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Research Application Summary

The atmospheric deposition of phosphorus and nitrogen on Lake Kivu

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Abstract

Phosphorus and nitrogen are most often identified as the nutrients limiting algal biomass and productivity in aquatic ecosystems. Sources of new nutrients for lakes include riverine input, atmospheric deposition, N fixation, and occasionally groundwater. For many regions, the relative importance of atmospheric deposition is uncertain. Annual dynamics of wet and dry atmospheric nutrients (phosphorus and nitrogen) deposition on Lake Kivu were investigated at three land stations and one an island station to estimate lake wide atmospheric nutrient input to Lake Kivu. The highest dry P (TP) loading rates were recorded at the southern end of the Lake with lower rates in the north. Annual dry atmospheric deposition was higher than wet deposition in all the four sites. The estimation of dry TP and TN deposition to entire Lake Kivu (2370 km^2) is 14.5 ± 16.26 kg m^{-2} yr^{-1} of TP and 506.3 ± 590.7 kg m^{-2} yr^{-1} of TN. And the wet TP and TN estimation rate for the all Lake Kivu was respectively 0.09 ± 0.07 kg m^{-2} yr^{-1} and 2.02 ± 0.16 kg m^{-2} yr^{-1}. Phosphorus and nitrogen deposition rates in atmospheric deposition around Lake Kivu were similar to the existing estimates of atmospheric phosphorus and nitrogen inputs to other African Lakes. Both biomass burning and soil suspension particles were suggested as possible sources. These estimates should be viewed as a first order approximation of actual phosphorus and nitrogen deposition on the Lake.

Key words: Atmospheric deposition, Lake Kivu, nitrogen, phosphorous

Résumé

Le phosphore et l'azote sont souvent des nutriments identifiés comme limitant la biomasse algale et la productivité dans les écosystèmes aquatiques. Les sources des nouveaux nutriments dans les lacs comprennent les apports des rivières, la déposition atmosphérique et la fixation de l'azote. Dans plusieurs régions, l'importance relative de la déposition atmosphérique est incertaine. La dynamique annuelle des nutriments

(Phosphore et Azote) dans la déposition humide et sèche a été étudiée dans trois sites dans les stations terrestres et dans un site dans l'ile du Lac Kivu pour estimer la contribution de l'atmosphère dans les apports des nutriments dans le lac. Le taux élevé du phosphore total (TP) a été enregistré dans la partie Sud et le taux faible vers le Nord du lac. Le taux de déposition sèche était très élevé que le taux le taux de la déposition humide dans tous les sites d'étude. L'estimation de la déposition sèche du phosphore total (TP) et de l'azote total (TN) dans l'ensemble du Lac Kivu (2370 Km^2) est 14.5 ± 16.26 kg m^{-2} yr^{-1} de TP et 506.3 ± 590.7 kg m^{-2} yr^{-1} de TN. Et le taux de deposition humide du TP et TN estimee pour l'ensembel du lac, était respectivement de 0.09 ± 0.07 kg m^{-2} yr^{-1} et 2.02 ± 0.16 kg m^{-2} yr^{-1}. Le taux de déposition du phosphore et de l'azote dans la déposition atmosphérique autour du Lac Kivu est similaire aux taux de déposition atmosphérique mesurés dans d'autres lacs africains. Les feux de brousse et les particules des sols dans l'atmosphère ont été suggères comme sources possibles de ces nutriments dans l'atmosphère. Cette estimation devra être vue comme première approximation de l'actuelle déposition du phosphore et de l'azote dans le Lac Kivu.

Mots clés : Déposition atmosphérique, nutriments, phosphore, Azote, Lac Kivu

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Background

Phosphorus and nitrogen are most often identified as the nutrients limiting algal biomass and productivity in aquatic ecosystems. The fluctuation of these elements in lakes is often invoked to explain algal productivity and species succession on time scale from days to millennia (Langenberg *et al.*, 2003). Nutrient sources for a lake include riverine input, atmospheric deposition, and N fixation. Recycling processes within a lake determine the distribution of nutrients within the water column and between the water and sediments. Groundwater inflow may be an additional source in some lakes (Rogora *et al.,* 2001; Hecky *et al.,* 2003). Rivers have received much attention as the source of nutrients to lakes (Hecky *et al.,* 2003). However, the relative importance of atmospheric nutrient deposition can be expected to be significant in a lake such as Lake Kivu, with its large surface area to watershed area ratio and long residence time. Recently, the importance of atmospheric input as a nutrient source to tropical lakes has received growing attention (Lewis, 1981; Andreae *et al.,* 1990; Bootsma and Hecky, 1993; Bootsma *et al.,* 1996). Atmospheric input can account for a significant proportion of the nutrient flux to surface waters, directly enhancing biological activity and influencing algal and fish production. A number of studies have shown that the atmosphere can be a significant source of both phosphorus and nitrogen to lakes (Schindler *et al.,* 1976; Scheider *et al.,* 1979; Cole *et al.,* 1990; Bootsma *et al.,* 1996). These nutrients can be deposited in particulate, gaseous or dissolved form in precipitation or dry deposition, with rates varying according to the chemical species, meteorological conditions and the deposition surface (Bootsma *et al.,* 1996; Rogora *et al.,* 2001).

Atmospheric deposition represents an important non point source of nutrient and can significantly alter nutrient budgets of sensitive systems (Bootsma *et al.,* 1996; Langenberg *et al.,* 2003; Tamatamah *et al.,* 2005). Increased nutrient inputs can result in an increase in lake fertility and primary production. At moderate levels, they may lead to enhanced production at all trophic levels. However, excessive levels of nutrient loading may result in algal blooms, coupled with a decline in water clarity, increased prevalence of hypoxia and anoxia, fish kills, and lower fishery production. Atmospheric deposition may also alter nutrient loading ratios, which in turn may affect algal species compositions. The ultimate cost of continued high deposition rates may be long term ecosystem degradation. Industrial activities can have effects on atmospheric chemistry but non-industrial human activities such as deforestation, agriculture and biomass burning can also have a large impact on atmospheric chemistry (Lewis, 1981). Biomass burning in particular is prevalent in the Central and East Africa region (Andreae, 1993).

Data on rain chemistry in Africa is limited to a relatively small number of studies (Visser, 1961; Lacaux *et al.,* 1992; Bootsma *et al.,* 1996; Langenberg *et al.,* 2003; Tamatamah *et al.,* 2005). Data on precipitation chemistry in the Kivu region are very sparse. Measurements made by Muvundja *et al.* (2009) suggest that Lake Kivu is similar to other large East African lakes in that the internal loading exceeds external loading. However, current knowledge on the nutrient content of the different hydrological inputs for Lake Kivu is very limited. Apart from some temporal chemical and physical measurements of tributaries on the Congolese side (Isumbisho, 2005; Bagalwa, 2006) little is known about external nutrient loading. Specific processes in the Lake Kivu ecosystem such as plankton production and fisheries production have received some attention (Kaningini, 1995; Isumbisho, 2005), but there remains a need to determine how these processes are linked to external nutrient loads. With continued population growth, it is inevitable that land use patterns will change around the lake, and these changes will almost definitely be accompanied by changes in nutrient input to the lake. Because changes in nutrient input will have implications for algal and fish ecology, an understanding of how nutrients enter the lake and how these nutrients are cycled once they are in the lake is essential in the development of a whole lake management plan. Such understanding will facilitate prediction of the impact of nutrient input to the lake and guide management actions to prevent or mitigate undesirable changes.

Limited data on nutrient dynamics (Lacaux *et al.,* 1992; Bootsma *et al.,* 1996; Downing *et al.,* 1999) in the African Great Lakes suggests that the atmosphere plays a significant role in supplying nutrients and carbon to these ecosystems. Bootsma *et al.* (1999) estimated the dissolved nitrogen and phosphorus load to Lake Malawi from the atmosphere to be comparable to that from rivers. Tamatamah *et al.* (2005) suggested that the increase in phosphorus in Lake Victoria was primarily due to increases in atmospheric deposition from forest burning and wind erosion. It was estimated that forest burning and wind erosion accounted for 55% of the total phosphorus input to Lake Victoria from the atmospheric deposition, although there remains some uncertainty about river loading estimates. For Lake Tanganyika, Langenberg *et al.* (2003), found that wet atmospheric deposition provided approximately 83% of dissolved inorganic nitrogen, 37% of total phosphorus, 63% of total dissolved phosphorus, 65% of soluble reactive phosphorus, but only 1% of soluble reactive silicate of external source loading. Muvundja *et al.* (2009) concluded that atmospheric deposition and river nutrient loads were roughly equal for Lake Kivu. In their study, which was limited to six wet and six dry deposition samples, ammonium (mainly via rainwater) and nitrate (mainly via rivers) were primary sources of the dissolved inorganic N input (5400 t N /year), with both species combined contributing 50%. This paper addresses the annual dynamics of atmospheric nutrient (phosphorus and nitrogen) deposition on Lake Kivu at three land stations and one island station and uses these measurements to estimate totalannual atmospheric nutrient input to Lake Kivu.

Study description

Four stations located around Lake Kivu were selected for atmospheric deposition measurements. These include: Iko Island station (2° 14.064' S; 28° 53.555' E) where land use is characterized by cultivation, Goma station in the northern part (1° 41.58' S; 29° 22.690' E) in a built up area, Bukavu station representing an urban setting in the southern part (2° 29.817' S; 28° 51.558' E), and Lwiro station next to Kahuzi Biega National Park in the western part (2° 14.228' S and 28° 48.441' E) where cultivation characterized the land use (Fig. 1).

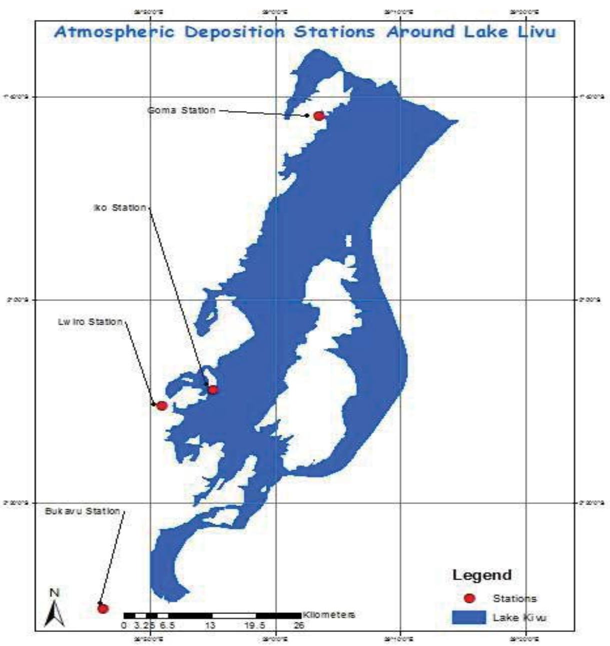

Figure 1. Map of Lake Kivu showing locations of the four atmospheric deposition sampling stations.

Methods

Atmospheric deposition collection and analysis

Sampling was conducted from October 2005 to September 2006, a period of time covering the dry and wet seasons. At each station, sampling buckets were placed on the roofs of an office building, with at least 10 m between the sampler and the nearest tree. Collection buckets were placed on 0.5 m tall stands to prevent contamination due to splashing on the roof surface. Dry deposition was sampled at intervals not greater than 13 days at the station of Lwiro and one sampling per month at other stations. The dry samples were collected from all stations within one day of each other. Polyethylene sampling collectors for dry deposition were 30 cm diameter with a capacity of 5 liters. Each container was filled with 2 L of deionised water and exposed for ~24 hours. Initial and final sample volumes as well as the exposure time were recorded.

Wet deposition was sampled in 5-liter plastic buckets. A bucket was placed on a stand on the roof of the house at the beginning of a rain event and retrieved immediately after the rain event for each site. Rain samples were transferred to polyethylene sampling bottles and transfer to the laboratory for analysis. The wet deposition sampling frequency was about two times per month at Bukavu, Goma and Iko during the period of the study and more frequently at Lwiro due to easier access to this station.

To estimate monthly deposition, we first calculated the volume-weighted mean (VWM) concentration of a nutrient for each month. This was determined as:

$$(C1 \text{ x } V1 + C2 \text{ x } V2 + C3 \text{ x } V3 + \dots) / (V1 + V2 + V3 + \dots)$$

Where C is the concentration of nutrient in a given sample and V is the volume of that sample. The VWM concentration for a nutrient was multiplied by the total monthly rainfall to determine total monthly deposition of that nutrient. To determine the annual dry deposition over the entire lake, the average daily deposition rate was multiplied by the lake area (2370 km^2) and the number of dry days per year (201), based on the long-term meteorological record in the region (Muvundja *et al.,* 2009). Dry deposition was assumed to be negligible on days with rain (Bootsma and Hecky, 2003). The total precipitation during the period of the study at the meteorological station of Lwiro was 1722 mm with 152 days of rain and 932 mm at the station of Goma and only 594 mm at the meteorological station of Bukavu.

Laboratory Analyses

Various forms of dissolved and particulate phosphorus and nitrogen were analyzed following standard analytical methods (Wetzel and Likens, 2000). Total phosphorus (TP) and total nitrogen (TN) were measured by persulphate digestion of non-filtered samples, followed by TP analysis using the molybdate method and TN analysis using the indophenol blue method after passing to zinc columm. Before analysis for dissolved components, each sample was filtered through a Whatman GF/F filter. Analyses of soluble reactive phosphorus (SRP, colorimetric, molybdate), nitrate (NO_3-, colorimetric after reduction to NH_4+ in a zinc column), ammonium (NH_4+, colorimetric indophenol blue method) were generally done immediately after sample collection, but occasionally filtered samples were stored frozen in polyethylene bottles for later analysis. Samples for particulate P and particulate N were dried and sent to the University of Wisconsin-Milwaukee School of Freshwater Sciences for analysis. Particulate N was measured on a Finnigan MAT delta S isotope ratio mass spectrometer with an elemental analyzer front end. Standards of known concentrations were run at approximately 10-sample intervals. Particulate P was measured by combusting filters with samples at 550oC, followed by digestion in a hot (104oC), 0.17 N HCl solution, followed by analysis for SRP using the standard molybdate method (Stainton *et al.* 1977).

Results

Annual rainfall amounts differed among stations around Lake Kivu. During the study period 1722 mm of rainfall was recorded at the station of Lwiro, 832 mm at the station of Goma and 594 mm at the station of Bukavu. The daily atmospheric deposition at the different sites are presented in Table 1 below.

The volume-weighted mean (VWM) concentration of a nutrient in wet atmospheric deposition varied significantly among sites (p= 0.05) using t-test and months p=0.06 using ANOVA. Some of the sampling sites were not continuously operational for the whole 12 months study due to inaccessibility of sites during heavy rain. The concentration of TP and TN increased in the rainy season (September to May) in general except for the TP at the station of Lwiro.

Table 1: Mean and standard deviation rates of dry (µmol m^{-2} day^{-1}) and wet (µmol m^{-2} $event^{-1}$) atmospheric nutrient deposition around the Lake Kivu.

Station	TP	SRP	TN	NH_4+	NO_3-	PP	n
Dry deposition							
Goma	1.6± 3.8	0.89 ± 2.03	201.8 ± 157.2	84 ± 66.9	95.3 ± 95.1	1.18 ± 1.05	10
Iko	9.5 ± 8,9	4.46 ± 5,19	275.8 ± 396.5	141.5 ± 284.2	35.393 ± 48.3	1.93 ± 0.89	15
Lwiro	14.2 ± 14.3	7.4 ± 8,2	272.8± 419.6	79.2 ± 357.6	67.4 ± 127.2	0.32 ± 1.9	16
Bukavu	4.3 ± 5.4	2.98 ± 5.1	21.6 ± 8.9	8.96 ± 5.8	9.8 ± 5.01	0.63 ± 0.46	13
Mean total	7.4 ± 8.1	3.9 ± 5.13	212.9 ± 149.7	82.8 ± 75.3	52.4 ± 33.4	1.02 ± 0.65	
Wet deposition							
Gom	1.4 ± 0.1	0.04 ± 0.04	9 ± 0.264	5 ± 0.2	4 ± 0.2	2.3 ± 2.3	10
Iko	5.2 ± 5.98	2.98 ± 3.61	217.4 ± 13.7	5.3 ± 2.1	6.9 ± 4	ND	4
Lwiro	3.2 ± 0.2	1.9 ± 0.14	15 ± 1.4	4 ± 0.1	2± 0.1	ND	13
Bukavu	7.6 ± 9.5	2.78 ± 4.56	101.2 ± 128.1	26.5 ± 28.2	11.6 ± 12.6	1.1± 0.46	5
Mean total	4.4 ± 4	1.5 ± 2.1	85.7 ± 35.8	10.2 ± 7.7	6.1 ± 4.2	1.7 ± 1.89	

TP: Total Phosphorus, TN: Total Nitrogen, PP: Particulate Phosphorus, SRP: Soluble reactive phosphorus

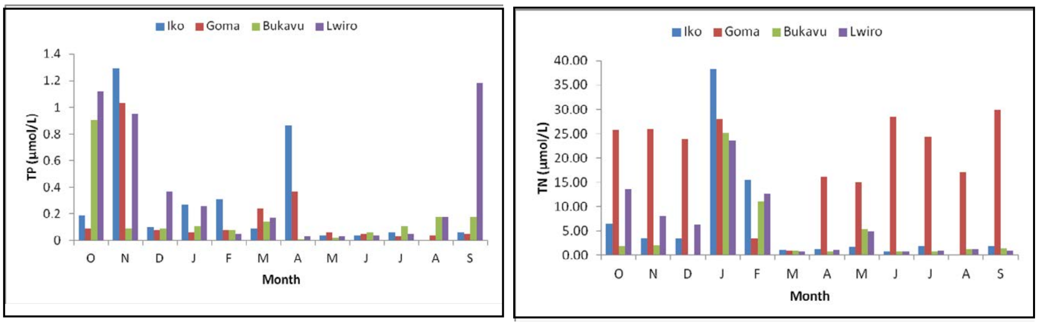

Figure 2. Monthly variation of concentration of TP and TN in different sites

The sites located at Lwiro and Iko were found to have higher nutrient concentrations in dry deposition than the sites of Bukavu and Goma, both of which are urban site. Lwiro and Iko sites are located in the rural area where agriculture is the main activity, and where there is extensive deforestation. But when we observed the rates of deposition for wet atmospheric deposition, we found that the sites of Bukavu and Iko have high nutrient values. The total means for the four sites was about 7.4 ± 8.1 µmol m^{-2} day^{-1} for TP and around 212.9 ± 149.7 µmol m^{-2} $day^{-1}$of TN for both dry and wet atmospheric deposition.The annual deposition rates of nutrients calculated to the all Lake Kivu during the sampling period are presented in Table 2. The annual rates of atmospheric deposition of nutrients varied with stations and it was relatively higher in dry deposition than in wet deposition.

Table 2: Annual deposition rates for Lake Kivu

Stations	TP (kg P/yr)	SRP (kg P/yr)	TN (kg N/yr)	NH_4+ (kg N/yr)	NO_3- (kg N/yr)	PP (kg P/yr)
Dry deposition						
Goma	251	138	14330	5967	6768	185
Iko	1501	701	19582	10049	2513	305
Lwiro	2231	1158	19372	5622	4783	59
Bukavu	674	359	1533	635	695	99
Mean total1	124	59	15117	5880	3721	159
Wet deposition						
Goma	4.2	0.12	27	15	12	6.9
Iko	15.6	8.94	652.2	15.9	20.7	ND
Lwiro	9.6	5.7	45	12	6	ND
Bukavu	22.8	8.34	303.6	79.5	34.8	3.6
Mean total	13.05	5.77	256.95	30.6	18.38	5.7

TP: Total Phosphorus, TN: Total Nitrogen, PP: Particulate Phosphorus, SRP: Soluble reactive phosphorus

The annual rates of atmospheric deposition of nutrients varied among the stations and it was high in dry deposition than in wet deposition. Table 3 presents a comparison with data from Muvundja *et al.* (2009).

Table 3. Comparison of nutrients in dry and wet deposition

		Unit	SRP	NH_4+	NO_3-
Dry	Muvundja *et al.* (2009)	µg m^{-2} day^{-1}	43 - 160	662 - 2730	366 - 483
Dep.	Present study	µg m^{-2} day^{-1}	4.43±6.8	85±341.2	80.5±126.7
Wet	Muvundja *et al.* (2009)	µg L^{-1}	1 - 45	121 - 521	51 – 150
Dep.	Present study	µg L^{-1}	0.23±0.26	3.41±5.51	2.99±4.89

The dry phosphorus deposition rate at the stations around the Lake Kivu (4.43±6.8 µmol m^{-2} day^{-1}) is lower than the values recorded in Lake Victoria (17.4 to 26.2 µmol m^{-2} day-1) and Lake Malawi (24.7 µmol m^{-2} day^{-1}) (Bootsma *et al.,* 1999; Tamatamah *et al.,* 2005).

Discussion

Several studies have indicated that biomass burning may be a major source of phosphorus to the atmosphere (Bootsma *et al.,* 1996). Lewis (1981) has shown that ash from biomass burning is a rich source of available phosphorus and Okin *et al.* (2004) concluded that particulates in tropical air are enriched in phosphorus relative to phosphorus in the earth's crust because of phosphorus enrichment by biomass burning. Tropical Africa has the highest aerial coverage of biomass fires, dominating the global biomass burning budgets for many compounds (Scholes and Andreae, 2000).The sites of Bukavu and Goma have lower volume-weighted mean (VWM) concentration of TP compared to other places (Bootsma *et al.,* 1996; Langenberg *et al.,* 2003; Tamatamah *et al.,* 2005). The same trends were observed by Muvundja *et al.* (2009) in the Lake Kivu area. It appears that developed urban areas are a smaller source of atmospheric P than agricultural areas are. This is shown in Table 1 where the wet TP concentration at Goma is lower than at the other three stations. At Bukavu, the roads conditions are madly and produce a lot of dust.

As shown in Table 3, the VWM SRP, NH4+ and NO_3- concentrations for all stations were comparable to those recorded by Muvundja *et al.* (2009). High dry nitrogen deposition rates were recorded at Iko and Lwiro (275.8 ± 396.5 µmol m^{-2} day^{-1} and 272.8 ± 419.6 µmol m^{-2} day^{-1} respectively) with lower rates in Bukavu (21.59 ± 8.917 µmol m^{-2} $event^{-1}$). This rate of dry nitrogen deposition in Lake Kivu was less than that recorded in the Lake Malawi (560 µmol m^{-2} day^{-1}) (Bootsma *et al.,* 1999). Possible sources of atmospheric fixed nitrogen are emissions from soil bacterial processes, lightning, combustion of fossil fuels, biomass burning and ammonia volatilization (from animal and human excreta, soil and senescing vegetation). Bootsma *et al.* (1996) indicated that biomass burning was responsible for the elevated N concentrations in precipitation near Lake Malawi. At the stations of Lwiro and Iko, during the planting period immediately before the rains, the dry deposition was higher than in other stations. During this period the farmers regularly use burning to prepare fields for agriculture.

Nitrogen and phosphorus are key elements limiting algal production in lakes. When present in excess, they can result in high levels of algae in freshwater and marine systems (Downing *et al.,* 1999). The seasonal pattern that emerged from the data was predictable for dry N and P deposition at most stations. Nutrient deposition rates peaked between November and February at Bukavu, Lwiro and Iko, but at Goma deposition rates peaked in April. Higher deposition rates during these months were not strange because this period coincides with vegetation harvesting and burning in the region. Near Goma intensive volcanic activity was observed in April, which generated visible smoke in the atmosphere, likely explaining the high phosphorus and nitrogen deposition rates in that month. The estimation of total dry TP and TN deposition to all of Lake Kivu (2370 km^2) is 14.5 ± 16.26 kg m^{-2} yr^{-1} of TP and 506.3 ± 590.7 kg m^{-2} yr^{-1}. The estimated wet TP and TN rates were respectively 0.09 ± 0.07 kg m^{-2} yr^{-1} and 2.02 ± 0.16 kg m^{-2} yr^{-1}. The mean phosphorus and nitrogen deposition rates varied from wet and dry deposition during the period of sampling. In general, dry deposition rates were higher than wet deposition rates. This was also the case in other lakes in Africa such as Lake Victoria and Lake Malawi (Bootsma *et al.,* 1996; Langenberg *et al.,* 2003; Tamatamah *et al.,* 2005). But for Lake Malawi, over the entire year, dry deposition is greater than wet deposition, because there are more dry days than wet days. The contribution of annual dry deposition is higher than the wet deposition to the entire Lake Kivu. This can be linked to road traffic conditions in the region which bring soil particles containing phosphorus in air and contribute to the increase in the concentration of phosphorus in water samples. Moreover the number of dry days are more than the number of wet days.

Potential sources of atmospheric phosphorus include domestic and soil particles, detergents, biomass burning, agricultural fertilizers and particulate material of industrial origin. It has been documented that the atmosphere plays a significant role in supplying P to various ecosystems including lakes and forests (Lewis, 1981; Andreae, 1993; Bootsma *et al.,* 1996; Tamatamah *et al.,* 2005). However, management of this nutrient source requires an understanding of the mechanisms by which P is loaded to the atmosphere. The data that presented in this study highlights the importance of atmospheric deposition as a route by which both N and P enter Lake Kivu, in agreement with the findings of Muvundja *et al.* (2009). Further research is required to understand the ultimate sources of these nutrients, and the atmospheric transport pathways that they follow. There are presently very little data on annual variability of rain chemistry for any part of Africa (Bootsma *et al.,* 1996). Due to the paucity of long-term data, determination of historical trends in these regions is difficult, although there is evidence that nutrient deposition rates have increased significantly over the past half century (Muvundja *et al.,* 2009). Establishing quality baseline data on atmospheric nutrient deposition and its seasonal variation is critical. The current lack of knowledge in Africa and the important role of atmospheric deposition are strong reasons to establish deposition monitoring programs on the African Great Lakes.

Conclusion

In general, there are some noticeable differences between the wet and dry chemistry near Lake Kivu. Annual dry TP and TN rate deposition was 3 to 4 greater than wet rate TP and TN deposition. The data presented in this study highlight the need for a long term sampling program in the Lake Kivu catchment. The result of this study suggested that the contribution of atmospheric deposition of P and N are significant.

Acknowledgments

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