumu)

TOC values in DK2 (Fig. 2) increased gradually until 40 cm (31.6 g/kg), after which they sharply increased at 10 cm (80.3 g/kg). BC concentrations in DK2 increased steadily from the bottom of the core and then increased sharply to 8.4 g/kg at 59 cm before declining again. The highest concentration (11.7 g/kg) occurred near the top of the core. The TN concentration followed a similar trend as TOC. TN increased from 1.30 g/kg at the bottom to 2.70 g/kg around 40 cm. C/N values started at 12.8 at the bottom of the core and remained relatively stable except for a spike at 14 cm. The TP values started at 203 (95 cm) mg/kg and decreased to 51 mg/kg (62 cm) before increasing to 1142 mg/kg (56 cm). The TP values then irregularly decreased up the core to 472 mg/kg (14 cm). IP values started at 126 mg/kg and then fluctuated between 100 and 200 mg/kg, except for spikes at 86 cm (456 mg/kg) and 46 cm (566 mg/kg). OP values in DK2 ranged between 51.0 mg/kg (95 cm) and 212 mg/kg. OP concentration generally increased up the core.

Table 3

Correlation matrix showing the correlation between total organic carbon (TOC), black carbon (BC), and total nitrogen (TN) in Lake Victoria and the catchment sites ($p < 0.05$).

OK2	TOC	BC	TN	*HK2*	TOC	BC	TN
TOC	1			TOC	1		
BC	0.18	1		BC	− 0.02	1	
TN	0.79	0.51	1	TN	0.91	0.09	1

KK2	TOC	BC	TN	*LV-95-2P*	TOC	BC	TN
TOC	1			TOC	1		
BC	0.76	1		BC	0.10	1	
TN	0.90	0.85	1	TN	0.90	0.01	1

SPK2	TOC	BC	TN	*BILL-2*	TOC	BC	TN
TOC	1			TOC	1		
BC	0.68	1		BC	− 0.30	1	
TN	0.99	0.62	1	TN	0.55	0.19	1

DK2	TOC	BC	TN
TOC	1		
BC	0.60	1	
TN	0.74	0.61	1

4.2.5. Site HK2 (Homa Bay)

TOC concentration in HK2 (Fig. 2) increased steadily for a short period before decreasing at 40 cm; TOC then increased near the top of the core. The concentration of BC in HK2 indicated an increasing trend until 50 cm. Above this depth, the BC levels showed high variability up to the top of the core. TN levels followed the TOC trend. The CN ratio was relatively constant in the upper part of the core until 34 cm before reducing to 11.2. TP concentration decreased core upward from 38.5 mg/kg at the bottom to 25.9 mg/kg (80 cm) before increasing to 22.1 mg/kg at 60 cm. TP concentrations indicated more fluctuations above this before reaching 30.7 mg/kg near the top of the core. IP concentration started at 23.0 mg/kg (96 cm) and rose to 25.0 mg/kg (52 cm) before decreasing to 18.9 mg/kg (40 cm) and then rising to 27.7 mg/kg (20 cm); the IP concentration finally settled at 25.4 mg/kg at the top of the core. OP concentration indicated a steady core upward increase from 1.50 mg/kg (96 cm), reaching the maximum value at 12 cm (6.90 mg/kg) before decreasing near the top to 2.80 mg/kg.

4.2.6. Site BILL-2 (Buvuma Channel)

The TOC concentration (Fig. 2) in the Buvuma Channel (BILL-2) ranged between 171 g/kg and 157 (1912–1927). The highest concentrations occurred at the top (171 g/kg; 5 cm), indicating a slight core upward increasing trend. The BC concentration increased to 17.0 g/kg (24 cm; 1946) and then generally decreased up the core to 5.40 mg/kg (0.5 cm; 1999). TN indicated a lower concentration in top sediments. For instance, in 1999, the concentration was 15.9 mg/kg compared to 17.1 mg/kg in 1912. The C/N ratio remained generally stable at about 10. The TP concentration in this core increased to 794 mg/kg at 8 cm (1975) and maintained the same up to the top, where it dipped sharply. IP levels fluctuated mildly in the lower part of the core and ranged between 116 and 222 mg/kg. OP concentration levels ranged between 157 and 328 mg/kg, with the lowest concentration at 35 cm (1922). The nutrient data at this site were plotted along with the diatoms (Fig. 3); the latter is detailed in Stager et al. (2009).

4.2.7. Site LV95-2P (mid-lake)

The TOC concentration in core LV95-2P decreased slightly from the bottom to the top (Fig. 2). The highest TOC concentration of 212 g/kg occurred at 46 cm (1880), whereas sediments at the top had slightly lower TOC concentrations, i.e., 177 g/kg and 175 g/kg at 10 cm (1970) and 1 cm (1996), respectively. The BC concentration indicated an irregular rise up the core. The TN concentration ranged between 10.7 g/kg (1 cm; 1996) and 12.4 g/kg (46 cm; 1860). The C/N ratio indicated a decrease from 16.8 (91 cm; 1710) at the bottom of the core to 16.6 at 61 cm (1810). The ratio increased to 17 at 40 cm (1880). The highest value (17.6) was near the top of the core at 4 cm (1990). The highest TP concentration was at 11 cm (1970; 328 mg/kg) and the lowest at 72 cm (1787; 179 mg/kg). IP levels started high but decreased to 60 mg/kg and remained the same until 20 cm (1943) before increasing near the top of the core. OP levels indicated a steady core upward increasing trend.

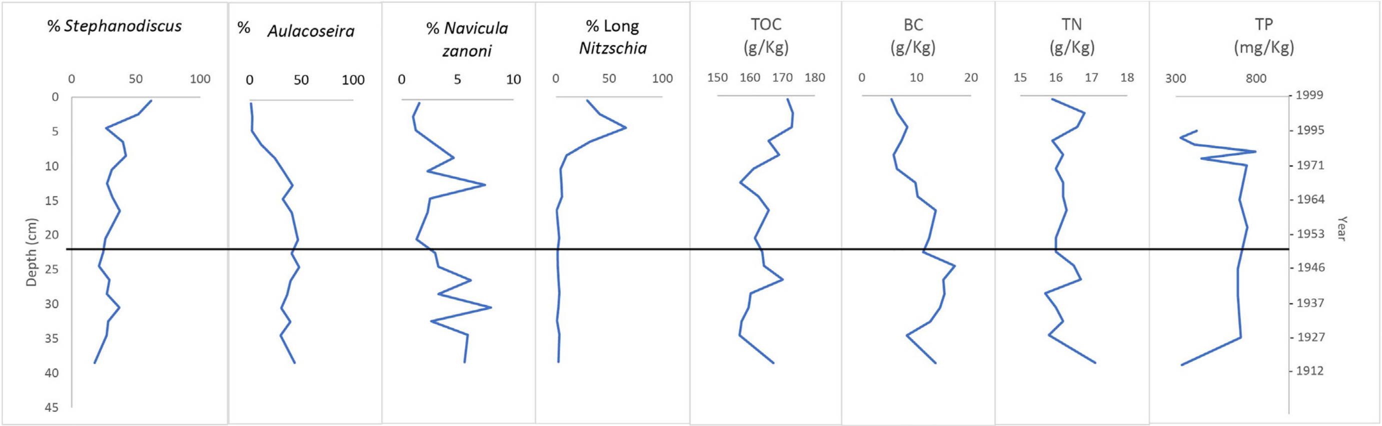

Fig. 3. Distribution of diatoms and nutrients in the Buvuma Channel, Lake Victoria.
(Data from Stager et al., 2009).

4.3. Land use changes in Lake Victoria Basin

Fig. 4 and Table 4 show land use and land cover changes in the catchment from 1985 to 2014 (see supplementary data Fig. F2 and Table T1). Urban area and farmland increased from 666% to 1022% and 23% to 48% in the Nzoia-Sio and Nyando-Yala basins, respectively; wetlands increased by 80% and 175%. In contrast, a decline was observed in woodlands by ~75%, indigenous forests by 27% and 9%, and grasslands by 36% and 46%, respectively, in the Nzoia-Sio and Nyando-Yala basins. Detailed land cover changes in km^2 are presented in Table 4.

4.4. Statistical analyses

The catchment-derived sediments showed a better correlation between the geochemical parameters (TOC, BC, TN) than the lake sediments (Table 3). The lake sediments revealed more fluctuation resulting in a low

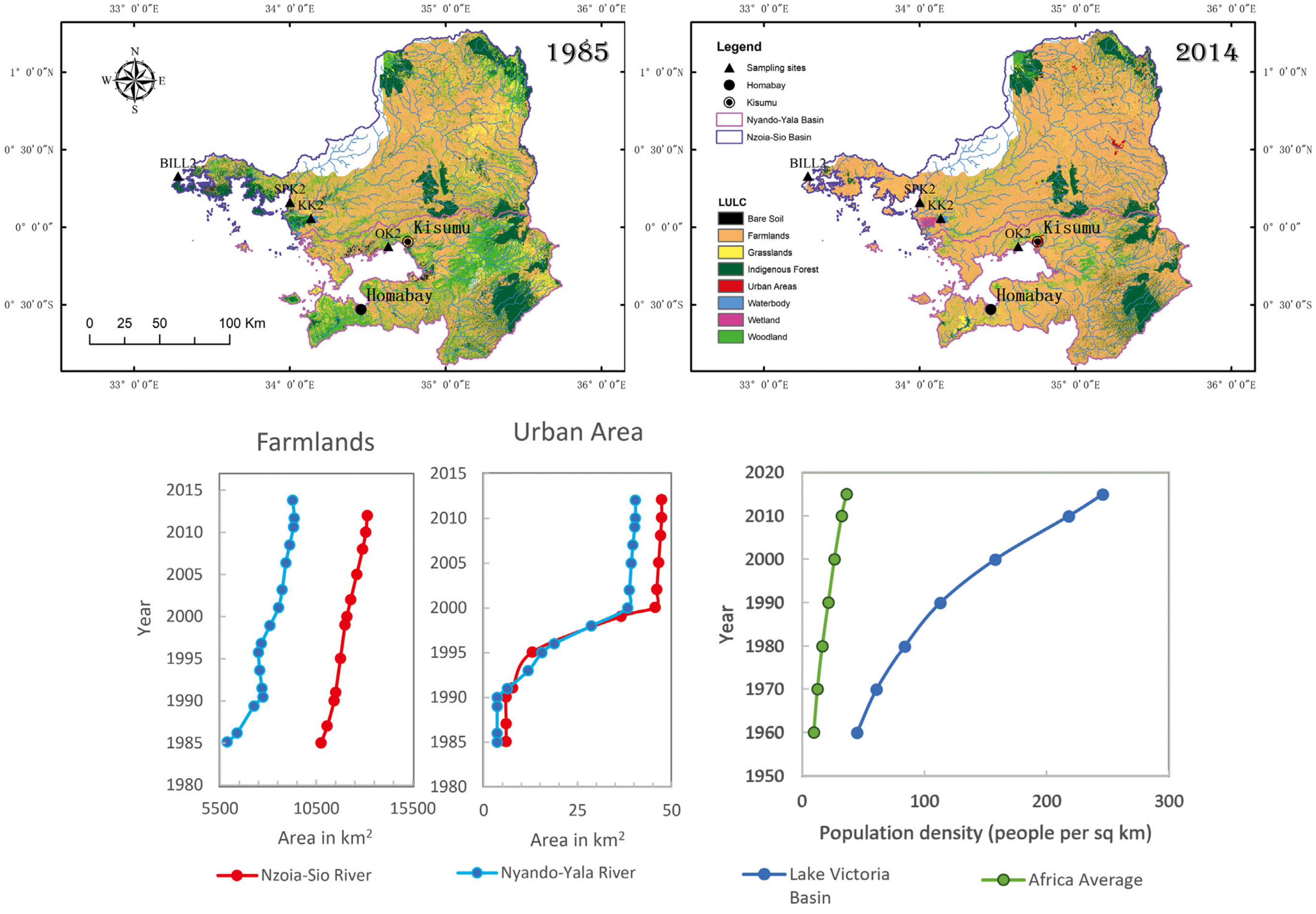

Fig. 4. Land use and land cover changes in Lake Victoria catchment in Kenya, namely Nzoia-Sio and Nyando-Yala basins. (a) Year 1985 land-use, and (b) Year 2014 land-use, c) increase in farmland, d) increase in urban area, and e) population change in Lake Victoria basin.

Table 4
Land use and land cover changes in the Lake Victoria catchment (Kenya), namely Siaya and Busia (Nzoia-Sio Rivers) and Kisumu (Nyando-Yala Rivers) in km^2. Negative value indicates a decline in area, positive value indicates increase in area (km^2).

Year	Bare soil	Farmlands	Grasslands	Indigenous forest	Urban areas	Wetland	Woodland
	Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)
Nzoia-Sio basin	(KK2, SPK2; Nzoia River, Sio River)						
2014	108	13,267	1012	1904	47.5	228	527
2012	105	13,147	1081	1997	47.5	282	412
2010	104	13,071	1125	2056	47.5	316	338
2008	92.6	12,902	1249	2075	47.2	313	377
2006	76.7	12,657	1428	2103	46.8	309	434
2005	72.9	12,600	1470	2109	46.7	308	448
2002	52.5	12,286	1701	2145	46.2	303	521
2000	39.4	12,085	1848	2167	45.8	299	568
1999	39.8	11,992	1765	2225	36.7	265	751
1995	40.7	11,752	1549	2374	13.1	177	1227
1991	50.5	11,506	1947	2257	7.90	161	1193
1990	53.4	11,432	2061	2224	6.20	155	1187
1987	57.9	11,072	1807	2430	6.20	141	1619
1985	62.0	10,743	1573	2618	6.20	127	2015
% Change	74%	23%	−36%	−27%	666%	80%	−74%
Nyando-Yala basin	(OK2; Yala River)						
2014	25.9	8621	517	1858	40.4	103	691
2012	31.2	8711	610	1838	40.4	85.7	559
2010	35.5	8785	688	1822	40.4	71.7	450
2009	33.6	8746	717	1824	40.2	72.4	459
2007	25.3	8581	842	1833	39.7	75.4	497
2005	16.9	8414	968	1841	39.3	78.4	536
2002	8.60	8251	1092	1850	38.8	81.4	573
2000	0.60	8091	1213	1858	38.3	84.2	610
1998	10.4	7718	886	1900	28.7	92.6	1248
1996	21.0	7338	541	1942	18.8	101.1	1909
1995	24.5	7211	426	1957	15.5	104.0	2130
1993	55.6	7271	733	1735	11.9	85.4	1947
1991	103	7363	1203	1397	6.30	57.0	1665
1990	126	7407	1429	1234	3.60	43.3	1531
1989	125	7019	1313	1435	3.60	41.9	1850
1986	124	6272	1092	1823	3.60	39.0	2464
1985	124	5842	964	2046	3.60	37.4	2818
% Change	−79%	48%	−46%	−9%	1022%	175%	−75%

correlation. PCA results for land use and land cover changes showed that the first two components (eigenvalue 2.5) accounted for 87% of the variance (Fig. 5). The component matrix with loading for the first two components is indicated in the supplementary data (Table T1). Loadings higher than 0.7 and lower than −0.7 are highlighted in bold to show variables with strong loading. PC 1 indicated strong loading with TN, farmlands, and urban areas. It also had positive loading for TOC (SPK2 and OK2), bare soil (SPK2, OK2), BC (KK2), and wetlands (KK2). PC1 indicated strong negative loading for indigenous forests (KK2, SPK2), woodlands (KK2, SPK2), grasslands (SPK2, OK2), TOC (KK2), and C:N (KK2). PC 2 had strong positive loading with BC (SPK2) and wetlands (SPK2) and strong negative loading with bare soil (KK2), indigenous forest, wetlands, and woodlands in OK2. PCA analyses of diatoms and nutrients indicated that the three extracted principal components (PCs) defined 74% of the variables (Fig. 6). PC1, defined by the high abundance of *Stephanodiscus* and *Nitzschia*, increased with TOC and/or C/N, described 48.3% of the variance. PC2, defined by the high abundance of *Aulacoseira* and *Navicula*, which increased with an increase in BC, TP, and IP, described 15.2% of the variance. PC3 indicated that *Navicula* were affected by the rise in OP values and represented 10.4% of the variance (see Supplementary data Table T2).

5. Discussion

5.1. Multi-proxy trends

The changes in TOC concentration signify a combination of different natural and anthropogenic alterations within the lake's catchment (Kite, 1982; Talbot and Livingstone, 1989; Tamatamah et al., 2005). For example, an increase in TOC after 1960 might have been due to the rise in intense rainfall, which led to a >2.5 m rise in lake level since then (Kite, 1982). Rainfall plays an essential role in the input of nutrients because only a fraction of the inflow into the lake is from fluvial discharge, while the rest is from precipitation-based recharge from the catchment that directly drains into the lake (Nicholson, 1998; Tamatamah et al., 2005). Other possible sources have also been suggested to increase the TOC input and nutrients in lakes. For example, Talbot and Livingstone (1989) indicated that an increase in the decomposition of phytoplankton facilitates the deposition of organic matter in bottom sediments, and the release of nutrients serves as positive feedback to this process. Johnson et al. (2000) attributed the high concentration of TOC around the mid-section in the cores to biogenic productivity instead of direct terrestrial input. Consistent with this, in the last five decades, the forest cover has decreased considerably (Fig. 4), e.g., due to land use changes (Verschuren et al., 2002), resulting in increased runoff and deposition of solid particulate matter (SPM) into the lake (Machiwa, 2003). SPM is a source of high organic carbon and charred particles, and most likely, it contributes to the increase of TOC and BC in these sites (Fig. 2).

The catchment sediments store BC until they are removed by weathering and/or anthropogenic disturbances associated with agriculture and urbanization. Consistent with this, our study shows that the steady rise in BC concentration in the sediment cores during the last century matches the increase in population, agriculture, and land use changes reported in LVB (Verschuren et al., 2002), and the vegetation shifts to grasslands, deforestation, and expansion of settlements (Conway, 2002). Conway (2002) reported a shift in vegetation, which coincided with the alteration from montane forests to grasslands (although to a smaller extent in western Kenya) resulting from deforestation and burgeoning settlements in the LVB. The clearing and burning of forests in LVB (from ca. 1920 onwards)

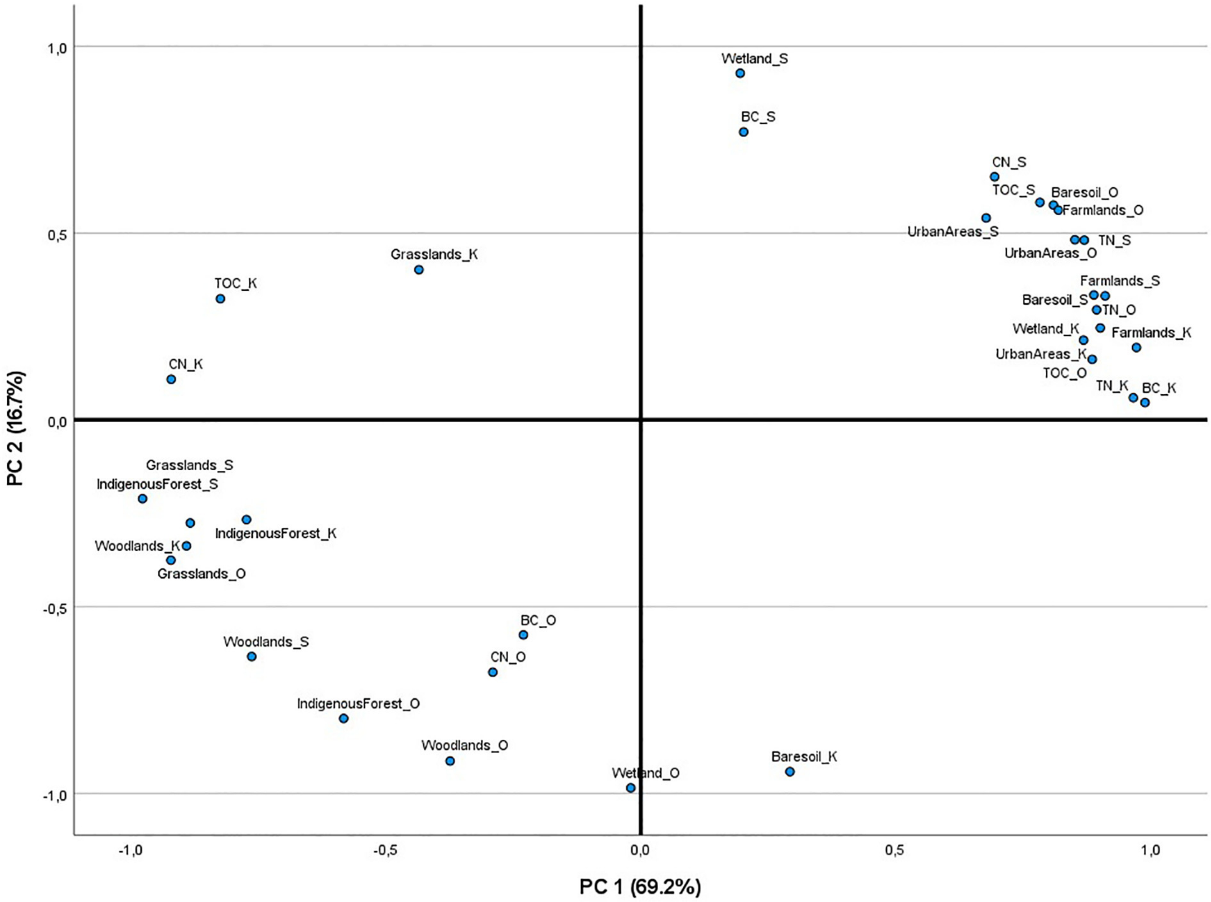

Fig. 5. Principal Component Analysis (PCA) plot showing the multivariate variation amongst nutrients and land use changes Busia, Siaya, and Kisumu. The first two principal axes explained 87% of the variance.

produced BC, which was transported into the open lake by winds. It is likely BC deposition increased during intense precipitation resulting in the high BC values observed in the lake cores (BILL2 and LVB-95; Table 2). The high levels of BC at sites DK2 and OK2 could be due to its proximity to Kisumu (Fig. 2; Table 2), one of the largest cities in Kenya that has undergone extensive land use changes and urban expansion in its surroundings. In addition, clearing of the adjacent wetlands, namely Dunga, Koguta, and Kusa, for urban development and agriculture contributed to the BC input. Owino and Ryan (2007) reported that from 1969 onwards, the papyrus-dominated wetlands in Kisumu were cleared as part of urban development resulting in ~50% habitat loss. Thus, at the OK2 site, BC started to increase as early as 1910, implying higher inputs from biomass burning coinciding with the increase of settlements, rise in agriculture, and operation of the railway line. The rail line (constructed by the British between 1896 and 1901) connecting Kisumu with Mombasa at the Indian Ocean coast ushered significant changes that impacted the landscape (Verschuren et al., 2002). Extensive land reclamation began in the Yala swamp (around 1965), involving motorized machinery, clearing of the wetlands, deforestation, and burning as part of agriculture and urban development (Owiyo et al., 2014). We associate these changes with the rise of BC at the OK2 site. Finally, there is additional input of BC in sediments coinciding with the emergence of fossil fuel combustion. This trend is noted worldwide (Gustafsson and Gschwend, 1998), and consistent with this observation, all four catchment sites (SPK2, KK2, OK2, and DK2) show an exponential increase in BC abundance from the early 20th century. In contrast, at Homa Bay (HK2 near the lake margin), the sediments are mixed due to agriculture, and there is more variability in BC levels. Further studies on source apportionment of BC based on PAH analyses can provide information on the proportion of biomass combustion vs. fossil fuel-derived inputs (Han et al., 2016; Kappenberg et al., 2019).

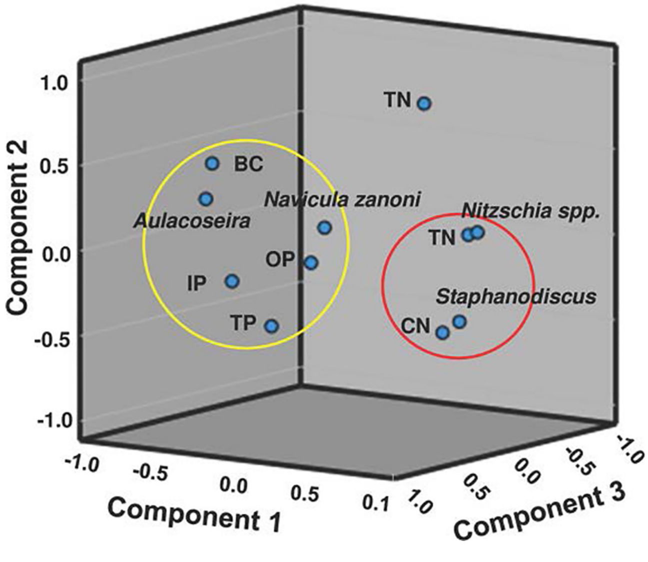

Fig. 6. Principal Component Analysis (PCA) plot showing nutrients and diatoms in Buvuma Channel. Component plot in rotated space, circles showing the clustered loadings defined by PC1.

BC is reported as recalcitrant and unreactive (Accardi-Dey and Gschwend, 2002; Gustafsson and Gschwend, 1998). However, Middelburg et al. (1999) indicated contrary results confirming the chemical and biological reactivity of BC, which is supported by recent studies too (Cheng et al., 2008; Zimmerman, 2010; Rojas et al., 2015; Toth et al., 2019). BC affects aquatic life by stimulating primary productivity and CO_2 production (Malits et al., 2015). Malits et al. (2015) indicate that BC deposition stimulates heterotrophic bacterial production by serving as a carbon source or stimulating organic matter adsorption. Other studies have also confirmed the reactivity of BC through laboratory experiments and in situ monitoring (Zimmerman, 2010; Cheng et al., 2008). In addition, BC can combine with nitrogenous compounds during combustion (Cornelissen et al., 2005), which can then be utilized by phytoplankton and algae and increase primary productivity (Paerl et al., 2002). For example, in Lake Tahoe, lacustrine productivity increased immediately after forest fires because the input of P complexed with BC triggered the change (Jaworski et al., 1997; Zhang et al., 2002). Bisiaux et al. (2011) indicated that refractory BC added into Lake Tahoe was rapidly degraded; the unexpected rapid turn-over prevented a build-up in lake sediments. Similarly, biomass burning influenced the atmospheric input of nutrients and primary productivity in Lake Baikal (Kobanova et al., 2016). In Lake Victoria, the increased flux of BC (Fig. 2) and enhanced primary productivity in recent decades (Verschuren et al., 2002; Stager et al., 2009; Hecky et al., 2010) suggest a causality that needs further investigations.

The vertical distribution of TN in the catchment sites is very similar to the TOC trends. (Fig. 2). All the sites showed an upward increase in TN, consistent with the rise in the deposition of N released from burning and clearing of the forest cover as part of land use changes that started as early as the 1920s (Hecky, 1993). Satellite images of the lake's catchment support the systematic decadal changes in land use and land cover management (Osinubi et al., 2016; see below), which probably contributed to the enhanced nutrient flux. However, N input in Lake Victoria from surface runoff and direct atmospheric deposition accounts for only 15% of the total N, whereas >80% of N is from nitrogen fixation as in Nyanza Gulf (Gikuma-Njuru et al., 2013) and in the open parts of the lake (Mugidde et al., 2003). Consistent with this, N-fixing phytoplankton species such as *Anabaena* and *Cylindrospermopsis* are common in the lake (Okungu et al., 2005). Therefore, it is likely that N input from the catchment is not the primary driver of eutrophication in Lake Victoria. An additional reason for the high TN levels in LVB sediments is microbial activity and algal/cyanobacterial growth in the water column leading to N fixation and denitrification (Gikuma-Njuru et al., 2013), a process that occurs in many lake systems (Routh et al., 2007; Das et al., 2008, 2009). Thus, in-lake production and contribution to the N pool are important for primary productivity shifts observed in this lake.

The C/N ratio reflects primary productivity in terrestrial and aquatic environments (Avramidis et al., 2015; Das et al., 2008). After the deposition of sediments, C/N does not undergo significant diagenetic alteration in limnic settings, and it is a good indicator of the source material (Meyers and Ishiwatari, 1995; Routh et al., 2004, 2007). C/N values higher than 20 indicate organic matter primarily from terrestrial vascular plants, whereas lower values signify aquatic input (mainly of algal origin). The highest C/N value in Kisumu (OK2 site close to the lake's shoreline) is 21, which appears in sediments from 1909 onwards. The high C/N value coincides with increased agricultural activity, deforestation, and expansion of existing settlements by the lake just after the arrival of the East African Railway (Fig. 1). The woody plants and charred debris in the lower sediment intervals in the core indicate possible deforestation near the lake when people settled the area. In contrast, the C/N value at the top in Siaya (site KK2) is low (~5 around 2011). Between 1997 and 98, the LVB had extremely heavy El Niño-enhanced rainfall, causing a rise in water level by >1.0 m (Conway, 2002). Catchment sediments record this event in Siaya, indicating the low C/N value derived possibly from algal inputs. The low C/N ratio could also be associated with increased N due to the mineralization of organic matter in these sediments (Gichuki et al., 2005). Meanwhile, the high C/N ratio observed in the older lake sediments (LV-95 and BILL-2) results from a mixture of organic matter derived from aquatic and terrigenous sources.

Since 1960, the human population in East Africa has been increasing at an annual rate of 3.1% compared to the African average of 2.5% (Kolding et al., 2008). The increase in population coincided with an acceleration of anthropogenic activities in the LVB, e.g., farming, deforestation, industrialization, and urban development in the last 50 years (Gikuma-Njuru et al., 2013; Verschuren et al., 2002), and are indicated by high N and *P* values in recent sediments around major towns such as Mwanza (Tanzania; Tamatamah et al., 2005), Jinja (Uganda, Mugidde et al., 2003), Nyanza Channel (Kenya, Gikuma-Njuru et al., 2013; Gikuma-Njuru and Hecky, 2005), and Kisumu (Kenya, this study).

Atmospheric inputs to the lake include terrestrially derived air-blown soil, dust, and ash (from biomass burning). Tamatamah et al. (2005) reported an annual atmospheric flux of 1.80–2.70 kg ha^{-2} $year^{-1}$, equivalent to 55% of the total P input into the open lake. In particular, the authors indicate that the spatio-temporal distribution and deposition of nutrients are influenced by local meteorological factors like precipitation and wind. Furthermore, Gikuma-Njuru et al. (2013) suggested that the main lake itself is a source of inorganic phosphorus (IP) in the Nyanza Gulf. This and other studies show that catchment derived-P as a fluvial input is restricted, and the major contribution is via dry or wet deposition (Tamatamah et al., 2005; Gikuma-Njuru and Hecky, 2005; Gikuma-Njuru et al., 2013). Notably, hydrological recharge and differences in nutrient pattern result in P deficiency in the shallow gulf waters vs. N deficiency in the open lake Gikuma-Njuru and Hecky, 2005; Gikuma-Njuru et al., 2013). The authors indicate that seasonal mixing and stratification of the open lake favor the diazotrophic cyanobacteria and diatom population in Lake Victoria. In particular, the input of IP, which is more bioavailable (Sitoki et al., 2012) results in increased productivity of cyanobacteria (*Microcystis*) and algae (Okungu et al., 2005; Gikuma-Njuru et al., 2013). Organic phosphorus, however, follows a more complex pathway, and changes in OP content are not clearly understood, as indicated by many researchers (Reddy and DeLaune, 2008; Wang et al., 2013). Besides, the OP fraction is believed to have a slow decomposition rate under anaerobic conditions making it less bioavailable. In Busia and Siaya, the P levels increased in the last few decades even though both sites are not urban centers. However, farming is widespread in these rural districts. Therefore, artificial fertilizers may have contributed to the terrestrial deposition of IP in the basin via surface runoff coinciding with the steady increase in precipitation (Okungu and Peterlis, 2002). In addition, scattered carbonatite deposits with traces of apatite are reported in the LVB (Guya, 2019). These rocks would release P on natural weathering and are a source of nutrients transported by rivers discharging into the lake.

5.2. Land use changes

The different catchment sites in this study indicate increased land use and associated land cover changes from natural vegetation to farmlands and urban development (Fig. 4 and Table 4). Furthermore, the increase in farmlands and urban areas coincides with the increase in nutrients, as PCA shows (Fig. 5). For instance, between 1984 and 2012, in Rivers Nzoia and Sio watersheds (KK2 and SPK2), indigenous forests and woodlands reduced at the expense of farmlands, urban areas, and bare soil, which all increased. As a result, during this same period, there is a sharp increase in all the nutrients (except IP) in SPK2. Similarly, in Rivers Yala and Nyando watersheds (OK2 and DK2), the urban area increased by over 1000% between 1985 and 2014. This coincides with an increase in nutrient levels in both cores. The land use change was driven by the exponential human population growth observed in East Africa since the 1950s (UNDESA, 2020) and urbanization to meet the increasing population, infrastructure, and energy demands (Gikuma-Njuru et al., 2013; Currie and Musango, 2016; Khanani et al., 2021). In particular, the need for housing and food security led to the decline of forested areas in the LVB, and farmlands and built-up regions around towns replaced these.

NDVI showed that vegetation cover in the LVB increased from 31 km^2 in 1984 to 36 km^2 in 2017, including farmlands (Awange et al., 2019). This change is attributed to expanding sugarcane farming amongst other agriculture activities. Kenya had only two privately owned sugar companies around pre-independence. After independence, Africans were allowed to cultivate sugarcane, and six companies were established; sugar cane plantations have extended to cover over ~220,000 ha (Mati and Thomas, 2019). Life cycle analysis of sugar production in Kenya shows many pathways through which nutrients and BC are added to the environment. First, fertilizers contribute to the average input of 147 kg/ha N and 79 kg/ha P, respectively (Otieno et al., 2019). Secondly, the need for lime in sugar processing has seen the development of industries such as the Homa Lime Mining Company and others. This has led to increased P input resulting from quarry dust (Opala et al., 2018; Guya, 2019). Thirdly, the transport of sugarcane and sugar to different destinations increases the use of large diesel trucks and trains, increasing emissions from fossil-fuel combustion (Yator et al., 2017). Lastly, the burning of sugarcane as a harvesting practice to improve soil fertility could have increased the atmospheric deposition of BC and P within the lake's catchment (Hiscox et al., 2015; Zhang et al., 2015; Guya, 2019; Dattamudi et al., 2020; Nyilitya et al., 2020). This is further supported by modeled wind flow patterns in western Kenya (MeteoBlue, 2021), which show wind speeds of about 5 km/h to 19 km/h blowing from the ENE to WSW direction, especially during the periods between November to February. However, further analysis is required to show a more explicit link between the relative contribution of farmland and urbanization to IP input.

5.3. Pelagic diatom communities

The modeled input of nutrients into Lake Victoria is driven by atmospheric transport and land runoff which account for ca. 90% of P and 94% of N from increased human activities such as agriculture and the burning of forests (Scheren et al., 2000). Other studies, e.g., Lung'ayia et al. (2001), based on actual data, reported increased phytoplankton biomass during the rainy season in the Nyanza Gulf, implying that wet atmospheric deposition contributes to enhanced nutrient and biomass loading. Tamatamah et al. (2005) revised the wet and dry atmospheric deposition estimates of TP in Lake Victoria at 55% (ca. 1.9 kg ha^{-2} yr^{-1} or 13.5 ktons of P deposited annually), which is significantly lower than the modeled values by Scheren et al. (2000), but a considerable amount. Stager et al. (2009) observed increased accumulation of phenanthrene from the 1970s onwards and suggested atmospheric deposition of nutrients from biomass combustion. Consistent with this evidence, our results also show an increase in diatoms corresponding to the nutrient levels in the Kenyan waters around our current site (Verschuren et al., 2002) and the Buvuma Channel (Stager et al., 2009). The diatom and cyanobacteria proliferation in Lake Victoria is evidence of cultural eutrophication (Kilham et al., 1986; Verschuren et al., 2002; Stager et al., 2009; Simiyu and Kurmayer, 2022).

Verchuren et al. (2002) indicated that between 1820 and 1940 *Cyclostephanos* and *Aulacoseira* dominated, which was overtaken by *Nitzschia acicularis*. *Nitzschia* was the dominant species in the lake between 1970 and 1980 before being overtaken by cyanobacteria blooms in the late 1980s. Eutrophication led to a decline in dissolved Si and water transparency and increased total P concentrations in the main basin (Hecky, 1993). Eventually, the reorganization of the phytoplankton community to one dominated by cyanobacteria overlapped the decline in biogenic Si levels, which limited diatom growth in the open lake.

Stager et al. (2009) reported the diatom communities in the BILL-2 core in Buvuma Channel. The total *Aulacoseria* count reported peaked in 1946 (Fig. 3). In the early 20th century, this genus accounted for 54% of the total diatom counts. The abundance of other species reported followed the trend: *Stephanodiscus* (18%), *Navicula* (6%), and *Nitzschia* (2%) until 1974, before being overtaken by *Nitzschia*. From 1975 to 1999, *Stephanodiscus* was the dominant community increasing from 42% to 62%. In the 1980s, a shift from *Aulacoseria* to *Nitzschia* dominated the water body and reached maximum counts around 1988. This trend then declined around 1999. The dominance of *Stephanodiscus* could be due to its ability to grow under Si and P-limited conditions and reduced penetration of sunlight (Kilham et al., 1986). In addition, the change in the phytoplankton community in the water column is an important ecological indicator. For example, the switchover to *N. acicularis* is the possibility of this species dominating under moderate to low Si in the open waters of Nyanza Gulf (Simiyu and Kurmayer, 2022). Likewise, external nutrients (N and P) inputs drive the phytoplankton community's shift from diatoms to cyanobacteria (*Microcystis*; Gikuma-Njuru et al., 2013). While the input of nutrients could trigger the changeover in diatom communities, other parameters such as climate change, weaker winds (stratification), silt deposited from soil erosion, and the introduction of the Nile perch could also play a role in driving this observed change.

The principal components (PC) grouped the diatom species and geochemical proxies in Buvuma Channel into two clusters. Cluster 1 in red is defined by the high abundance of *Stephanodiscus* and *Nitzschia*, which increase with TOC and C/N levels in the core (Fig. 6). The cluster indicates eutrophication and reduced mixing regimes in the lake (Simiyu and Kurmayer, 2022). Some of the *Nitzschia* spp. could co-occur with cyanobacteria, and many of the elongated needle-shaped species represent reduced mixing regimes. Cluster 2 in yellow is defined by the high abundance of *Aulacoseira* and *Navicula*, which rise with TP and IP and, interestingly, BC levels in the core. It represents a situation where the lake mixes deeply or is under less eutrophic conditions in which solar heat absorption by phytoplankton contributes less to thermal stratification. The recent shift from heavy to lightly silicified *Aulacoseira* to *Nitzschia*-dominated assemblages in the lake (Fig. 3) signals eutrophication (Hecky, 1993; Simiyu and Kurmayer, 2022). Some cyanobacteria can fix their N and dominate with rising P inputs. Hence, a positive relationship is likely with C/N ratios if corresponding cyanobacteria abundances are also investigated in the core (similar to diatom stratigraphy). Finally, PC3 indicates that *Navicula* abundances can be affected by the increase in P. This supports the inference from PC1, where diatoms in cluster 2 are related to TP and BC. Thus, multi-proxy biogeochemical data and statistical analysis provide a better understanding of the changeover in the diatom community. This changeover is associated with cyanobacteria dominance, stratification, a decline of biogenic Si, high P levels, and turbidity (Hecky, 1993; Verschuren et al., 2002; Stager et al., 2009; Simiyu and Kurmayer, 2022).

The rise in TOC and BC levels (up to the mid-section followed by the decline in BC core upward) and TN and TP at this site correlate with the increase in primary productivity of diatoms in Lake Victoria, implying a causality in this observed relationship. An increase in eutrophication and change in phytoplankton and diatom community with increasing TOC, TN, and TP is well established in most aquatic bodies (Wetzel and Limnology, 2001), including Lake Victoria (Hecky, 1993; Gikuma-Njuru et al., 2005; Stager et al., 2009; Güereña et al., 2015a, b). In this context, the role of BC and aquatic productivity is not well investigated. Hence, understanding the reactivity of BC, which is related to its structure, surface chemistry, and size, is an important parameter (Cornelissen et al., 2005). Researchers indicate that oxidation of BC improves with time due to its change from phenol to the more reactive carboxylic group (Cheng et al., 2006). Chemical oxidation increases due to acidic functional groups that make BC molecules more hydrophilic and prone to further chemical and biological activity (Bird et al., 1999; Cheng et al., 2006). The hydrophilic component of BC retains nutrients that can be transported and made available for phytoplankton uptake. During the degradation of BC, oxygen is utilized (Liang et al., 2006; Nguyen and Lehmann, 2009), causing anoxic conditions to develop in deeper waters (Cheng et al., 2008). Under anoxic conditions, N becomes limiting, and denitrification starts, promoting enhanced cyanobacterial growth (Cornelissen et al., 2014; Das et al., 2009; Hecky et al., 1994). Thus, the input of BC (besides nutrients) is an essential component that drives the water column chemistry and ecology.

There is a strong likelihood that inputs from both far-flung atmospheric and nearby catchment-derived sources enhance productivity in the lake, and extensive monitoring is warranted to understand these trends. While the present study provides an additional context indicating the change of trophic status in the lake, it is still inadequate to understand the different complex interactions that control eutrophication. For example, diatoms are only part of the algal community in the lake's trophic chain. Moreover, diatoms, algae, and phytoplankton respond differently to specific nutrients, and there is a need for multi-proxy studies investigating these changes. Similar to the diatom studies (Verschuren et al., 2002; Stager et al., 2009; Simiyu and Kurmayer, 2022), further research on algal and cyanobacteria distribution, its relationship with the availability and distribution of different nutrients at key locations in the LVB will be helpful.

6. Conclusions

Eutrophication in Lake Victoria has increased in the last few decades resulting in multiple investigations in the lake to understand the mechanisms driving the productivity shifts and trophic status. While most of these studies investigate the changes in the open lake, there are few studies on land tracing the impacts of human activities which aggravate the changes. These changes occurring in the catchment play a role in influencing the water quality and trophic status. In this context, the catchment and lake sediments are a promising sedimentary archive for preserving human-driven activities and tracking environmental changes.

A comprehensive investigation conducted in this study tracked the human-induced changes in the Lake Victoria Basin and how land use changes and nutrient input influenced eutrophication. The results indicate that the geochemical characteristics in sediments from the basin varied over spatial and temporal scales. The anthropogenic changes coincided with the rise in TOC, BC, TN, and P concentrations in the catchment and lake sediments. These changes also indicate the different pathways, i.e., surface/fluvial recharge, precipitation, and atmospheric transport, which play an important role in transferring the nutrients into the lake. For example, biomass burning led to the increase in BC while atmospheric transport coincided with P input. The major inflection point in these geochemical proxies (where reasonable dating exists at these sites) is around the 1960s. Since the early 20th century, colonization and population growth saw rapid changes in land use. Urban areas such as Kisumu and Homa Bay grew multifold and expanded rapidly (up to 1022%), coinciding with the clearing of forests, rise in biomass combustion, and industries. During the same period, more rural areas such as Busia and Siaya underwent extensive clearing of land for agriculture (up to 48%). The increase in nutrients led to a change in diatom communities in the lake. This change coincided with the decrease in *Navicula* and *Aulacoseira* and the proliferation of *Staphanodiscus* and *Nitzichia*. In recent years, the switchover and dominance of elongated *Nitzichia* species and cyanobacteria mark productivity changes and enhanced eutrophication in the lake.

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CRediT authorship contribution statement

Dennis M. Njagi: Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Joyanto Routh:** Conceptualization, Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Moses Odhiambo:** Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Chen Luo:** Visualization, Data curation, Writing – original draft, Writing – review & editing. **Laxmi Gayatri Basapuram:** Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Daniel Olago:** Investigation, Data curation, Writing – original draft, Writing – review & editing. **Val Klump:** Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Curt Stager:** Data curation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare they have no known competing financial or other interests that could have influenced the work reported in this manuscript.

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