CHAPTER EIGHT
Eutrophication of Lake Victoria, Uganda

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***ABSTRACT**. Excessive fertilization (eutrophication) has become one of the most important causes of water quality deterioration in Lake Victoria. Excessive nutrients in Lake Victoria arise from a variety of cultural activities in the cathment that include deforestation, intense cultivation, animal husbandry and mining. These activities disrupt biogeochemical cycles and accelerate the transport of nutrients (phosphorus, nitrogen and other elements), which have consequences on water quality and ecosystem health of Lake Victoria. The lake receives water enriched with nutrients from a variety of sources that include dry and wet fall from the atmosphere, runoff from agriculture and from sewage and municipal systems.*

Lake Victoria has clearly shown signs of eutrophication since the late 1980s. Nutrient enrichment in the water column and in the sediment accelerated after the 1960s. Phosphorus concentrations have risen by a factor of 2 to 3. Total phosphorus concentrations range from 1.0μ M to 12.0 μ M, average (2.7 μ M). The total nitrogen concentrations vary from 20 μ M to 250 μ M, with average values increasing from 37.0μ M in offshore to 110 μ M in inshore. The amount of nitrogen in the lake has not increased to march the increase in phosphorus as indicated by the total nitrogen (TN) to total phosphorus (TP) ratios in the range 8.0 to 42.0, average 15.7. Average TN: TP ratios were almost double in inshore than offshore indicating that P is excess relative to N in offshore than inshore. The higher phosphorus relative to nitrogen concentrations have stimulated growth of nitrogen fixing algae that fix and bring in approximately 480 kilo tonnes a year of atmospheric nitrogen. The average Silica concentrations (17.3 $\pm$ 13.6 μM) have decreased by a factor of 10 since the 1960s, as a result of increased phosphorus loading. The high nutrient concentrations support elevated algal primary production and algal biomass. Algae, macrophytes and invertebrates species composition have responded to changes in nutrient enrichment. Average algal primary production has increased 2-fold and supports a 4 – to 5 – fold increase in fish yield compared to the 1950s. However, adverse eutrophication effects include excessive algal biomass, harmful algal blooms associated with fish kills, reduction in lake transparency, changes in algal and invertebrates communities, loss of desirable fish species and seasonal bottom water oxygen depletion (anoxia).

The changing climate in Lake Victoria basin could be enhancing eutrophication effects and putting additional stress on the beneficial uses that are already impaired. The control of eutrophication is normally based on the nutrient limiting aquatic plants or can be made to limit phytoplankton growth. In Lake Victoria, it is effective to control phosphorus given that nitrogen can be fixed from the gaseous atmospheric source.

Keywords: algal bloom, eutrophication, Lake Victoria, nutrients.

INTRODUCTION

Eutrophication occurs when natural water bodies become excessively fertilized by nutrients especially nitrogen and phosphorus. High levels of biological productivity often accompany the increase in available nutrients. Eutrophication promotes plant growth as well as favoring changes in floral and faunal species composition and may lead to loss of biodiversity. Enhanced plant growth often disrupts normal functioning of the aquatic ecosystem and may lead to deterioration in ecosystem health, recreational and aesthetic values. Deterioration in the ecosystem health occurs where eutrophic conditions promote production of toxic algal blooms and excess bacterial growth and interfere with drinking water treatment.

Until about mid twentieth century, eutrophication had not been recognized as a pollution problem worldwide. Since then, eutrophic conditions have already happened in many parts of the world including Lake Victoria (Hecky 1993). More scientists now have the insight to recognize that human activities including over fishing, deforestation, intense cultivation animal husbandry, and introduction of exotic fish species can accelerate high rates of nutrient inputs resulting in changes in the physical, chemical and biological properties of a large water body such as Lake Victoria (Bugenyi and Balirwa 1989; Ogutu-Ohwayo 1990; Hecky 1993; Hecky *et al.* 1994; 1996; Lipitau *et al.* 1996). Indeed, increasing human population and corresponding settlement within the Lake Victoria basin have accelerated land-derived nutrients loads into the lake (Lipiatou *et al*. 1996). The nutrients enter the lake through runoffs from agriculture and industrial development, rivers, direct precipitation (dry and wet), septic systems and sewers.

Worldwide, management of the numerous eutrophication effects has become controversial as beneficial impacts that promote fish production and deleterious impacts that constrain resource use and ecosystem health can occur contemporaneously. Hecky *et al.* 2003 examined extensive reviews on possible water quality and ecosystem health on influencing fish production in tropical aquatic ecosystems and concluded that disruptions in the catchment will lead to increased primary production in freshwaters and potentially large changes in tropical freshwater communities. Indeed, these changes have already happened in Lake Victoria, and are attributed to several factors that include limnological shifts, climate change, the introduction of the Nile perch and ensuing food web changes.

Prior to the 1960s, Lake Victoria seemed to have coped fairly well as ecosystem and eutrophication changes were not obvious. But Verhuschuren *et al*. (2002) saw changes in the deep-water dissolved oxygen and silica cycle as early as 1940s. Between the 1960s and the 1990s, Lake Victoria underwent a drastic limnological transition that became manifest as reduced lake transparency, increased algal abundance, proliferation of aquatic weed especially water hyacinth, population explosion of the introduced Nile perch and reduced populations of endemic and native fish species. Certainly, heavy predation by the Nile perch contributed to the decimination of the native fish species that had already been overexploited in Lake Victoria. But eutrophication contributed to the species loss due to reduced lake transparency which is believed to have accelerated hybridization of the cichlids that are picky in choosing mates and use visual cues of bright male coloring to identify suitors of their own species (Seehausen *et al*. 1997)

In Lake Victoria primary producers reaped the benefits of nutrient enrichment as evidenced by elevated algal biomass and productivity. There is now a two-fold higher algal primary production, which undoubtedly has supported a 4 to 5-fold rise in fish production in the lake since the 1950s. Increased fish production is good as more local people have turned to the lake for their livelihood and fish exports to international markets earn foreign exchange for the riparian states. But there are three major troubling eutrophication impacts that include changes in species composition and dominance, decreased biodiversity, and toxicity effects in Lake Victoria. Proliferation of algal blooms and water hyacinth (*Eichhornia crassipes*) threaten continued beneficial use of the lake resources. Algal blooms and high algal biomasses limit light penetration to bottom dwelling organisms, especially in shallow inshore waters, and have contributed to a 4-fold reduction in the lake transparency since the 1960s.

The eutrophication effects on the physico-chemical environment, biological productivity and algal species composition have been documented since the early 1990s in Lake Victoria (Hecky 1993; Hecky *et al.* 1994; 1996; Mugidde 1992; Kling *et al.* 2001). Water quality and ecosystem changes have become more central and Lake Victoria now experiences seasonal peaks and declines in fish availability. Domestic and commercial fish operations are immediately suspect of the fish changes in Lake Victoria. However, counter arguments refer to eutrophication impacts that have altered the fish habitat and fish food, which in turn, affects the bountiful fish resource of Lake Victoria. Several authors have debated the potential effects of the stressed and altered physical, chemical and biological environment that has changed the fish habitat and potential impacts on the fisheries (Hecky and Bugenyi 1992; Hecky 1993; Hecky *et al.* 1994; 1996; Lehman *et al*. 1998 and Kling *et al*. 2001).

This paper provides evidence and discusses the general aspects of eutrophication prior and after the start of the Lake Victoria Environmental Project (LVEMP) in 1997. Emphasis is placed on evidence as provided by the changes in nutrient concentration (phosphorus and nitrogen), algae biomass and species composition and water clarity since the 1960s and potential impacts to the biota and the relationship of scientific understanding to policy considerations. Standard methods were used in the collection of data in this study (APHA 1998).

RESULTS AND DISCUSSIONS

Temperatures and Thermal Stratification

Generally, three major phases of thermal stratification were recognized in Lake Victoria from 1997 to 2003. The lake rapidly warms in September throughout to March/April and cooling occurs between May to August. Early thermal stratification occurs between September and December, persistent thermal stratification in January to April and deep and stronger mixing as indicated by re-oxygenation of deeper waters both inshore and offshore (Tables 1 and 2) occurs in June. These phases of thermal stratification and de-stratification are consistent with past observations in Lake Victoria (Talling 1965; 1966; 1969). The lake experiences high surface water temperatures in the range 23.0 to 29.0 ^{o}C throughout the year. There are always small temperature differentials (0.1 to 3.0 ^{o}C) between bottom and surface values but are very minimal and /absent during the deep mixing period. Maximum surface-bottom temperature differentials occur when the lake is thermally stable between September and March/April. Although temperature stratification occurs in sufficiently deep waters ($Z_{max} \geq 20.0$ m) some inshore shallow waters located in sheltered bays and gulf experience thermal stratification and deep-water hypoxia (oxygen < 4.0 mg l^{-1}).

Overall, Lake Victoria is now more thermally stable than in the 1960s (Hecky 1993; Lehman *et al.* 1998). Minimum water temperatures during the mixing period in June-July are 0.5 ^{o}C warmer in the 1990s to 2000s than it used to be in the 1960s. High water temperature due to stronger thermal stratification affects water chemistry in a number of ways. Elevated temperatures accelerate chemical reactions and microbial processes such as denitrification –nitrification, thus affecting nutrient cycling and availability and as well as algal biomass development and oxygen availability. More stable thermal stratification makes the lake less able to mix effectively and promotes low oxygen conditions in deep waters while surface water remain well oxygenated (Tables 1 and 2) due to replenishment in day light by high algal photosynthetic activity. In Lake Victoria, complete mixing of the lake occurs around June-July allowing almost uniform distribution of dissolved oxygen and nutrients in the water column (Tables 1 and 2). On the other hand, thermal stratification shortens the mixed layer, which in turn affects the vertical distribution of nutrients as well as light availability.

A less visible but a fundamental and threatening eutrophic effect is the seasonal bottom water oxygen depletion (anoxia) in Lake Victoria. The eutrophic conditions influence dissolved oxygen, which is required by all respiring plants and animals in the lake. High photosynthetic rates during day lead to super saturated oxygen conditions, while at night when there is no photosynthesis, hypoxia occurs especially in sheltered bays and gulf and aerobic organisms including fish may suffocate. Lake Victoria experiences seasonal deoxygenating of deep waters (≥ 60 m) created by decomposition of algal biomass, uptake by microorganisms and aggravated by stronger thermal stability (Hecky *et al.* 1994; 1996; Lehman *et al.* 1998). Low oxygen condition is an undesirable change that directly affects distribution of organisms including invertebrates and precludes stable demersal fishery in lakes.

Data collected from the 1990s to 2003 indicate that hypolimnetic anoxia has spread horizontally into the inshore shallow bays and gulfs such as Napoleon Gulf (UL3), and vertically into the water column to as high as 30 to 40 m deep in some deep offshore waters (Tables 1 and 2). This spread has led to loss of approximately 50% of aerated fish habitat since the 1960s, and lowers potential fish production in Lake Victoria. Low oxygen conditions directly affect distribution of organisms including invertebrates and fish in Lake Victoria.

TABLE 1. Temporal variation of temperature and dissolved oxygen from inshore waters UL3 (Napoleon Gulf) of Lake Victoria, 1998 to 2003.

Month	**Temperature (^{o} C)**		**Dissolved oxygen (mg l^{-1})**		**Mixing depth**
	Surface	Bottom	Surface	Bottom	Z_{mix} (m)
January	27.4	26.4	8.3	2.1	12.0
March	28.1	26.9	9.7	4.4	8.0
July	25.3	24.3	10.6	6.2	20.0
August	25.9	25.3	6.6	0.04	10.0
October	25.6	25.4	5.8	1.3	6.0
November	27.7	25.8	9.8	0.5	6.0
December	26.8	23.9	7.0	0.6	8.0

TABLE 2. Temperature and dissolved oxygen from offshore (≥ 65 m) deep water (UPL2) of Lake Victoria, 1998 to 2003.

Month	**Temperature (^{o} C)**		**Dissolved Oxygen (mg l^{-1})**		**Mixing depth (m)**
	Surface	Bottom	Surface	Bottom	
March	26.7	24.4	8.2	0.4	25.0
May	26.6	25.7	7.7	5.6	40.0
July	25.4	25.1	6.1	6.0	65.0
September	26.6	24.4	9.0	4.7	40.0
November	27.7	25.8	11.0	2.2	30.0
December	25.2	24.7	7.4	2.4	30.0

Bottom water oxygen depletion (anoxia) is thought to have forced haplochromine and tilapiine fish species into the surface waters where they experienced heavy predation by the predatory Nile perch. Among the invertebrates, *Caridina nilotica* has become a keystone species as it is resilient to low oxygen conditions (Branstrator *et al.* 1996). Anoxia and toxic algal blooms are often associated with fish kills in Lake Victoria. Overall, the length of the food chain from algae to invertebrates and leading to the Nile Perch has been shortened due to both trophic cascading effects and as well as eutrophication effects.

Inshore and Offshore Trends in Nutrient Concentrations

Lake Victoria is spatially variable with relatively high algal biomass (Tables 3, Figures 1, 2, 4a) and high nutrient concentrations (Table 3) in inshore than in offshore regions of the lake (Table 4). In inshore shallow waters dissolved inorganic P was about 2 to 4-fold lower than in offshore regions of the lake. In contrast, inshore waters had the highest values of particulate P, N and C. Chlorophyll-a, particulate P, N and C decreased along the transect from Portbell in Uganda to the Tanzania offshore waters and then increased again on the Tanzanian inshore waters. Total N was higher in the Ugandan and Tanzanian inshore portions of Lake Victoria. Inshore-offshore nutrient transects show that Bugaia marked the beginning of deep offshore waters, while the Far station and XL1-XL5 were typical offshore sites with low chlorophyll-a and particulate nutrient concentrations (Tables 3).

TABLE 3. Average nutrients, chlorophyll-a, euphotic and mixing depth and their standard deviation in Lake Victoria.

Parameter	**Inshore**	**Offshore**
Chlorophyll-a ($\mu g\ l^{-1}$)	70.0 ± 100.4	13.5 ± 5.8
Particulate N (μM)	48.8 ± 7.1	10.6 ± 4.4
Total N (μM)	106.4 ± 28.2	37.1 ± 18.7
Total P (μM)	2.7 ± 2.1	3.1 ± 0.9
N-fixation ($g\ N\ m^{-2}\ y^{-1}$)	14.0 ± 4.2	7.3 ± 3.7
Euphotic depth (m)	4.7 ± 1.2	9.2 ± 2.0
Mixing depth (m)	7.1 ± 2.6	35.0 ± 12.6

Total Phosphorus and Nitrogen

Total P concentrations were in the range of 1.5 to 12.0 μM (Figure 3). Variance analysis of total P concentrations showed no significant differences between inshore and offshore stations ($P = 0.05$). Average total P concentrations were in the range of 2.3μM to 3.1 μM. Total P showed different quantitative trends compared to nitrogen, as it remained fairly constant from inshore to offshore. Data collected from inshore shallow bays and gulfs and deep open waters of the lake since the 1990s compared to historic records of the 1930s and 1950 - 1960s show that phosphorus concentrations are 2 to 3 times higher today (Figure 3). Similarly, total nitrogen concentrations varied from 20 μM to 250 μM, and average values increased from 35.0 1μ M inshore to 110 μ M offshore. Total nitrogen concentrations were 3 to 4-fold higher inshore than offshore (Table 4). Generally, average total N, total dissolved N and particulate N were two to three times higher near shore than offshore. Average total N was of similar magnitude in the shallow Napoleon Gulf, Pilkington Bay and Buvuma Channel.

Total Nitrogen and Total Phosphorus Ratios

Examination of total nitrogen (TN) to total phosphorus (TP) ratios indicates that nitrogen has not marched the increase in levels of phosphorus in Lake Victoria. Total nitrogen to total P ratios were in the range 8.0 to 43.0 (average 16.0) (Table 5). Average TN: TP ratios are almost double in inshore (14.5) than offshore (8.1) indicating that P was in excess relative to N in offshore than inshore of Lake Victoria. Based on the criteria of Guildford and Hecky (2000), inshore regions tended toward N deficiency (TN: TP ratios < 20) for most of the year while offshore was only N-deficient when TN: TP ratios rose to maximum values. Based on the TN: TP ratios, Lake Victoria is classified as a P-sufficient ecosystem with inshore shallow bays tending to N-deficiency during the mixing period.

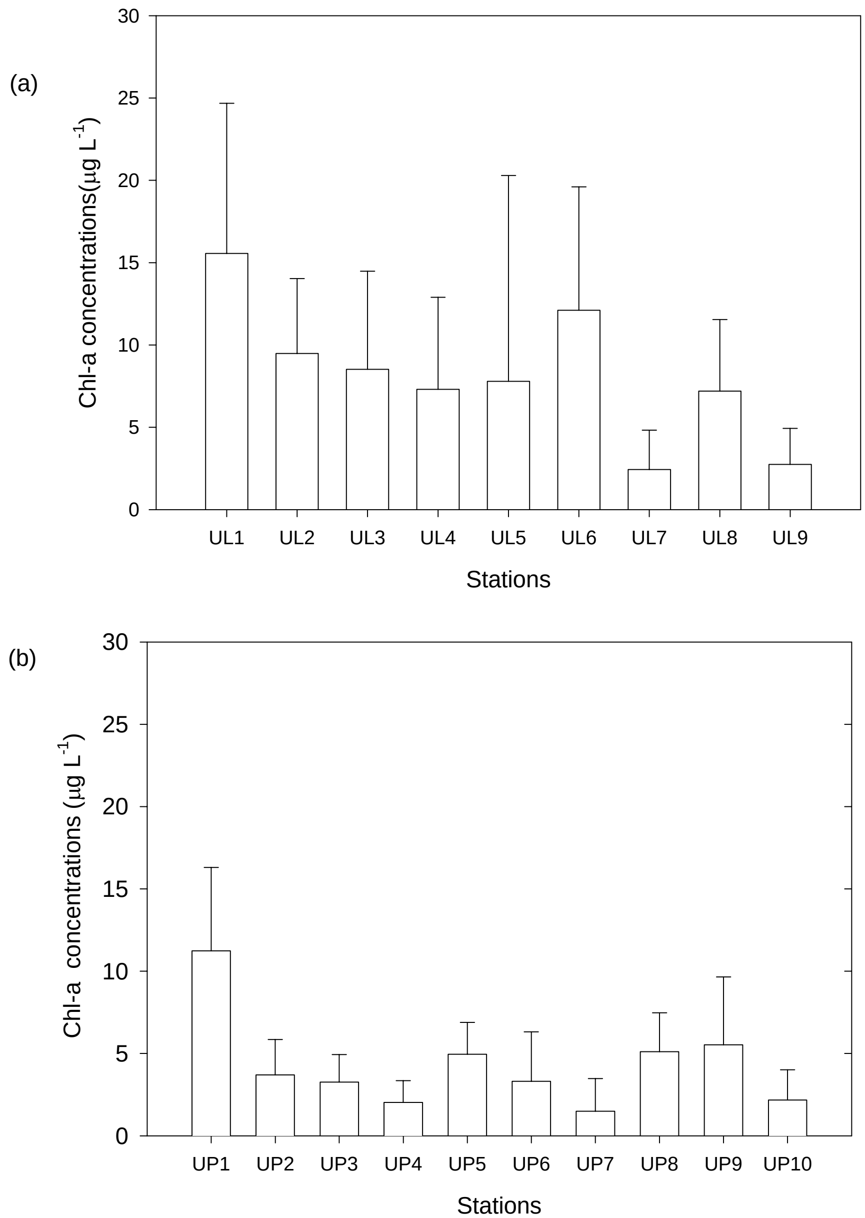

Figure 1. Average chlorophyll-a concentrations from (a) inshore and (b) offshore regions of Lake Victoria from November 2000 to June 2001.

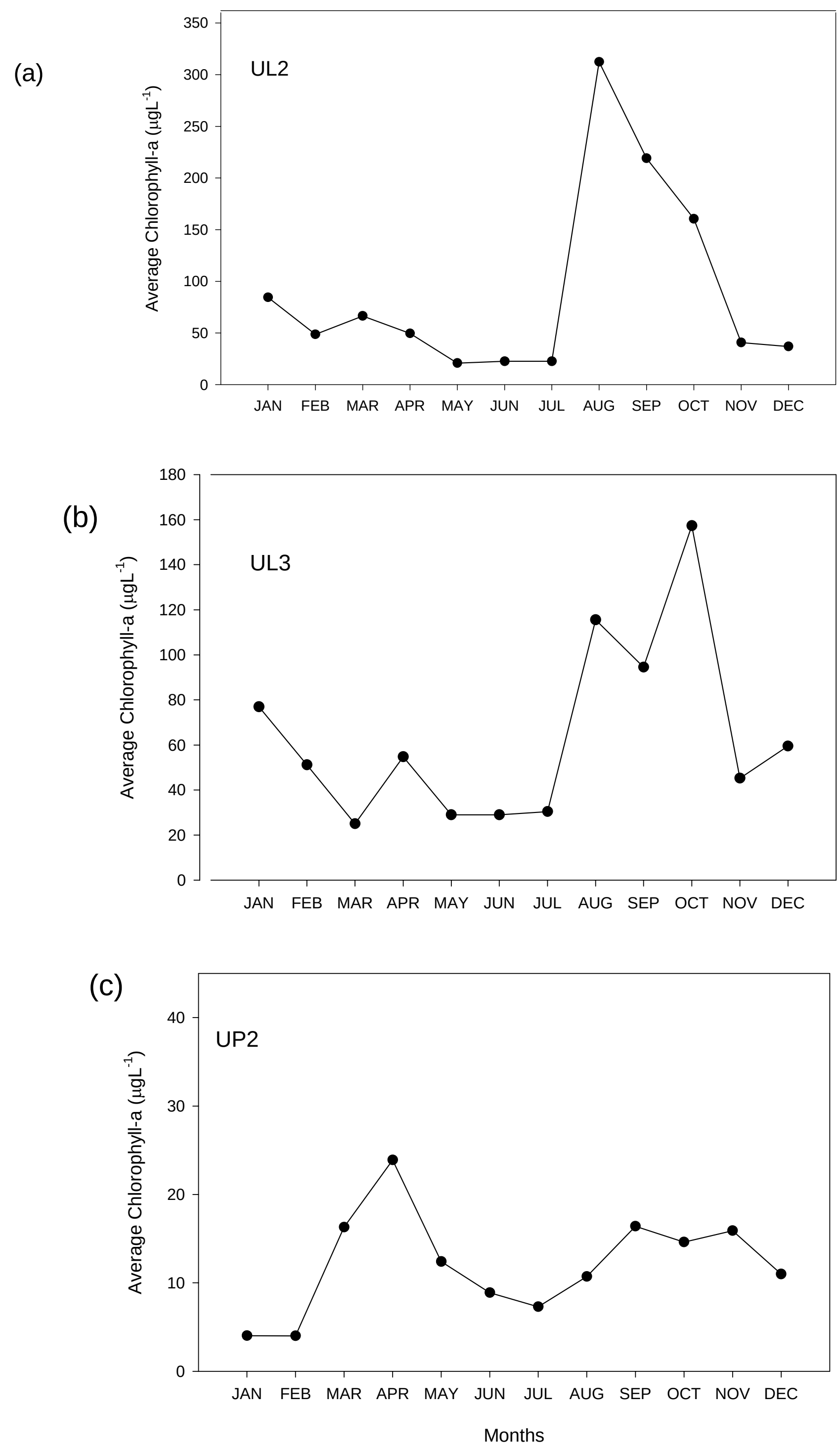

FIG. 2. Temporal variations of average chlorophyll-a concentrations in the inshore (a and b) and (c) offshore stations of Lake Victoria, 1997 to 2003.

TABLE 4. Average soluble reactive phosphorus (SRP), total dissolved phosphorus (TDP) and total phosphorus (TD) and their standard deviation from the inshore (0-5 m) and offshore (0-10 m) surface waters of Lake Victoria. Numbers in brackets indicate sample size.

Station	**SRP (μM)**	**TDP (μM)**	**TP (μM)**
Bugaia	2.0 ± 0.7 (25)	2.5 ± 1.1 (25)	3.1 ± 0.9 (13)
Far Station	1.1 ± 1.2 (14)	1.7 ± 1.2 (4)	2.6 ± 1.3 (2)
Itome Bay	1.5 ± 1.5 (14)	1.5 ± 1.2 (6)	2.3 ± 1.0 (6)
Uvula Channel	0.8 ± 0.9 (13)	2.5 ± 0.1 (15)	3.1 ± 0.7 (7)
Napoleon Gulf	0.8 ± 1.3 (20)	1.4 ± 2.5 (14)	2.9 ± 2.1 (9)
Pilkington Bay	0.5 ± 0.8 (11)	0.5 ± 0.8 (11)	2.3 ± 0.9 (7)

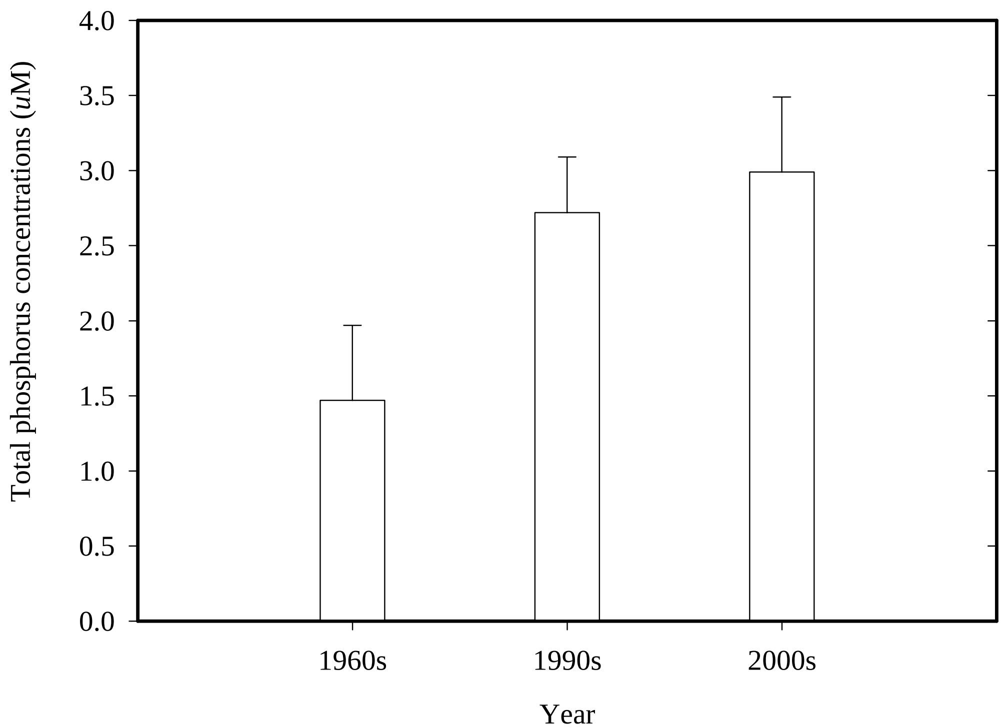

FIG. 3. Temporal variation average total P concentrations in Lake Victoria since the 1960s.

TABLE 5. Total nitrogen to total phosphorus ratios from the inshore and offshore regions of Lake Victoria

	Inshore	Offshore
Minimum	14.4	8.1
Average	14.5	14.5
Maximum	43.2	27.2

Spatio-temporal patterns of algal biomass

Given that Lake Victoria is enriched with phosphorus and nitrogen, both nutrients, in particular P loads, have to be reduced through watershed management including management of the wetlands if eutrophication is to be controlled. Phosphorus reduction is the most feasible way of controlling eutrophication as nitrogen has a gaseous phase.

Chlorophyll-a (chl-a) concentrations ranged from 2.5 $mg.m^{-3}$ to 657.0 $mg.m^{-3}$, mean of 41.2 $mg\ m^{-3}$ in the surface waters of Lake Victoria. In surface waters average epilimnetic chlorophyll-a concentrations exhibited a much wider range especially inshore. Average chlorophyll-a concentrations were 3 to 5-fold higher in inshore than in offshore Lake Victoria. In the surface waters of Lake Victoria, chlorophyll-a was lowest when the lake was deeply mixing around July and was highest during the stratified phase.

Seasonality in algal biomass in Lake Victoria was well defined. A temporal algal biomass plot shows major chlorophyll-a maximum in September at the onset of thermal stratification and when the lake is rapidly warming up. The present light extinction coefficients vary throughout the year and exhibit similar temporal trends as chlorophyll-a (Figures 4 a and b). Highest light extinction coefficients were in September to April and coincided with high algal biomasses and with periods of stable thermal stratification. The lowest in light extinction coefficients occur around July when the lake is deeply mixing and algal biomass is low (Figure 2, 4). High algal biomasses contribute to reduced lake transparency in the lake. Secchi depth has reduced by a factor of 3 to 4 and is generally in the range of 0.5 m to 2.0 m and occasionally as high as 4.6 m in offshore deep waters of Lake Victoria.

Chlorophyll-a – total P and total N relationship

Total P and chlorophyll-a concentrations split into inshore and offshore sets exhibited fundamental differences in TP- chl-a relationship (Figure 5). The coefficient of determination for the relationship of chl-a to TP for inshore was higher ($r^2 = 0.52$, n = 26) and the slope (15.6) was significant ($p = < 0.01$) compared to offshore where the relationship was very weak ($r^2 = 0.11$, n = 20) and not significant ($p > 0.05$). Offshore, chlorophyll-a did not increase with increases in total P concentrations indicating that phytoplankton in offshore regions of Lake Victoria are insensitive to P enrichment. The negative chlorophyll-a- total P relationship implies that further P loading may not increase algal biomass offshore, but could stimulate larger cyanobacterial blooms inshore. However, the chlorophyll-a vs. total N relationship was fairly strong ($r^2 = 0.42$, n = 27) and the slope was significant ($p < 0.05$).

N-fixation

Rates of biological N-fixation measured between 1994 to 1998 were high and often exceeded 0.5 $\mu g\ N\ l^{-1}\ h^{-1}$ (Figure 6 a). Maximum rates of volumetric N-fixation were orders of magnitude higher and average rates were approximately 8 times higher in inshore than in offshore regions of Lake Victoria. At both inshore and offshore stations, minimum rates of N-fixation were consistent with low light availability and algal biomass. Rates of annual N-fixation in the range of 1.0 $N\ m^{-2}\ y^{-1}$ to 24 $g\ N\ m^{-2}\ y^{-1}$ did not differ significantly ($p>0.05$) among inshore stations (Napoleon Gulf, Buvuma Channel and Pilkington Bay). However, Itome Bay, the deepest inshore station, did have lower average and maximum rates than the other inshore stations, being intermediate between inshore and offshore rates.

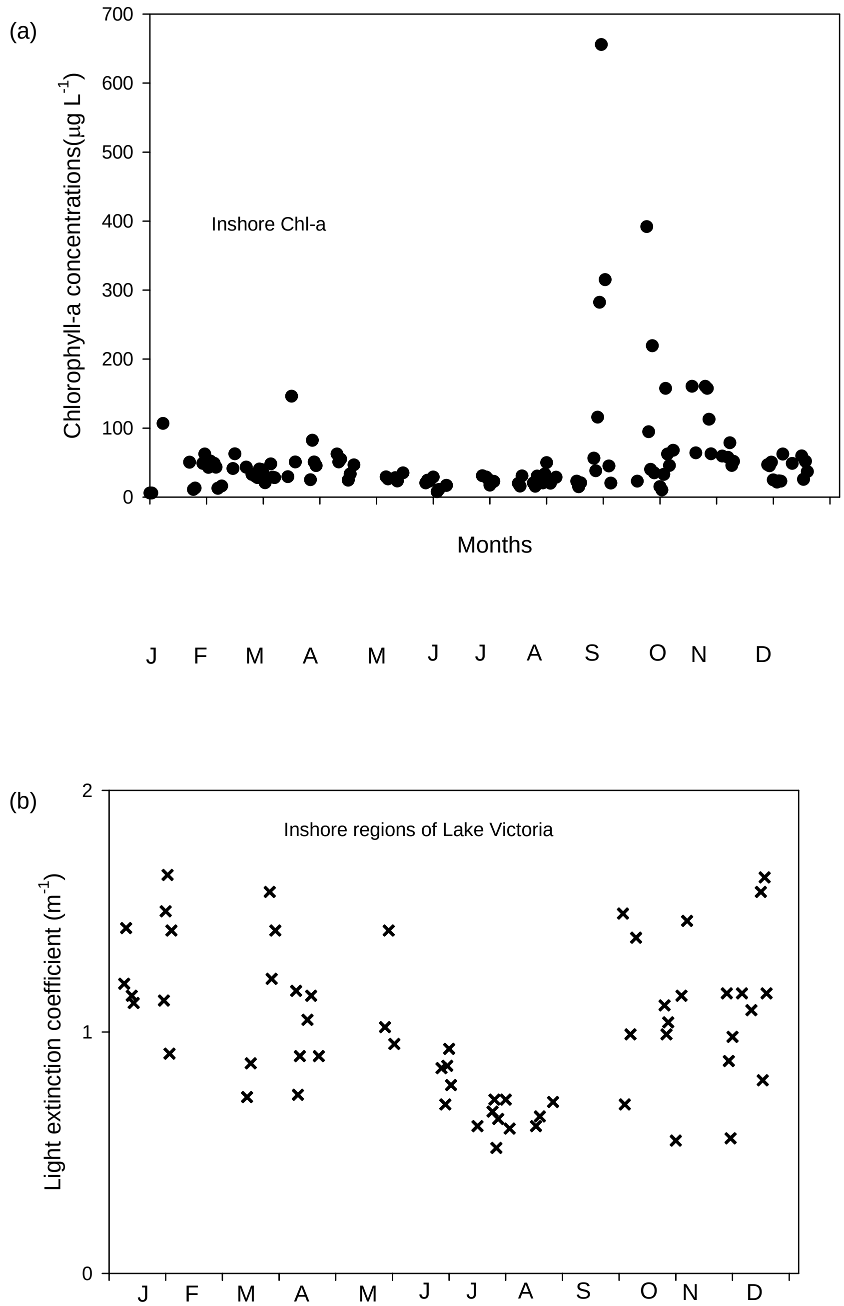

FIG. 4. Temporal variation of (a) Chlorophyll-a concentrations and (b) light extinction from the inshore Lake Victoria from 1990 to 2004.

(b) light extinction from the inshore Lake Victoria from 1990 to 2004.

Although N-fixation contributed a small fraction on average to the daily N demand of the phytoplankton community, it is important in the N-budget of Lake Victoria and contributed ≥ 60% of the total annual N input into the lake (Figure 6). Biological N-fixation is the largest input of fixed N to Lake Victoria, greatly exceeding estimates of atmospheric deposition and river inputs (Figure 6). This relatively high N contribution via fixation is not unique to Lake Victoria as fixation contributes over half of the total N input in the shallow tropical Lake George in Uganda (Horne and Viner 1971).

Status of phytoplankton primary production

Algal photosynthesis now occurs in a shrunken euphotic depth of 4 m to 10 m (Table 3). Phytoplankton primary productivity was in the range 8 to 50 g O_2 m^{-2} d^{-1}, with the mean average of 18.3 g O_2 m^{-2} d^{-1} that was twice higher than the values recorded in the 1960s (Mugidde 1992; 1993). Overall, the algal photosynthetic efficiency is now lower as indicated by average productivity per unit biomass of 18.1 mg O_2 mg $chl^{-1}h^{-1}$ in the 1990s compared to 25 mg O_2 mg $chl^{-1}h^{-1}$ in the 1960s. Currently Lake Victoria is inefficient in using nutrients, as algal primary productivity is light limited over most of time. However, algal primary productivity supports remarkable levels of secondary production including fish production in Lake Victoria.

Status of algal species composition

The very fertile conditions support elevated algal wet biomass which are in the range 5 to 250 mg l^{-1} (Figure 7 a) and have risen by a factor of 4 to 5 since the 1960s (Kling *et al.* 2001). Lake Victoria has had a shift in dominance from the historical algal communities dominated by diatoms such as *Aulacoseira* and green algae to blue-green algae in response to increased P loading and high N-demand (Hecky 1993; Lipiatou *et al.* 1996; Verschuren *et al*. 2002) and increasing N-demand by phytoplankton (Mugidde *et al*. 2003).

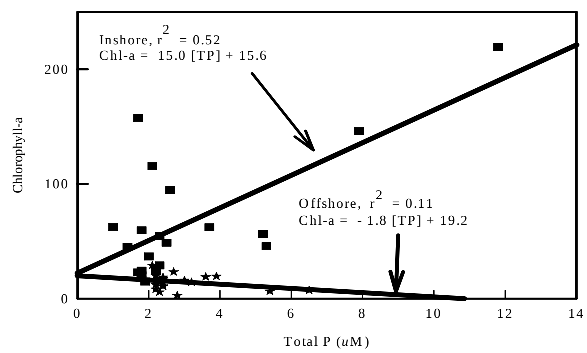

FIG. 5. Chlorophyll-a Versus Total phosphorus.

The high N-demand favour dominance of blue-green, dominated by *Cylindrospermopsis*, *Anabaena* and *Microcystis* (Figure 7). In Lake Victoria, there is seasonal succession in species composition of algae with increasing dominance of N-fixing blue-green algae during the early stratified period followed by non-fixers later in the stratified period and during the deepest mixing period in June-July.

In the present Lake Victoria, the large green algae such as *Pediastrum* are rare and /or absent in part due to 10 -fold reductions in soluble reactive silica. Silica concentrations are now in the range 5 to 60 μM, averages 17.3 ± 13.6 μM in the Lake Victoria (Figure 8). This silica draw down is due to eutrophication effects of high P loads into Lake Victoria.

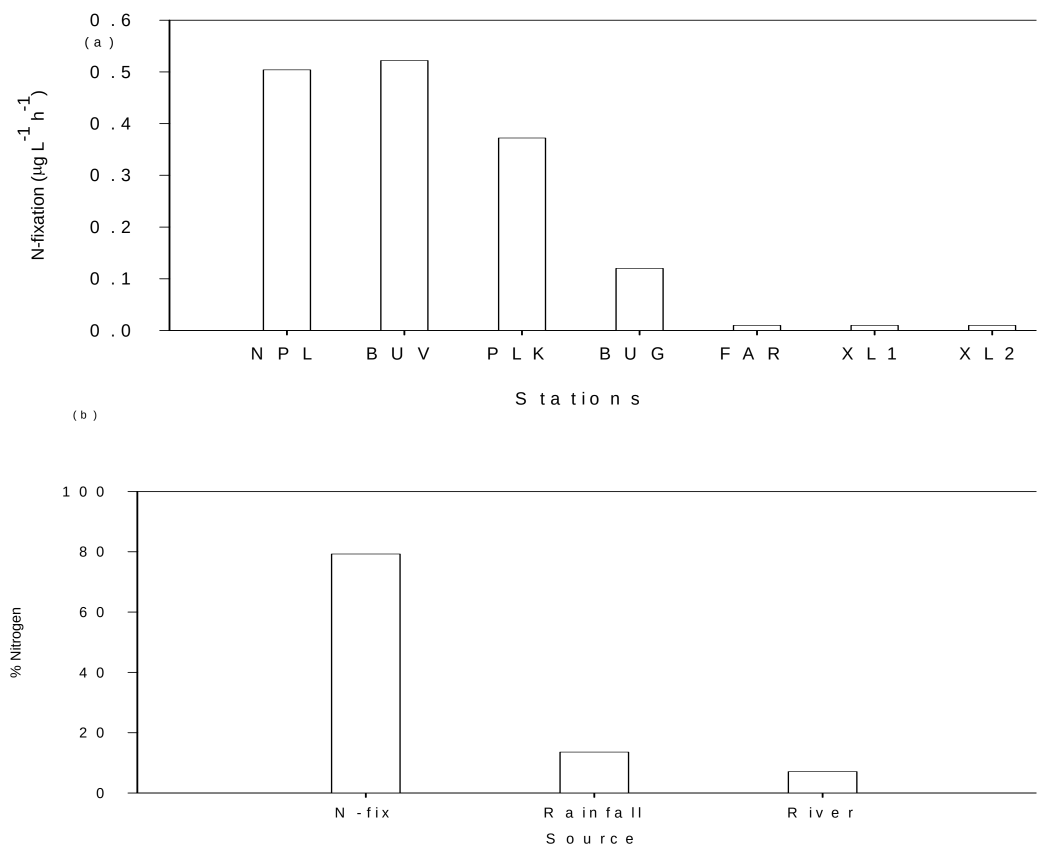

FIG. 6. (a) Volumetric rates of N-fixation and (b) % concentration from different sources to the N-budget of Lake Victoria.

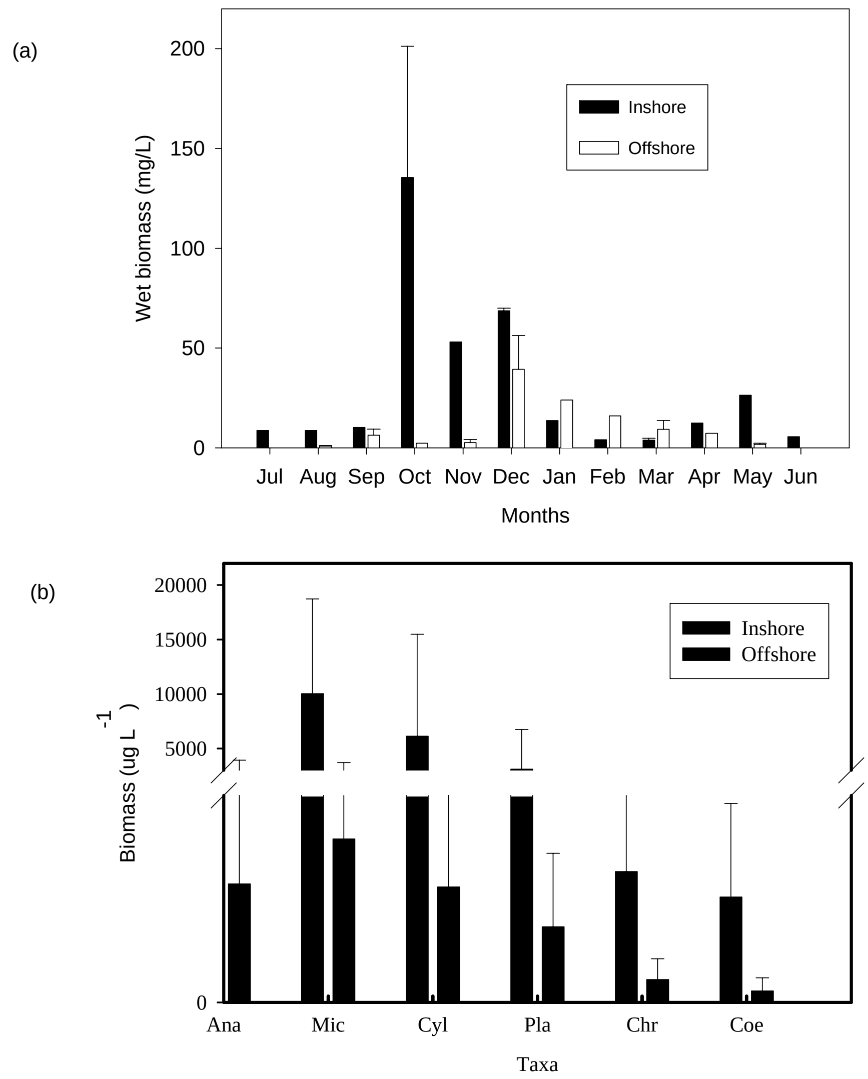

FIG. 7. (a) Variation of algal biomass with time; (b) with type in the inshore and offshore regions of Lake Victoria. Ana = Anabeana; Mic = Microcystis; Cyl = Cylindrospermopsis; Pla = Planktolyngba; Chr = Chrococcus and Coe = Coelosphrarum

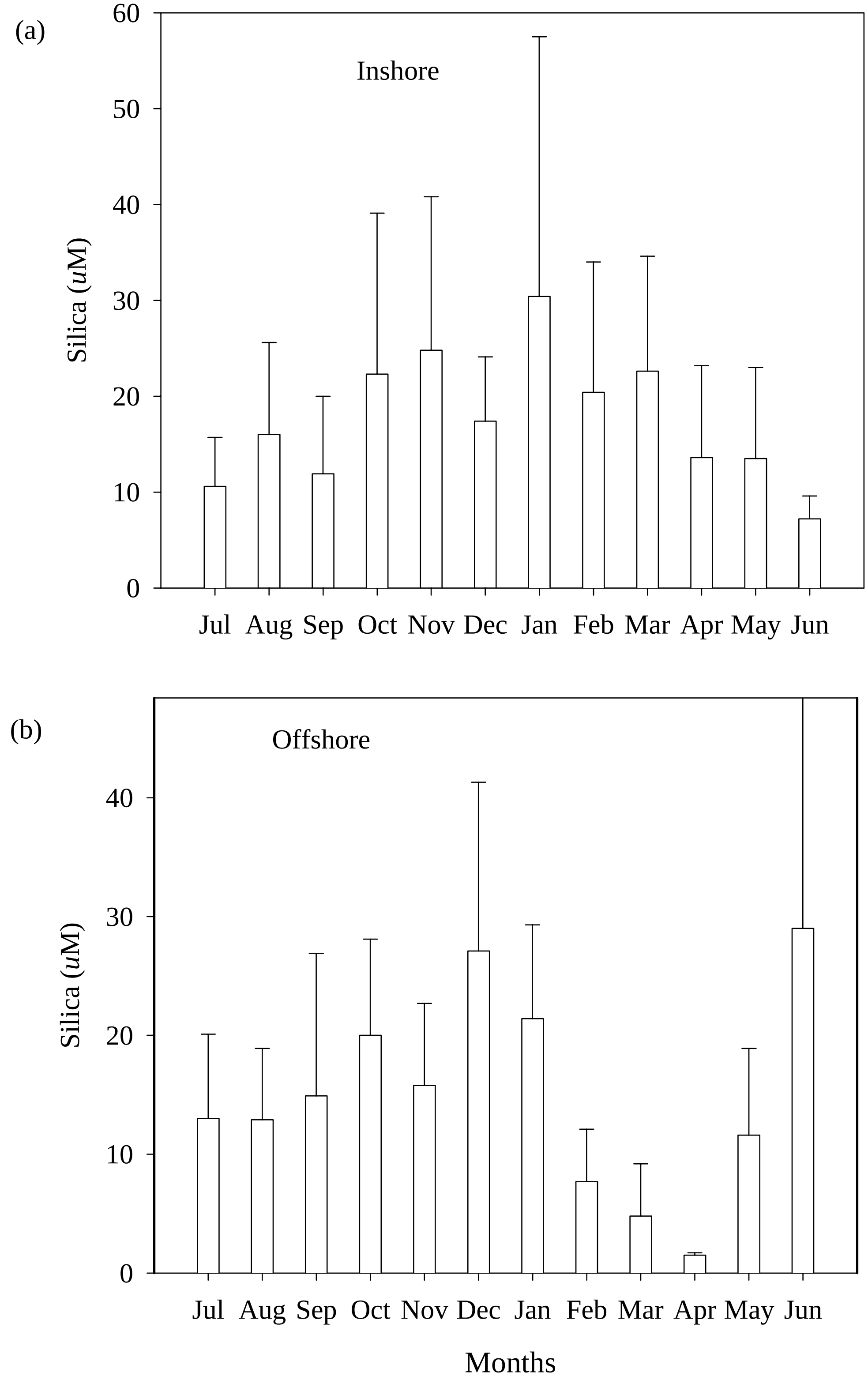

FIG. 8. Monthly average silica concentrations in (a) inshore and (b) offshore surface waters of Lake Victoria, 1990-2003. Vertical bar = standard deviation

The shift in diatom dominance from Aulacosiera (Melosira) to Nitszchia, which formed the main food of the native commercially important tilapiine *Oreochromis esculentus*, and its reduction might have affected stocks of this species. The dominance of cyanobacteria including toxic forms, could have led to reduction of available food for the native fish species. Besides, cyanobacteria are less digestible and provide poor quality food that may have contributed to the reduction or loss of planktivorous haplochromines and tilapiines that once flourished in Lake Victoria. It is, therefore, reasonable that changes in the fishery may have resulted, in part, from dramatic shifts in phytoplankton species composition in Lake Victoria.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The high nutrient loads into Lake Victoria are characteristic of disturbed watershed where extensive agriculture and land clearing are common (Carignan *et al.* 2000). In Lake Victoria, phophorus loads are dominated by external sources that include rainfall, dry–fall, rivers, industrial and municipal inputs.

Rainfall contributes approximately 5 kt per year of TP into Lake Victoria and rivers almost twice as much. Total N loads income through rainfall contributes approximately 83-kilo tonnes year^{-1} and half as much enters through rivers. The magnitude of nutrient loads through precipitation is magnified because rainfall accounts for >80% of water budget of Lake Victoria. *In situ* biological nitrogen fixation is an extremely important source of nitrogen as it brings in approximately 480 kilo tonnes per year of TN, which accounts for ≥ 60 % of the total N budget of Lake Victoria. High N income through biological fixation is because N supply from the hypolimnion is reduced by denitrification and N from the catchment is insufficient to support algal production (Lehman and Branstrator 1993). Present studies indicate that atmospheric loads are a large source of P and N to Lake Victoria and are consistent with past observations.

Changes in phytoplankton biomass and species composition have been attributed to general increases in P and N loading, changes in fish communities and climate change in Lake Victoria (Lehman *et al. 1*996). The undesirable algal blooms and excess biomasses in Lake Victoria will persist if increased nutrient loads in particular P loads and conditions of anoxia and high rates of denitrification continue. Management strategies to protect water quality of the lake should, therefore, give high priority to actions that control nutrient loads that stimulate growth of algal blooms and other aquatic plants.

Both phosphorus and nitrogen contribute to eutrophication in Lake Victoria. According to the OECD boundaries values for fixed trophic classification (Table 6), Lake Victoria is a typical eutrophic system based on total phosphorus and Secchi depth. However, the minimum chlorophyll-a lower range is about three fold lower than the corresponding typical range. This is because the algal community is suppressed by light limitation rather than nutrients as indicated by stocks of dissolved inorganic P, which are large, and often in excess of 1.0 μM. Overall, eutrophication effects are suppressed offshore due to severe light limitation caused by deeper mixing depth (≥ 20 m) most of the year.

TABLE 6. OECD boundaries values for fixed trophic classification system.

	Lake Victoria	**Typical Eutrophic system**
Total P ($\mu g\ L^{-1}$)	46-372	35 -100
Mean chlorophyll-a ($\mu g\ L^{-1}$)	2.5 -70	8 – 25
Maximum chlorophyll-a ($\mu g\ L^{-1}$)	8-675	25 – 75
Mean Secchi (m)	2 – 1.0	3 - 1.5
Minimum Secchi (m)	1- 0.5	1.5– 0.7

Given high nutrient concentration, reductions of their loads, in particular P loads is key to the control of eutrophication that threatens the ecosystem health of Lake Victoria as any reductions in N inputs from terrestrial sources are likely to be offset by increased N input by fixation. Phosphorus reduction will lead to reduction in blue-green algal biomass and blooms, including genera known to produce phytotoxins such as *Cyclindrospermopsis* and *Anabaena*. This should relax some of the negative consequences of high algal biomass such as excess oxygen demand and nutrient-and light-limited algal growth. Reductions in algal biomass will improve the light environment which will lead to improved algal productivity and ecological efficiency in the transfer of energy to higher levels in the food-web and sustaining high levels of fish production in Lake Victoria. Reduced plant biomass will improve the underwater light availability and expand the euphotic zone and also reduce organic loading to the stratified, anoxic deep waters.

Nutrient reduction into Lake Victoria requires reductions of direct and indirect anthropogenic loads that contribute to enrichment of rivers and to modification of the precipitation chemistry of Lake Victoria. Reduction of nutrient loads require watershed management and good soil conservation practices aimed at reducing extensive vegetation clearing, soil erosion and vegetation burning. In addition, municipal and industrial effluents should be of acceptable nutrient concentrations and ratios so as to reduce proliferation of algal biomass and weeds, such as water hyacinth.

Recommendations

Human settlement in the numerous urban and rural centers along the shoreline enhance pollution in the inshore regions, where nutrient loads from municipal and agricultural effluents are high. In light of these observations we recommend that an effective water quality monitoring system and research be continued to ensure collection of accurate data and information for informed decision-making. Further there is need for reduction of nutrient loads and pollutant input into the near shore through treatment of municipal and industrial effluents. We further recommend reduction of waste into the lake through promotion of cleaner production practices, promotion of good land-use practices in the catchment area, and conservation of the natural wetlands as well as promotion of constructed wetlands (CWs) as tertiary treatment systems for industrial and municipal effluents to include management of sources of nutrients contributing to atmospheric deposition. The riparian communities should be sensitized with regard to benefits of sound environmental management and harmonization of policies and laws on environmental protection and management as well as enhancement of analytical capability necessary to address emerging issues such as algal toxins, monitoring atmospheric deposition particularly phosphorus to establish amount that originate outside the basin boundaries, monitoring atmospheric and riverine loadings of potential toxic contaminants. There is need for improvement of sanitary conditions in shoreline settlements, enhancement of capacity for water quality management with the aim to enhance co-management of the lake waters. Finally, management should include, setting water quality objectives, primarily focusing on drinkability, fishability and minimization of waterborne and other water-related diseases as well as harmonization of environmental policies and laws among the Lake Victoria riparian states.

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