## Chapter 3

# The Atmospheric Deposition of Nutrients on Lake Malawi/Nyasa

***H.A. Bootsma , J. Mwita, & B. Mwichande***
SADC/GEF Lake Malawi/Nyasa Biodiversity Conservation Project
Malawi Inland Fisheries Research Centre, P.O. Box 311, Salima, Malawi

***R.E. Hecky***
National Water Research Institute
Environment Canada, Burlington, Canada

***J. Kihedu, J. Mwambungu***
Tanzania Fisheries Research Institute
P.O. Box 98, Kyela, Tanzania

## Introduction

Rivers have received much attention as the source of nutrients to lakes. The phosphorus loading model developed by Vollenweider (1979) predicts phosphorus loading to a lake, and the lake's biological response to this loading, as a function of the phosphorus concentration in tributary rivers and the turnover time of the lake. The success of this model as a management tool indicates that, for many lakes, rivers are the primary source of phosphorus. However, the relative importance of atmospheric nutrient deposition can be expected to increase in a lake such as Lake Malawi/Nyasa, with its high surface area to watershed area ratio and long flushing time.

The potential importance of the atmosphere as a nutrient source to lakes has recently received increased attention. 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; Manny and Owens 1983; Cole et al. 1990), and even the oceans may acquire a significant amount of nitrogen from the atmosphere (Paerl 1993, 1995; Jassby et al. 1994; Peierls and Paerl 1997). Dissolved inorganic nitrogen concentrations in the Laurentian Great Lakes have risen steadily over the past century as a result of increased atmospheric N deposition (Bennett 1986).

Because industrial activities can have dramatic effects on atmospheric chemistry, there is an abundance of data on rain chemistry for Europe and North America. However, other non-industrial human activities, such as deforestation, agriculture and biomass burning can also have a large impact on atmospheric chemistry (Lewis 1981; Delmas 1982; Munger 1982; Linsey et al. 1987). Biomass burning in particular is more prevalent in the Central-East Africa region than any other part of the world (Andreae 1993). Despite this realization, data on rain chemistry in Africa is limited to a relatively small number of studies (Visser 1961; Ganf and Viner 1973; Bromfield 1974; Bromfield et al. 1980; Gaudet and Melack 1981; Rodhe et al. 1981; Lacaux et al. 1992; Bootsma et al. 1996), and in only a few cases have measurements been put into the context of lake biogeochemistry (Gaudet and Melack 1981; Rodhe et al. 1981; Bootsma et al. 1996). Virtually no research has been done on dry deposition chemistry within the tropics.

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*Acknowledgments* – We are grateful to Mr. J. Soko, who collected rain samples at Nkhata Bay.

Previous research on atmospheric deposition near Lake Malawi/Nyasa (Bootsma et al. 1996) indicated that the atmosphere may be a significant source of P and a major source of N to the lake. This work included only a few measurements of dry N and P deposition, but these measurements suggested that annual dry N and P deposition were probably greater than wet deposition. Dry deposition of other nutrients (silica, sulphur) was not measured.

Within the SADC/GEF Lake Malawi/Nyasa Biodiversity Conservation Project, an atmospheric deposition monitoring program was initiated with the objective of improving estimates of atmospheric nutrient deposition on Lake Malawi/Nyasa. This research is part of a larger goal of constructing a whole-lake nutrient budget for the lake.

## Methods

The study period extended from October 1996 (when the first rains fell prior to the 1996/1997 rainy season) to April 1998 (shortly after the end of the 1997/98 rainy season). Rain was collected in two polyethylene collecting buckets placed on a stand 1.5 m above the ground. The stand was fitted with a cover, which was attached by side-arms to an automatic rain sampler (used for collecting separate rain samples for contaminant analysis). The cover is automatically removed from the buckets at the commencement of a rain event, and is replaced over the buckets when rainfall ceases. Diurnal rain samples were retrieved and processed within one hour following a rain event. Nocturnal rain samples were retrieved and processed early the following morning.

The rain water collected in each bucket was filtered through pre-ashed Whatman GF/F filters for particulate carbon, nitrogen and phosphorus (PC, PN and PP) analyses. An additional 50 ml was filtered through a polycarbonate membrane filter for particulate silica (PSi) analysis. Filter samples were desiccated and then stored frozen until shipment to the Freshwater Institute in Winnipeg, Canada. From the filtrate, 20 ml was removed and stored in a glass scintillation vial, with mercuric chloride as preservative, for dissolved organic carbon (DOC) analysis. 60 ml was stored at room temperature (no preservative) for soluble reactive silica (SRSi) analysis. Another 60 ml was stored at room temperature for major ion analyses: sodium ($Na^+$), potassium ($K^+$), magnesium ($Mg^{2+}$), calcium ($Ca^{2+}$), chloride ($Cl^-$) and sulphate ($SO_4^{2-}$). The remaining filtrate was either analyzed immediately, or stored frozen for the analysis of dissolved ammonium ($NH_4^+$), nitrate ($NO_3^-$), total dissolved nitrogen (TDN), soluble reactive phosphorus (SRP) and total dissolved phosphorus (TDP).

Analyses of dissolved $NO_3^-$, Si, TDN and TDP were conducted in the Senga Bay limnology laboratory, following the methods of Stainton et al. (1977). Due to $NH_4^+$ contamination problems with the automated $NH_4^+$ analysis method, $NH_4^+$ analysis was done using a modification of the manual method of Stainton et al. (1977), in which 10 ml of sample was reacted with reagents in a 10 ml syringe. Analyses of PC, PN, PP, PSi, DOC, and major ions were done at the chemistry lab of the Freshwater Institute (Winnipeg, Canada), following the methods of Stainton et al. (1977).

Daily rainfall was monitored in Senga Bay throughout the study period using an automated tipping bucket rain gauge connected to a Campbell Scientific CX10 logger.

In order to estimate dry deposition, every 13 days between April 1997 and March 1998 two buckets (38 cm diameter X 10 cm deep) were each filled with 5 litres of filtered lake water and placed on a stand 0.5 m high at the same location as the rain collector. At the time of filling the buckets, subsamples were taken for the analyses of $NH_4^+$, $NO_3^-$, TDN, SRP, TDP, SRSi and DOC. Buckets were left out for exactly 24 hours, after which they were retrieved, volume was measured, and the water was filtered for PC, PN, PP, and PSi analyses, as well as analyses of the dissolved components listed above. Daily deposition of a component was determined as the difference between the final and initial concentration of that component, divided by the surface area of the collector.

Lake Malawi/Nyasa is large, and therefore it is difficult to know how well atmospheric deposition measurements made at a single site represent deposition over the entire lake. To assess the potential magnitude of spatial variability of rain chemistry, rain samples were also collected at two other research stations, one approximately 5 km west of the lake shore near Nkhata Bay (near the centre of the lake on its north-south axis), and the other at the Tanzania Fisheries Research Institute (TAFIRI) office site in Kyela, at the north end of the lake. At each site, sampling buckets were placed on

elevated structures with at least 10 m between the sampler and the nearest tree. Sampling buckets were placed out immediately before a rain event, or late in the evening if rain was expected during the night. Buckets were retrieved immediately after a rain event, or the morning after a nocturnal rain event. Samples were filtered for PC, PN and PP analyses. 60 ml of filtrate was stored with no preservative for SRSi analysis. Because freezing facilities were not available at either Nkhata Bay or Kyela, samples for dissolved nutrient analysis were preserved by the addition of reagent grade KCl, to a final concentration of approximately 70 parts per thousand. We have not tested the efficacy of this preservation method for dissolved nutrients, but previous tests of this method for preserving samples for inorganic carbon analysis indicated that samples remain well preserved for approximately two months, after which inorganic carbon concentration slowly increases due to microbial activity. Rain samples from Nkhata Bay and Kyela were usually analyzed within two months of collection, but occasionally the time between collection and analysis was as great as 3 months. Because we could not be certain that individual inorganic nutrient species ($NH_4^+$, $NO_3^-$, $PO_4^{3-}$) were well preserved, samples from these two stations were only analyzed for TDN, TDP and DOC.

## Results and Discussion

**Rain Chemistry**. Quartile and volume-weighted mean concentrations of the measured rain components are presented in Table 3.1. The sum of the volume weighted mean concentrations of cations (18.45 μeq $l^{-1}$) is greater than that of anions (11.03 μeq $l^{-1}$). Previous work (Bootsma et al. 1996) has shown that this imbalance is probably made up by bicarbonate ($HCO_3^-$), which was not measured.

The most abundant cation (in terms of equivalent concentration, which is molarity times the ion valence) was $Na^+$, followed by $Ca^{2+}$, $H^+$, $NH_4^+$, $K^+$ and $Mg^{2+}$. The order of abundance of anions was $SO_4^{2-}$, $NO_3^-$, $Cl^-$, and organic acids. However, if the imbalance between cation and anion equivalent concentrations is accepted as being made up by $HCO_3^-$, then the equivalent concentration of $HCO_3^-$ (approximately 7.4 μeq $l^{-1}$) is greater than that of any other anion, making up 40% of the total anion equivalent concentration. The volume weighted mean $H^+$ concentration of 3.87 μM is equivalent to a pH of 5.4.

A comparison of measurements made in the present study with those made in 1990/91 near Monkey Bay reveals several differences. Both TDN and TDP concentrations were substantially greater in the present study. In this study, TDN and TDP analyses were conducted in the Senga Bay limnology lab, while these analyses were conducted in Winnipeg during the previous study. Recent comparisons have indicated that a significant amount of TDN and TDP may be lost during transport, when samples are not kept frozen, and therefore the differences in concentrations between the two studies is likely due to underestimates in the 1990/91 study, and do not reflect real differences in concentration between the two studies. While there are some other apparent differences between the two studies, the concentrations of all components in the two studies are similar relative to concentrations in rain collected in remote, non-marine regions (Galloway et al. 1982); i.e. there are no major differences in the rain chemistry data collected in 1990/91 and that collected in the more recent study.

There are some noticeable differences between the rain chemistry near Lake Malawi/Nyasa and that measured in remote non-marine locations. Relative to remote non-marine locations, Malawi rain has higher concentrations of $NH_4^+$, $Ca^{2+}$ and $K^+$, and a lower concentration of $H^+$ (Table 3.1).

High temperature combustion is an important mechanism by which atmospheric nitrogen is fixed. While this process is well documented in industrial areas (due to its role in the production of acid rain), there is evidence that the burning of vegetation in tropical areas also results in an increased flux of fixed nitrogen into the atmosphere (Lewis 1981; Crutzen and Andreae 1990; Lacaux et al. 1992), and in regions experiencing intense burning, the $NH_4^+$:cation ratio and $NO_3^-$:anion ratio are elevated (Lewis 1981; Crutzen and Andreae 1990). During both the 1990/91 study and the present study, the above ratios were greater in Malawi rain than in rain collected at remote non-marine areas

**Table 3.1**. Chemical composition of rain collected at Senga Bay between October 1996 and April 1998. Data are presented as percentile values and volume weighted means (VWM). n = number of samples analyzed. Bicarbonate ($HCO_3^-$) is calculated as the difference between equivalent concentration of measured cations and anions. 1990/91 values for rain collected near Monkey Bay (Bootsma et al. 1996) and remote non-marine data (Galloway et al. 1982) are included for comparison. All values are µmol $L^{-1}$. DIN = dissolved inorganic N ($NO_3^-$ + $NH_4^+$); Org. Ac. = organic acids. All other acronyms are explained in the text. The VWM TDP concentration is larger than the 75th percentile concentration, due to one large rain event (56 mm) with a high TDN concentration (11.6 µmol $L^{-1}$).

| Component | 25 % | 50 % | 75 % | VWM | 1990/91 VWM | remote non-marine | n |
|---|---|---|---|---|---|---|---|
| $NO_3^-$ | 2.05 | 3.42 | 7.62 | 3.59 | 3.2 | 1.9-4.3 | 98 |
| $NH_4^+$ | 1.76 | 2.94 | 6.64 | 3.16 | 5.4 | 1.1-2.3 | 82 |
| DIN | 3.89 | 6.09 | 11.29 | 6.21 | | | 78 |
| TDN | 6.74 | 13.6 | 18.74 | 13.13 | 8.4 | | 24 |
| PN | 0.50 | 0.71 | 2.04 | 0.71 | 1.0 | | 85 |
| SRP | 0.09 | 0.20 | .038 | 0.28 | 0.18 | | 93 |
| TDP | 0.10 | 0.24 | 0.62 | 0.78 | 0.1 | | 25 |
| PP | 0.03 | 0.03 | 0.13 | 0.06 | 0.04 | | 93 |
| DOC | 50 | 80 | 133 | 84 | 56 | | 83 |
| PC | 11.2 | 17.9 | 39.4 | 14.6 | 20 | | 84 |
| SRSi | 1.55 | 3.02 | 3.73 | 3.95 | | | 26 |
| PSi | 0.14 | 0.29 | 0.82 | 0.42 | | | 84 |
| $Ca^{2+}$ | 1.07 | 2.00 | 4.19 | 2.07 | 5 | 0.05-1.3 | 90 |
| $Mg^{2+}$ | 0.41 | 0.82 | 1.23 | 0.70 | 1.1 | 0.1-1.0 | 91 |
| $Na^+$ | 3.48 | 4.78 | 9.79 | 4.35 | 2.9 | 1.0-7.0 | 90 |
| $K^+$ | 1.02 | 1.79 | 3.07 | 1.53 | 0.6 | 0.6-0.9 | 91 |
| $H^+$ | 0.7 | 1.8 | 3.9 | 3.87 | 0.7 | 11-17 | 50 |
| $SO_4^{2-}$ | 1.41 | 2.60 | 4.69 | 1.89 | 2.5 | 1.4-3.5 | 60 |
| $Cl^-$ | 1.41 | 2.82 | 5.92 | 2.54 | 1.5 | 2.5-11.8 | 60 |
| Org. Ac. | 0.5 | 0.5 | 2.5 | 1.12 | 2.4 | <2-28 | 43 |
| $HCO_3^-$ | | | | 7.4 | | | |

**Table 3.2**. Regional comparison of nitrogen : total ion ratios in rain. Only ions common to all studies were used to calculate ratios. Congo data from Lacaux et al. 1992. Kampala data from Visser 1961).

| Ion Ratio | Malawi 90/91 | Malawi 96-98 | Remote Non-Marine | Congo | Kampala (Uganda) |
|---|---|---|---|---|---|
| $NH_4^+/(Ca^{2+}+Na^++K^++NH_4^+)$ | 0.29 | 0.24 | 0.22 | 0.22 | 0.23 |
| $NO_3^-/(Cl^-+SO_4^{2-}+NO_3^-)$ | 0.33 | 0.36 | 0.20 | 0.20 | 0.30 |

(where vegetation burning is presumably less intense) (Table 3.2), supporting the suggestion that biomass burning is responsible for elevated rain nitrogen concentrations near Lake Malawi/Nyasa.

Likewise, elevated $K^+$ concentrations may also be the result of burning (Lewis 1981; Delmas 1982; Andreae et al. 1988). This is not surprising, considering that the intensity of biomass burning appears to be greater in central and east Africa than in any other part of the world (Andreae 1993). Andreae's conclusion, based on the analysis of photographs taken from space, is supported by the observation of a brown haze over and around Lake Malawi/Nyasa, is particularly noticeable during the dry season.

The atmospheric deposition of phosphorus has not received nearly as much attention as that of phosphorus. However, in comparison to the few measurements of wet P deposition that have been made in Africa, South America, and North America, wet deposition rates measured at Senga Bay are high (Figure 3.1). While the cause of these high rates is uncertain, the fact that atmospheric deposition was even greater during the dry season (see below) suggests that much of the P originates in particulate form. Possible sources of particulate P are ash, aerosols, and soil. Ash is a direct product of biomass burning, while aeolian (wind) erosion of soil particles can be an indirect result of burning, deforestation and agriculture, all of which increase soil exposure. Evidence for the potential effect of burning on atmospheric P deposition has been presented for Lake Valencia in Venezuela (Lewis 1981), while the elevated $Ca^{2+}$ concentrations in Malawi rain support the potential importance of aeolian soil erosion (Munger 1982; Linsey et al. 1987).

While biomass burning has been invoked to explain acidic precipitation in some parts of the tropics (Lewis 1981; Crutzen and Andreae 1990; Lacaux et al. 1992), the relatively low $H^+$ concentration (relatively high pH) of rain collected at Senga Bay indicates that, at present, burning is not resulting in acidic precipitation on the lake. Similarly high pH measurements have been made for rain collected in other parts of East Africa (Visser 1961; Rodhe et al. 1981). The persistence of high pH appears to be due to the presence of alkaline buffer, probably $HCO_3^-$, associated with various base cations, $Ca^{2+}$, $K^+$ and $Na^+$.

**Seasonality of Rainfall and Chemical Composition**. The central and southern regions of Lake Malawi/Nyasa experience a well defined rainy season, commencing around late November or early December, and finishing around late March - early April (Fig. 3.2). Being closer to the equator, the northern region can experience two rainy seasons, the first being light and beginning in October, the second being heavier and extending from February to April or May. Average annual rainfall around the lake varies regionally, the general trend being less rain at the south of the lake and more at the north end. Using more than two decades of data (1954-1980) for more than 50 stations, Kidd (1983) calculated mean annual rainfall in the south (south of the Dwangsa watershed) to be 996 mm, that in the central area (Dwanga to Lufira watersheds) to be 1110 mm, and that in the north and northeastern area (Songwe to Ruhuhu watersheds) to be 1542 mm. Based on data for 16 lakeshore stations and one island station, Kidd (1983) estimated average annual rainfall directly on the lake to be 1414 mm. Rainfall measured at the Senga Bay lakeshore meteorological station was 996 mm during the 1996/97 rainy season, and 1400 mm during the 1997/98 rainy season, which is very close to the estimate for over-lake rainfall made by Kidd.

Carbon and sulphate deposition during measured rain events at Senga Bay are shown in Fig. 3.3 (no sulphate data are available for the 1997/98 rainy season). None of these components showed any strong temporal deposition trends within a season, although there is an apparent trend of increasing maximum DOC deposition through the 1996/97 rainy season. Mean wet PC deposition was similar in the two rainy seasons. DOC deposition, however, was significantly greater ($P<0.01$) in 1997/98 than in the previous rainy season (Table 3.3). This was due in part to larger rain events in 1997/98, and the fact that DOC deposition tends to increase with increasing rainfall (see below). However, the ratio of 1997/98 mean DOC deposition to 1996/97 mean DOC deposition was 2.85, whereas the ratio of mean rainfall per event between the two years is 1.38. The volume weighted mean rain DOC concentration during the 1996/97 rainy season was 45 μM, whereas the 1997/98 mean was 102 μM, indicating that the increased deposition in the second rainy season was due more to higher DOC concentrations than to larger rainfall events.

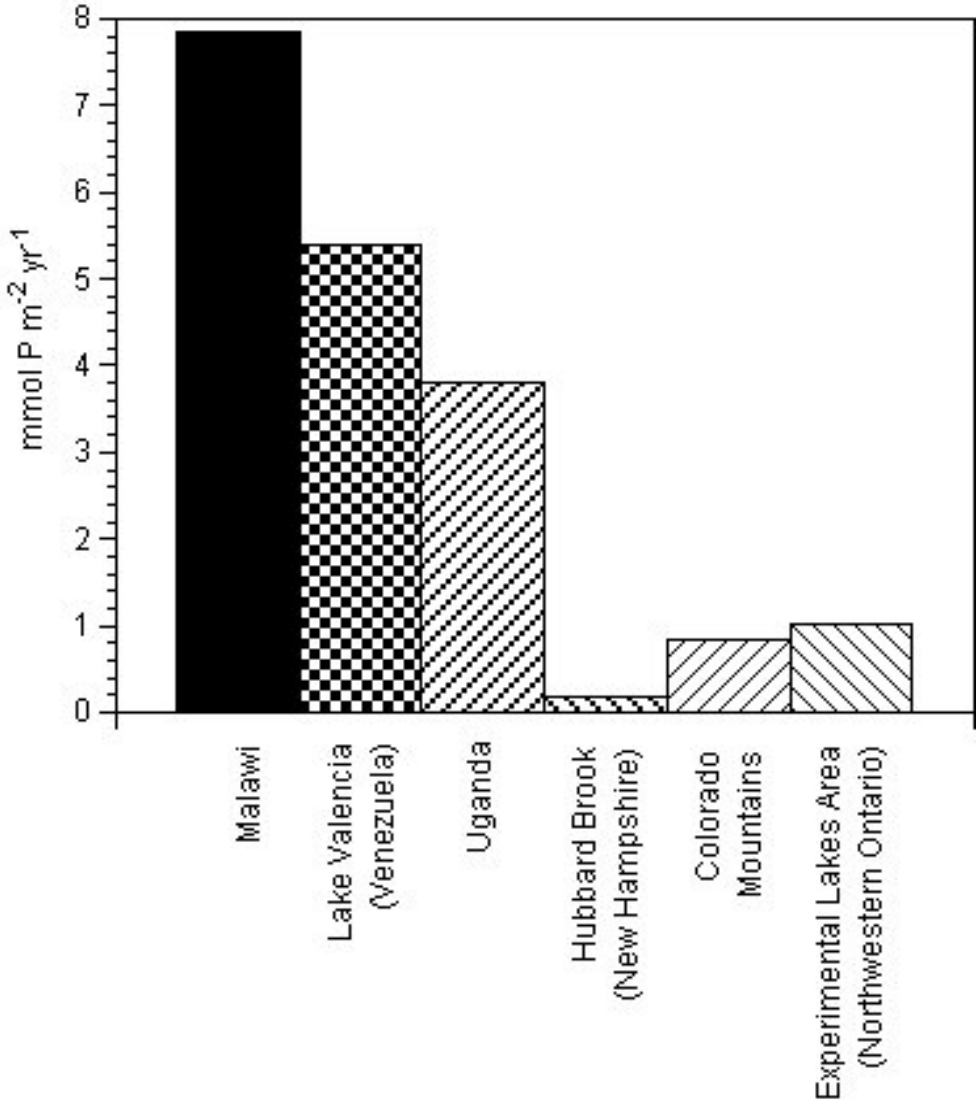


**Figure 3.1** A comparison of wet deposition rates for atmospheric phosphorus at various lakes and locations around the world.

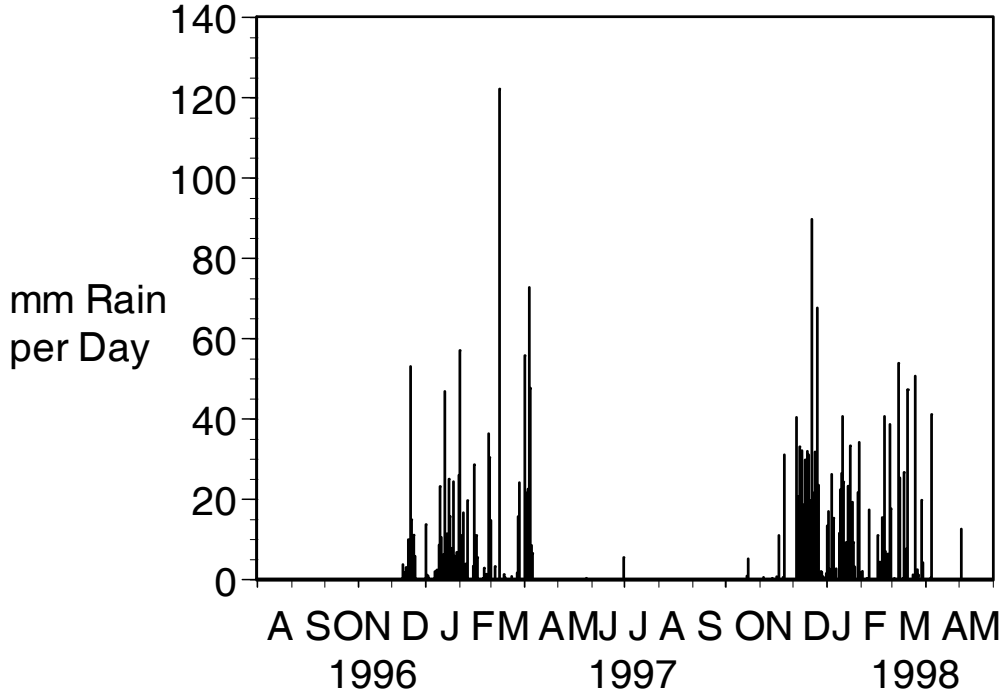


Fig. 3.2. Seasonality of rainfall at Senga Bay. Total rainfall in the 1996/97 rainy season was 996 mm. The total for the 1997/98 rainy season was 1400 mm.

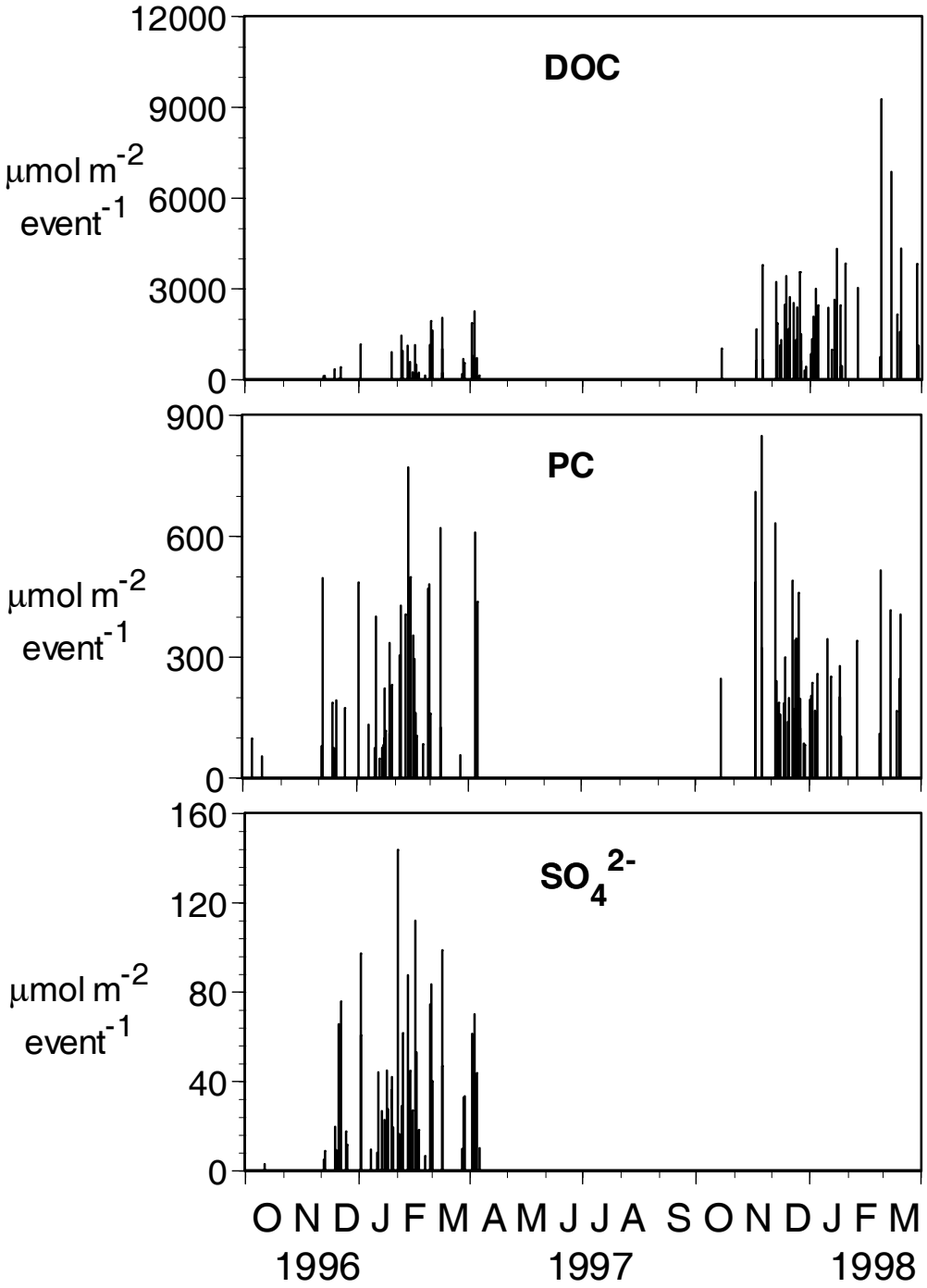


Fig. 3.3. Seasonality of wet carbon and sulphur deposition. Only sampled rain events are shown. $SO_4^{2-}$ data available for 1996/97 only.

**Table 3.3**. Comparison of rainfall and nutrient deposition at Senga Bay in two consecutive rainy seasons. All nutrient values are volume weighted mean μmol $m^{-2}$ $event^{-1}$. * indicates significantly different at P<0.05. The second SRP value for 1996/97 is the mean if three exceptionally high deposition rates are excluded.

| Component | 1996/97 | 1997/98 |
|---|---|---|
| Rain (mm $event^{-1}$) | 17.2 | 23.7 (P<0.06) |
| DOC | 766 | 2186 * |
| PC | 249 | 279 |
| $NO_3^-$- | 35 | 98 * |
| $NH_4^+$ | 75 | 59 |
| TDN | 332 | 260 |
| PN | 12.2 | 13.7 |
| SRP | 7.0 (2.9) | 4.53 (*) |
| TDP | 2.5 | 8.2 |
| PP | 0.88 | 1.44 |
| $Ca^{2+}$ | 41 | 33 |

Like DOC, $NO_3^-$ deposition was also significantly greater (P<0.01) the second year than the first (Fig. 3.4; Table 3.3). This was due primarily to higher rain $NO_3^-$ concentrations in the second rainy season (1996/97 VWM = 34.4 μM; 1997/98 VWM = 58.3 μM). $NH_4^+$ and PN deposition per event was similar in the two years (Fig. 3.4). There were insufficient TDN data to allow an assessment of TDN deposition seasonality (12 samples in each rainy season). A comparison of volume weighted mean TDN deposition rates between the two rainy seasons revealed no significant difference (Table 3.3).

The temporal pattern of SRP deposition was different in the first year than in the second (Fig. 3.5). In 1996/97 deposition rate was generally low, with the exception of three large deposition events. In contrast, deposition in the second year was generally higher than in the first, but less variable. If the three large SRP deposition events in 1996/97 are excluded from the analysis, SRP deposition in the second year was significantly greater than in the first (Table 3.2).

As for TDN, there were insufficient TDP measurements to allow assessment of temporal trends. Volume weighted TDP concentration was greater in the second year than in the first, as was TDP deposition rate (Table 3.3), but the variance within each rainy season was large, so that these differences were not statistically significant (P<0.12).

Due to several large deposition events, mean particulate phosphorus deposition was greater in the second year than in the first (Fig. 3.5; Table 3.3). The large events in the second year occurred at the beginning of the rainy season, and there was a general decline in PP deposition as the rainy season progressed (Fig. 3.5).

Calcium deposition exhibited no temporal trend within a rainy season, and was not significantly different between the two study years (Fig. 3.5, Table 3.3).

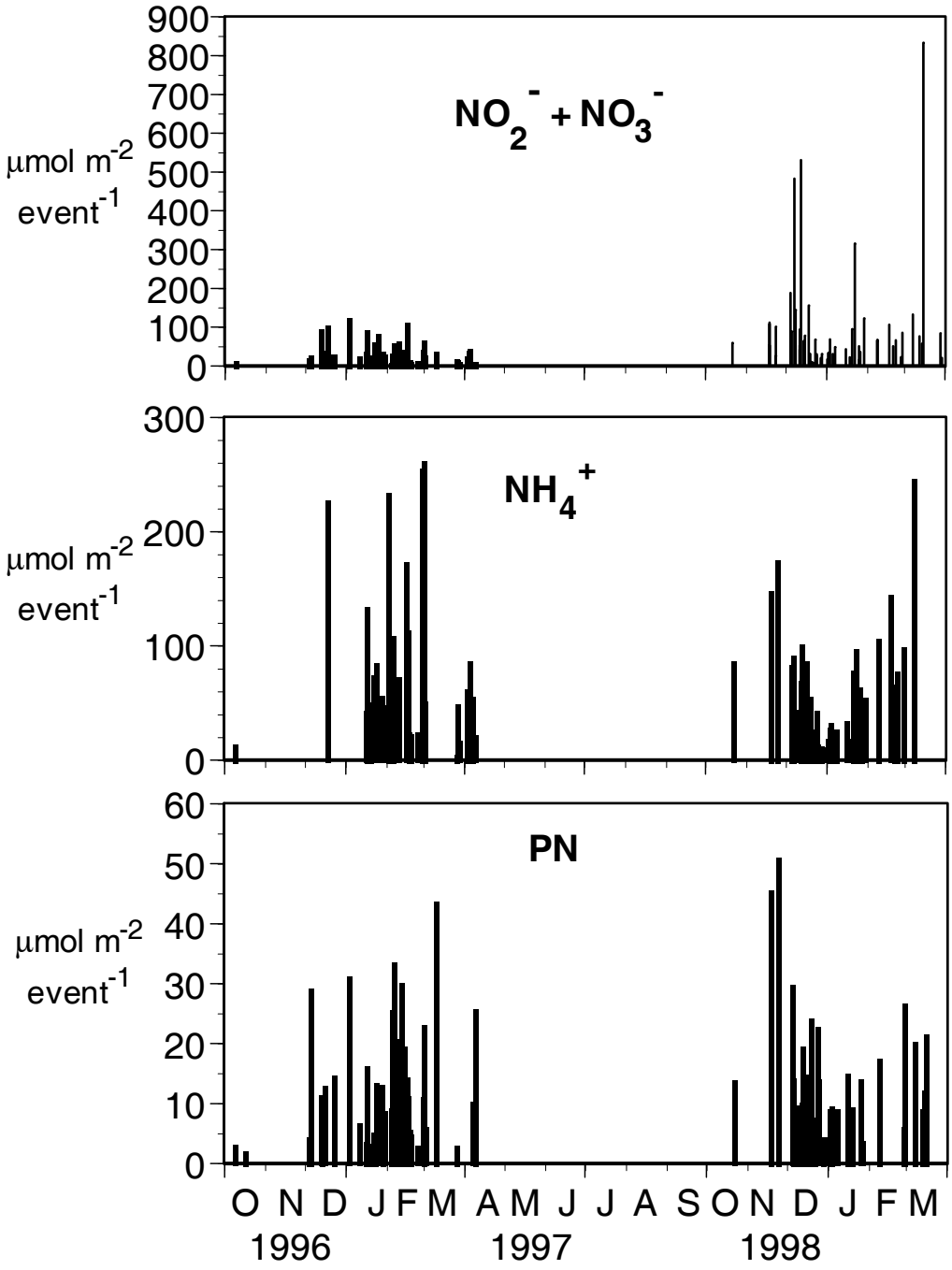


Fig. 3.4. Seasonality of wet N deposition. Not all rain events are shown.

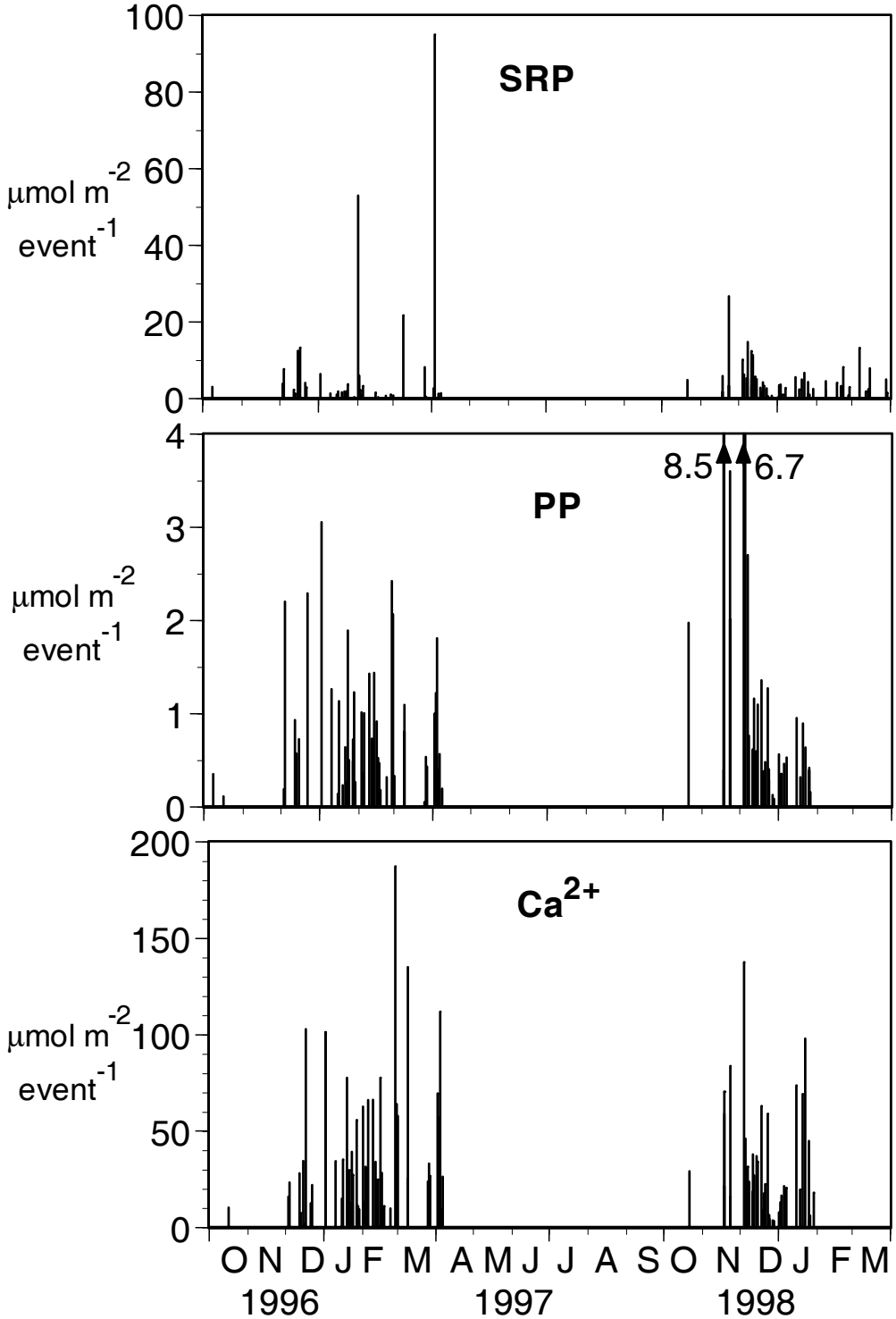


Fig. 3.5. Seasonality of wet P and $Ca^{2+}$ deposition. Not all rain events are shown.

**Relationship between areal deposition rate and rainfall**. In order to make valid temporal and spatial comparisons of nutrient deposition in rain, an understanding of the relationship between deposition and rainfall amount is required. For example, if the deposition of a particular component is proportional to rainfall amount, then greater deposition of that component in a certain year will simply be due to greater rainfall and will not necessarily reflect a change in atmospheric chemistry. This information also provides insight into possible mechanisms by which nutrients are put into and removed from the atmosphere. A trend of increasing deposition with increasing rainfall indicates that a compound is not readily stripped from the atmosphere, possibly due to a high abundance in the atmosphere and/or a low solubility. This is more likely to occur for atmospheric gases rather than for particulate material.

If deposition of a compound is not affected strongly by rainfall amount, then that compound is probably stripped from the atmosphere relatively quickly during a rainfall event. As rainfall volume increases, the concentration of the compound decreases. This is more likely to occur with particulates or highly soluble gases.

The relationship between areal deposition rate and rainfall amount for various nutrients is plotted in Figs. 3.6-3.8. A significant relationship between rainfall amount and deposition was observed for DOC, $SO_4^{2-}$ (Fig. 3.6), TDN (Fig. 3.7) and SRSi (Fig. 3.8). For all other components, no such relationship was observed, indicating that variability in their deposition was due more to variability of concentration than to rainfall amount.

Of particular interest is the difference in the DOC-rainfall relationship between the two rainy seasons (fig. 3.6). While a significant positive correlation was observed in both years, on average the DOC concentration for a given size of rainfall event was lower during the first year than during the second (Table 3.3; Fig. 3.6). None of the other components that displayed a rainfall-deposition correlation exhibited this interannual difference. Because DOC likely originates from terrestrial biota, it seems reasonable to consider whether differences in vegetation, and meteorological conditions controlling vegetation, might have caused the observed interannual difference. An examination of meteorological data collected at the Senga Bay laboratory indicates that several variables were significantly different between the two years. The temperature pattern during the 1996/97 rainy season was different than that in the 1997/98 season, but mean daily air temperatures during the two rainy seasons were very similar (Fig. 3.9). The most marked meteorological difference between the two years was observed for rainfall and humidity (Fig. 3.9). Not only was there much more rain in the 1997/98 rainy season, but the rains began about one month earlier than in the previous year. By mid-January of 1997/98, more than 4 times the amount of rain had fallen at Senga Bay than at the same time in the previous rainy season. While the suggestion of a link between rainfall, vegetative production, and DOC release to the atmosphere is based on circumstantial evidence, the data indicate that future research of this possible mechanism may be of interest.

**Spatial Variation of Wet Deposition**. One of the objectives of monitoring atmospheric nutrient deposition is to combine the resultant data with measurements of nutrient fluxes from other sources in order to construct a whole lake nutrient budget. For a lake as large as Lake Malawi/Nyasa, it is conceivable that atmospheric deposition of nutrients may vary spatially, and therefore some measure of how deposition measured at Senga Bay compares with other locations is required to determine how applicable the Senga Bay data will be for the purpose of constructing a nutrient budget.

Measured wet deposition rates of carbon, nitrogen and phosphorus at Senga Bay, Nkhata Bay and Kyela are presented in Fig. 3.10. For almost all the compared components, concentrations at Nkhata Bay and Kyela were similar to or greater than those measured at Senga Bay. The greatest differences were for particulate nutrients, which were 2.9 to 7.5 times greater in concentration at Nkhata Bay than at Senga Bay. The most likely cause of these differences is the fact that both the Nkhata Bay and Kyela sampling stations are located farther away from the lake than the Senga Bay station is, so that atmospheric conditions at these stations are influenced more by terrestrial vegetation, aeolian (wind-driven) soil suspension, and agricultural activities. In general, the deposition of particulate nutrients,

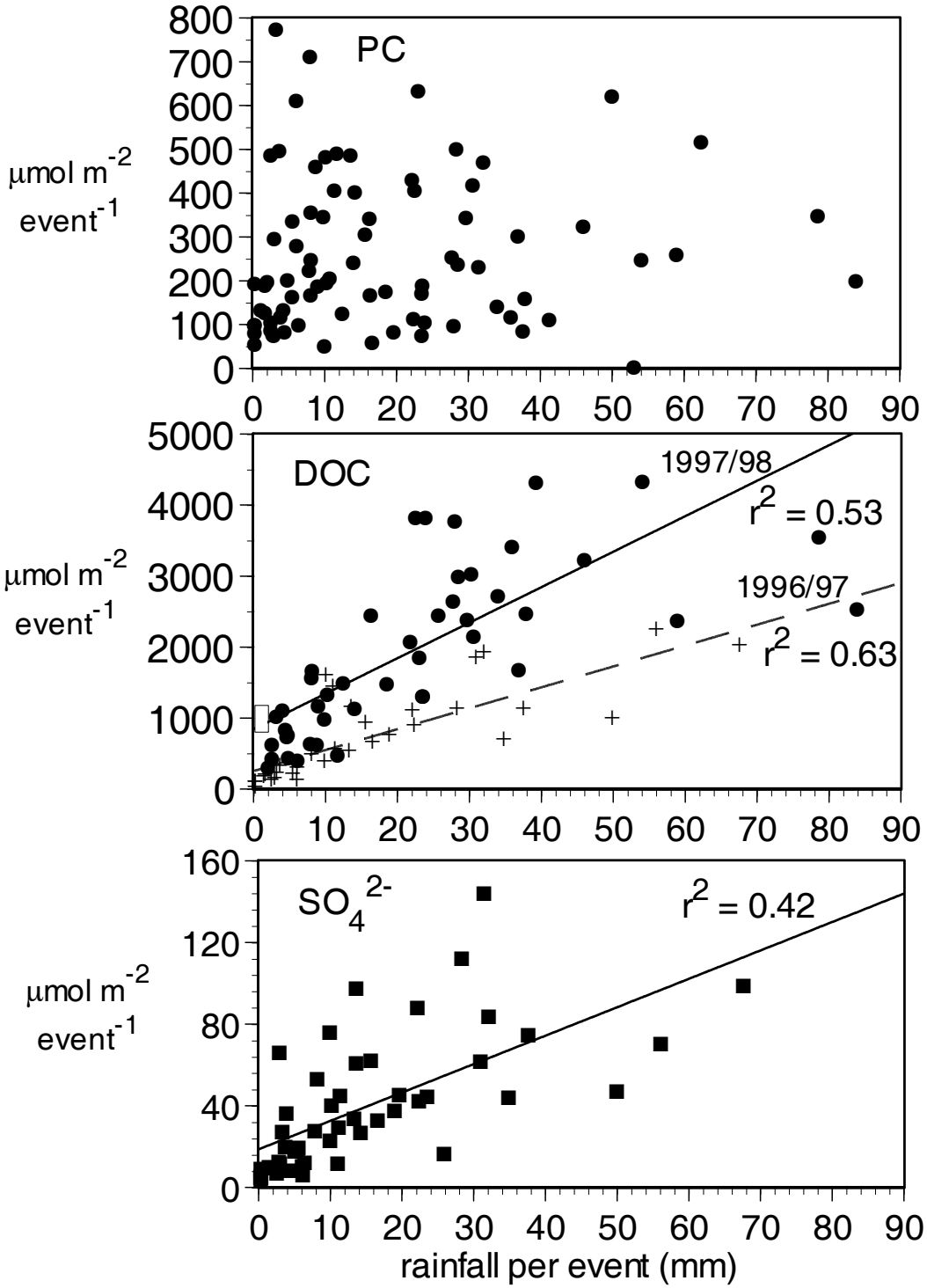


Fig. 3.6. Arial carbon and sulphate deposition related to rainfall.

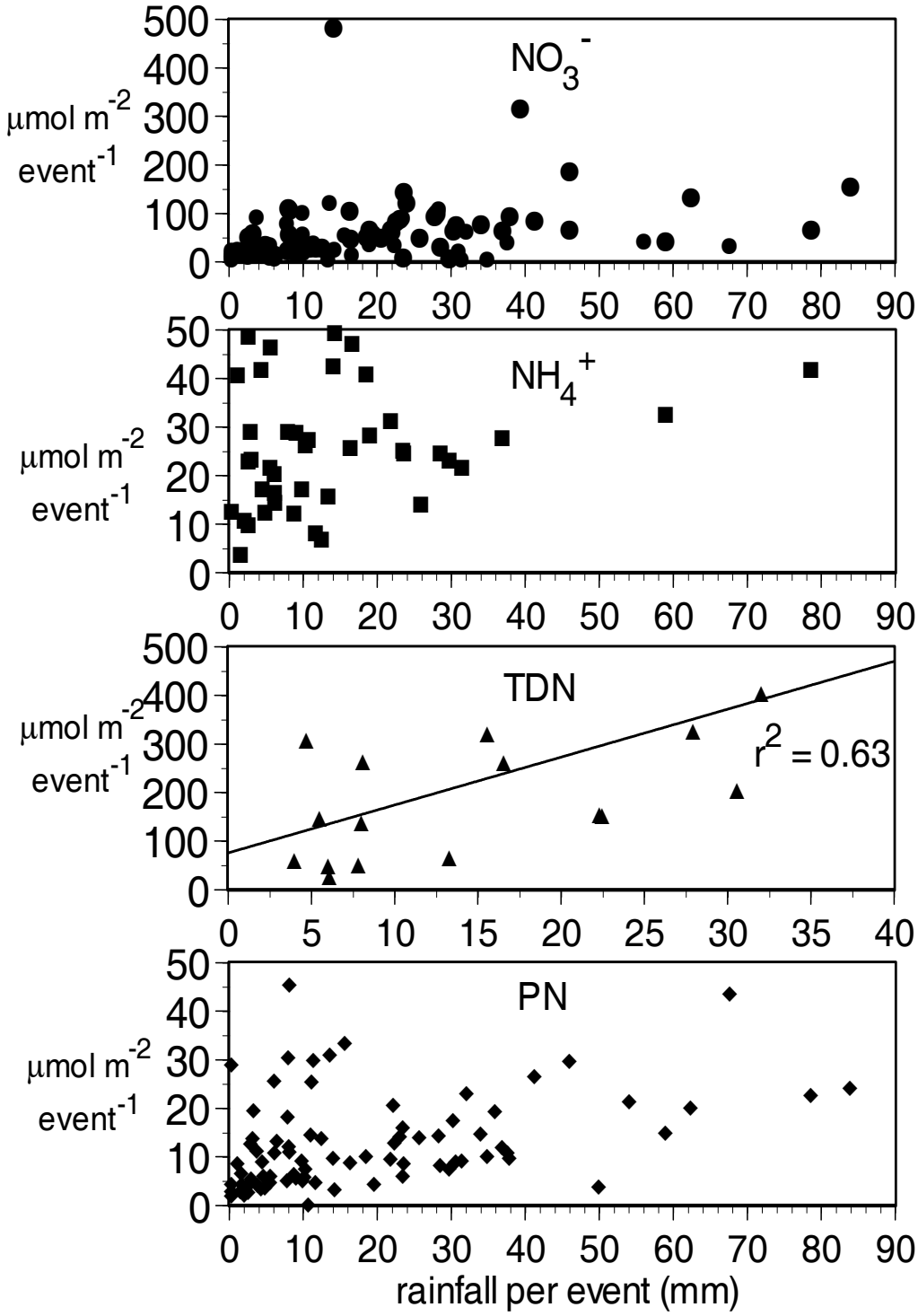


Fig. 3.7. Arial nitrogen deposition related to rainfall.

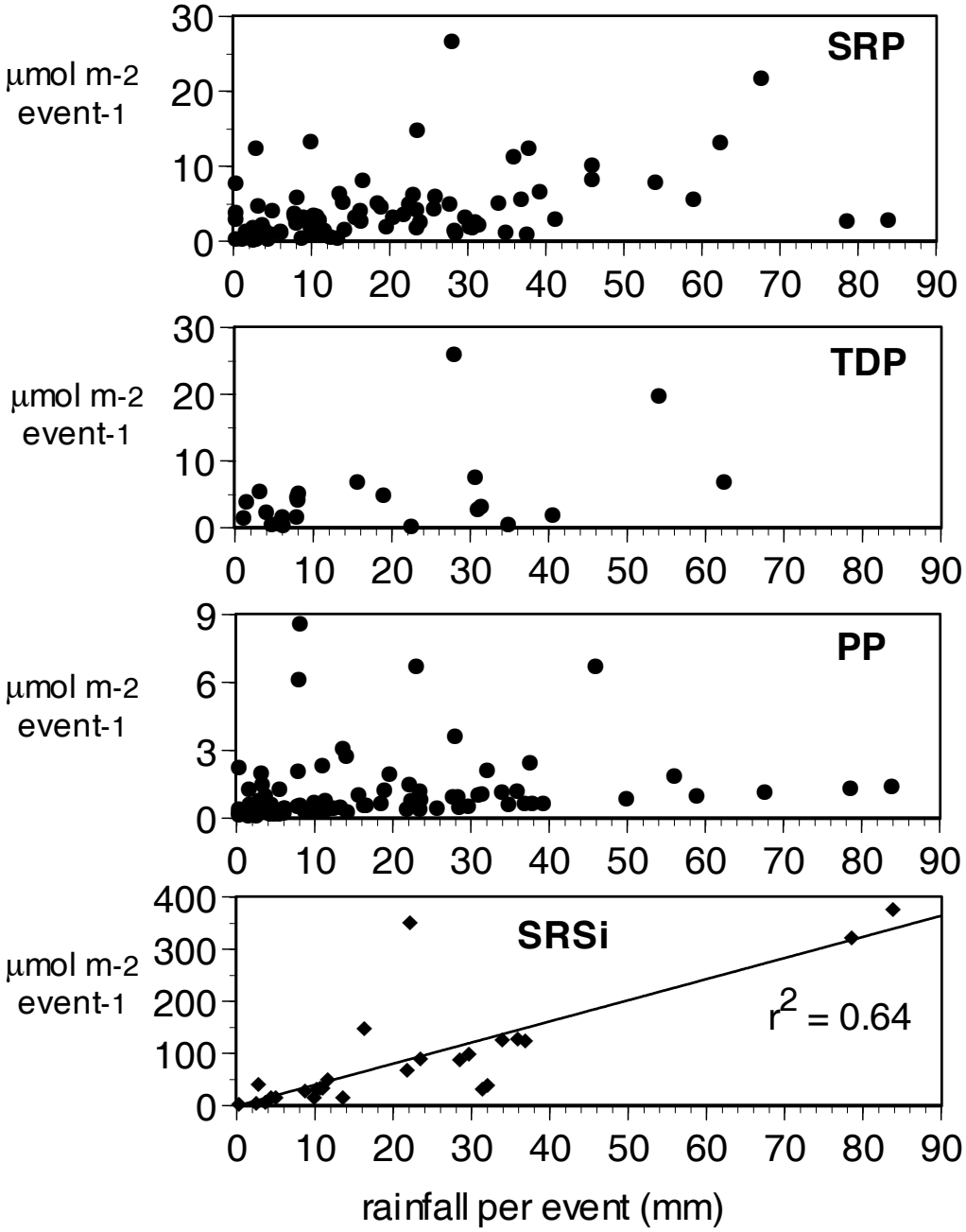


Fig. 3.8. Arial phosphorus and soluble reactive silicon deposition related to rainfall.

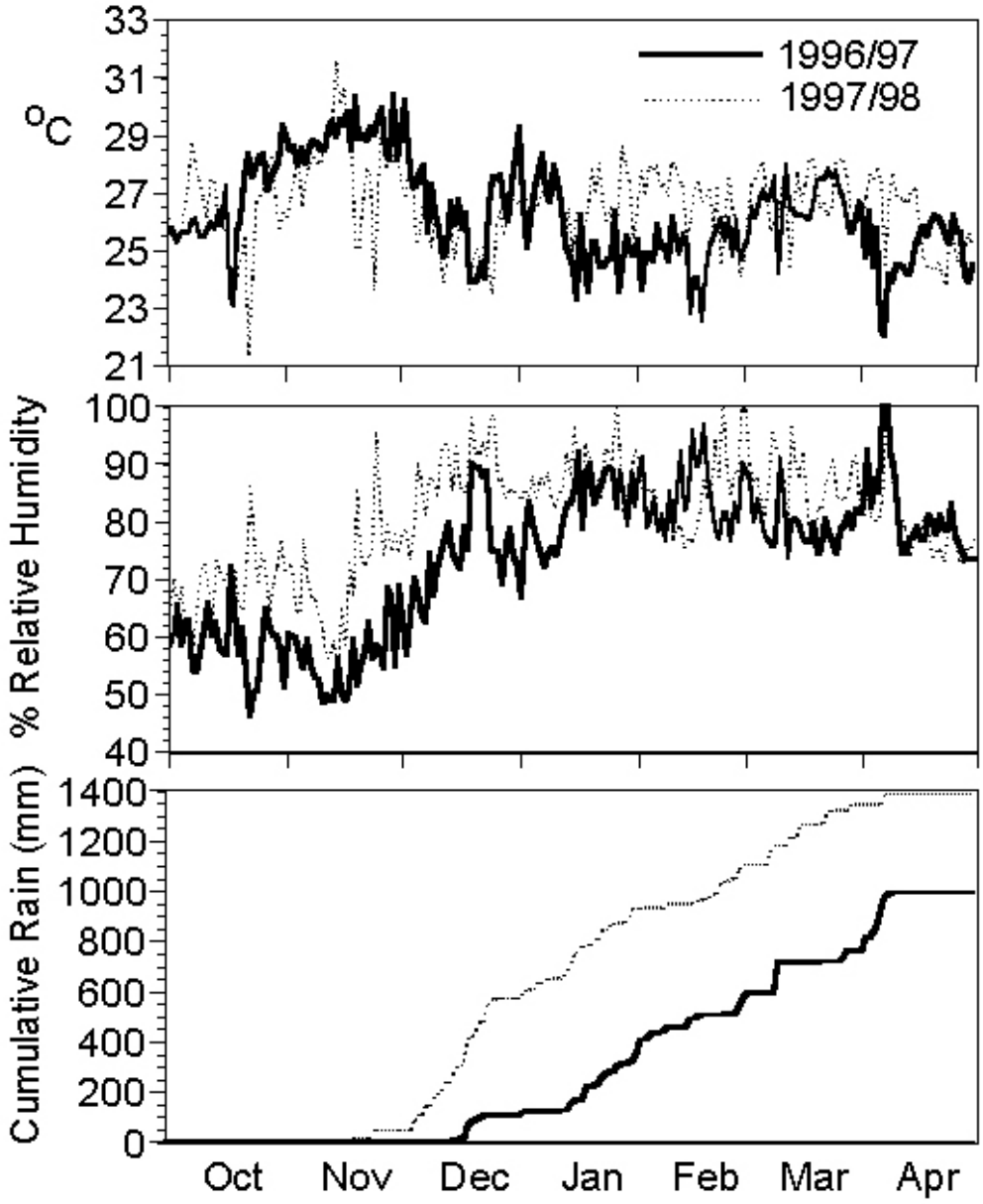


Fig. 3.9. Comparison of weather conditions during two rainy seasons at Senga Bay.

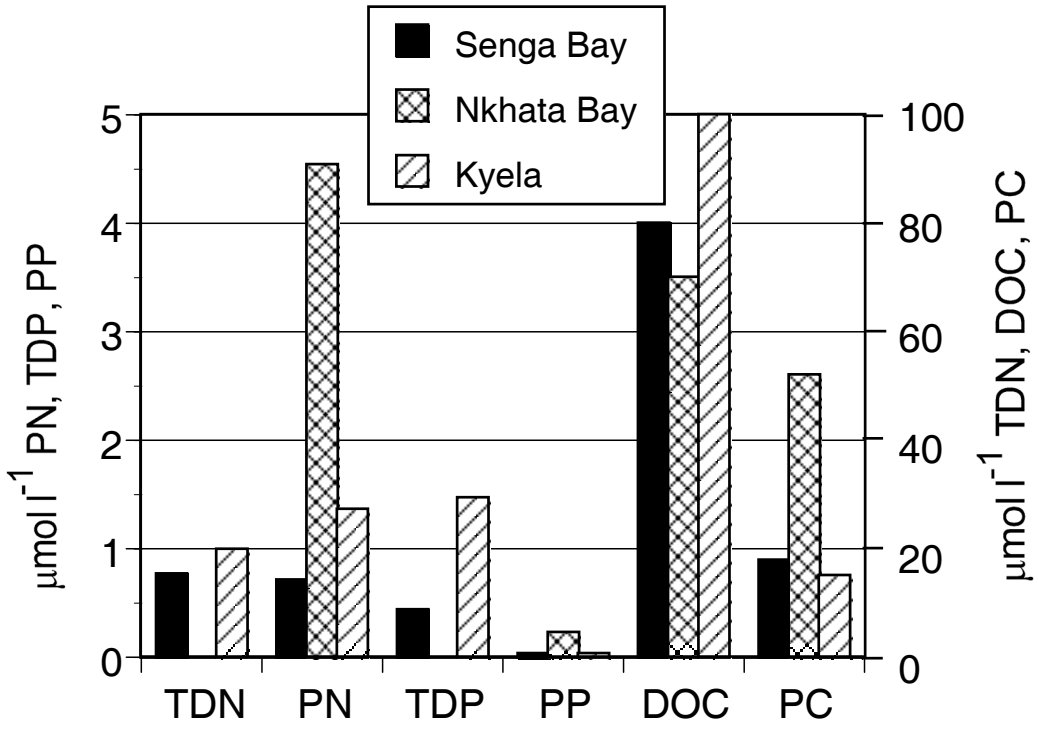


Fig. 3.10. Comparison of wet nutrient deposition at three sites Malawi/Nyasa. Bar height represents 50 percentile value. Periods collection are as follows. Senga Bay: October 1996 - April 1998; March - July 1997; Nkhata Bay: January - February 1997. No TDN or data are available for Nkhata Bay.

and some dissolved nutrients, over a lake can be expected to decrease with distance from shore (Cole et al. 1990).

During both the 1996/97 and 1997/98 rainy seasons, winds were predominantly from the south. The average wind direction for the period of December 1 to March 31 was 185$^o$ (from SSE to NNW) in 1996/97 and 186$^o$ in 1997/98. Travelling in this direction, air would pass almost 50 km over the southwest arm of the lake before reaching Senga Bay. Data from Likoma Island indicate that at that location, the prevalent wind direction was 158$^o$ in both years. If this direction is applied to the northern half of the lake, and the direction measured at Senga Bay is applied to the southern half, then about half of the lake surface is 50 km or less downwind from shore, in which case the Senga Bay station can be considered to represent mean conditions over the lake with regard to wind travelling distance from shore, even though the station is located on shore. This, and the absence of any huge discrepancies in dissolved nutrient concentrations in rain at the three different stations, suggests that measurements of wet deposition at Senga Bay can be considered to reasonably represent deposition over the lake as a whole.

**Dry Deposition**. Accurate measurements of dry nutrient deposition are technically more difficult to make than those of wet deposition. Dry deposition is influenced primarily by two factors: atmospheric concentration, and turbulence at the air-water interface. Because turbulent conditions above a sampling bucket on a beach can be different than conditions over an open lake, dry deposition over the bucket may not be the same as that over the lake. However, in the absence of an expensive, labour-intensive dry deposition monitoring programme, the method used in this study results in more meaningful measurements than the commonly used bulk collection method, and is useful in that it provides an estimate of the relative importance of dry deposition in comparison to other nutrient inputs. A similar approach has been used in the few other studies in which dry deposition of nutrients on lakes have been measured (Lewis 1983; Cole et al. 1990).

Dry deposition of DOC was highly variable, ranging from -7 to 17 mmol C $m^{-2}$ $day^{-1}$ (Fig. 3.11). On four occasions the DOC concentration after 24 hours of exposure was less than the initial concentration. This difference may represent either a real flux from the filtered water to the atmosphere, or conversion of DOC to PC by microbial processes during the incubation period. The occasional decrease in $NO_3^-$ (Fig. 3.12) and SRP (Fig. 3.13) during a sample period indicates that some microbial activity probably occurred in the collection buckets. In this case, flux estimates of total carbon, total nitrogen and total phosphorus will not be affected, since the lost dissolved portion will be accounted for in the particulate portion. The potential for conversion of dissolved nutrients to particulates suggests that dissolved fluxes may be slightly underestimated on some occasions. However, in some cases (e.g. the negative flux of DOC in January 1998), the increase in particulate nutrient is insufficient to account for the loss of dissolved nutrient, and the observed negative flux (loss to the atmosphere) may be real.

As for carbon, deposition of the dissolved species of nitrogen was more variable than that of particulate N (Fig. 3.12). Dry deposition of $NO_3^-$ was generally greater than dry $NH_4^+$ deposition. However, because $NH_4^+$ is susceptible to oxidation to $NO_3^-$, it is safer to combine the two species to derive an estimate of dissolved inorganic nitrogen (DIN) deposition. Only 9 measurements of dry TDN deposition are available. TDN deposition was variable, and generally several times greater than DIN deposition. PN deposition was similar in magnitude to DIN deposition.

Dry TDP deposition was generally several times greater than dry SRP deposition, while TDP and PP deposition were similar in magnitude (Fig. 3.13).

For both N and P, mean total dissolved deposition rates were several times greater than dissolved inorganic deposition rates, indicating that much of the dry deposition is in soluble organic form. For each of these nutrients, soluble organic deposition (total dissolved minus dissolved inorganic) was similar in magnitude to particulate deposition. However, this does not necessarily indicate that atmospheric gaseous organic concentrations are similar to particulate concentrations, since some or all of the measured dissolved organic portion may represent particulate nutrients that have dissolved after deposition.

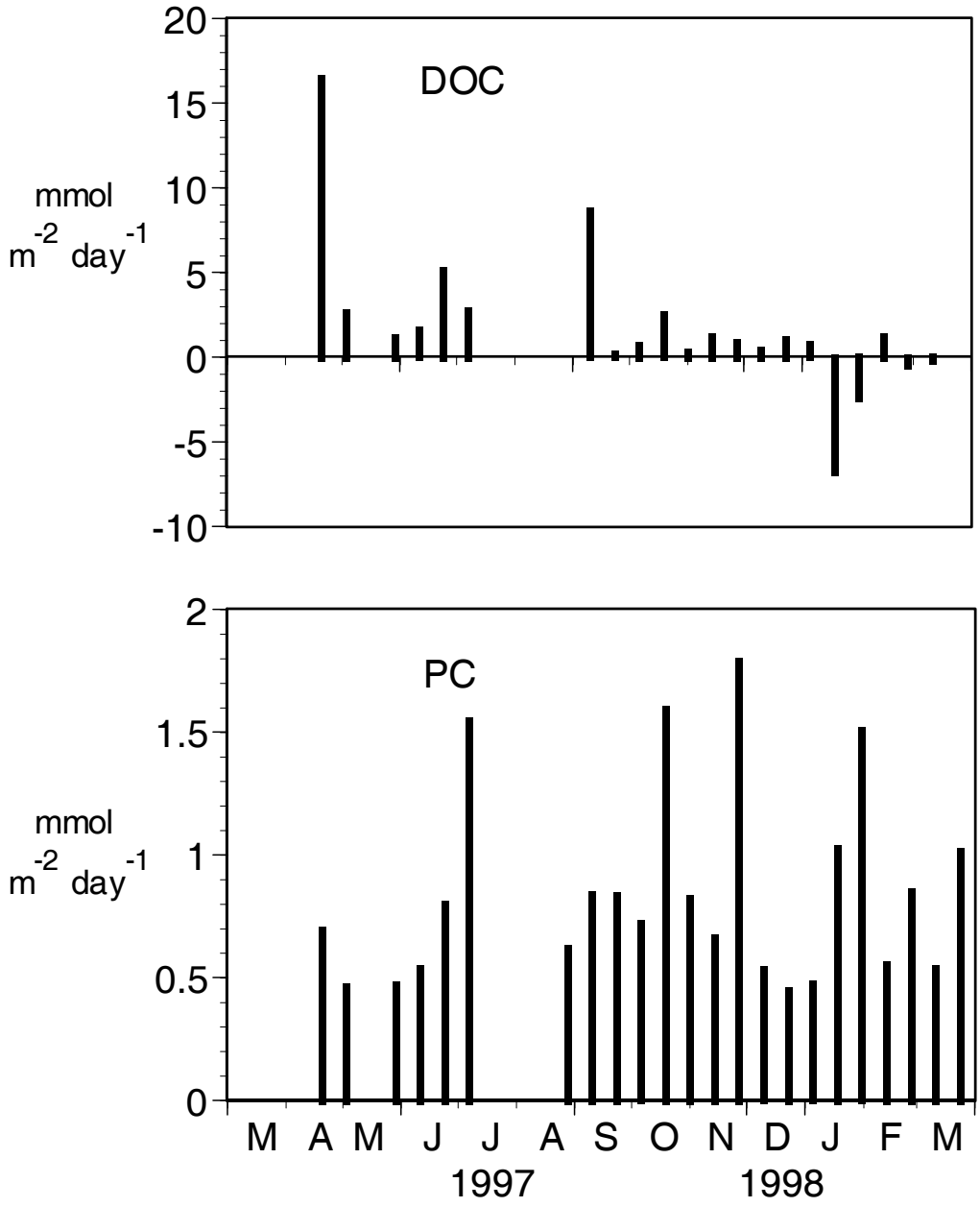


Fig. 3.11. Dry deposition of dissolved organic and particulate carbon.

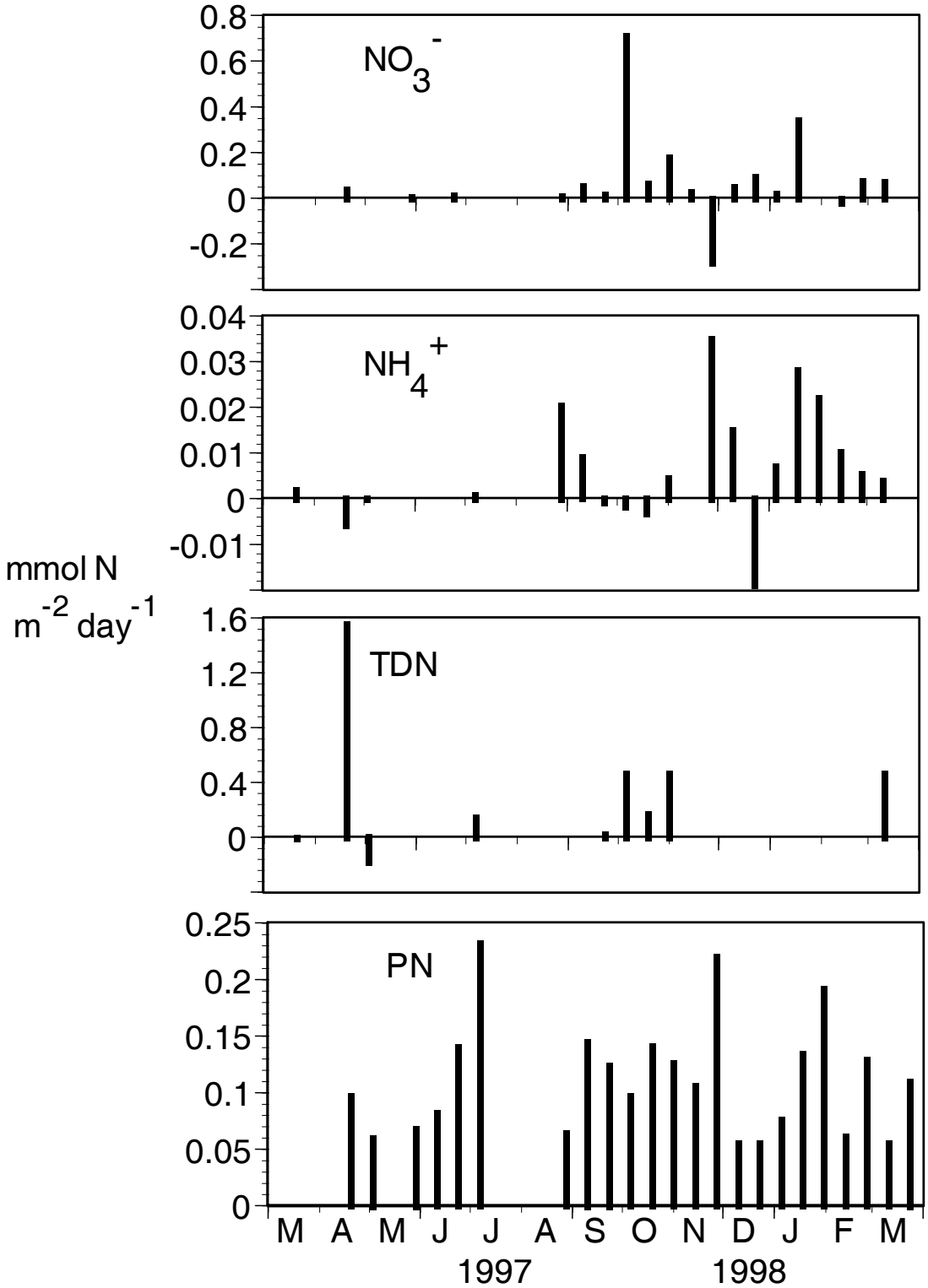


Fig. 3.12. Dry deposition of nitrogen at Senga Bay.

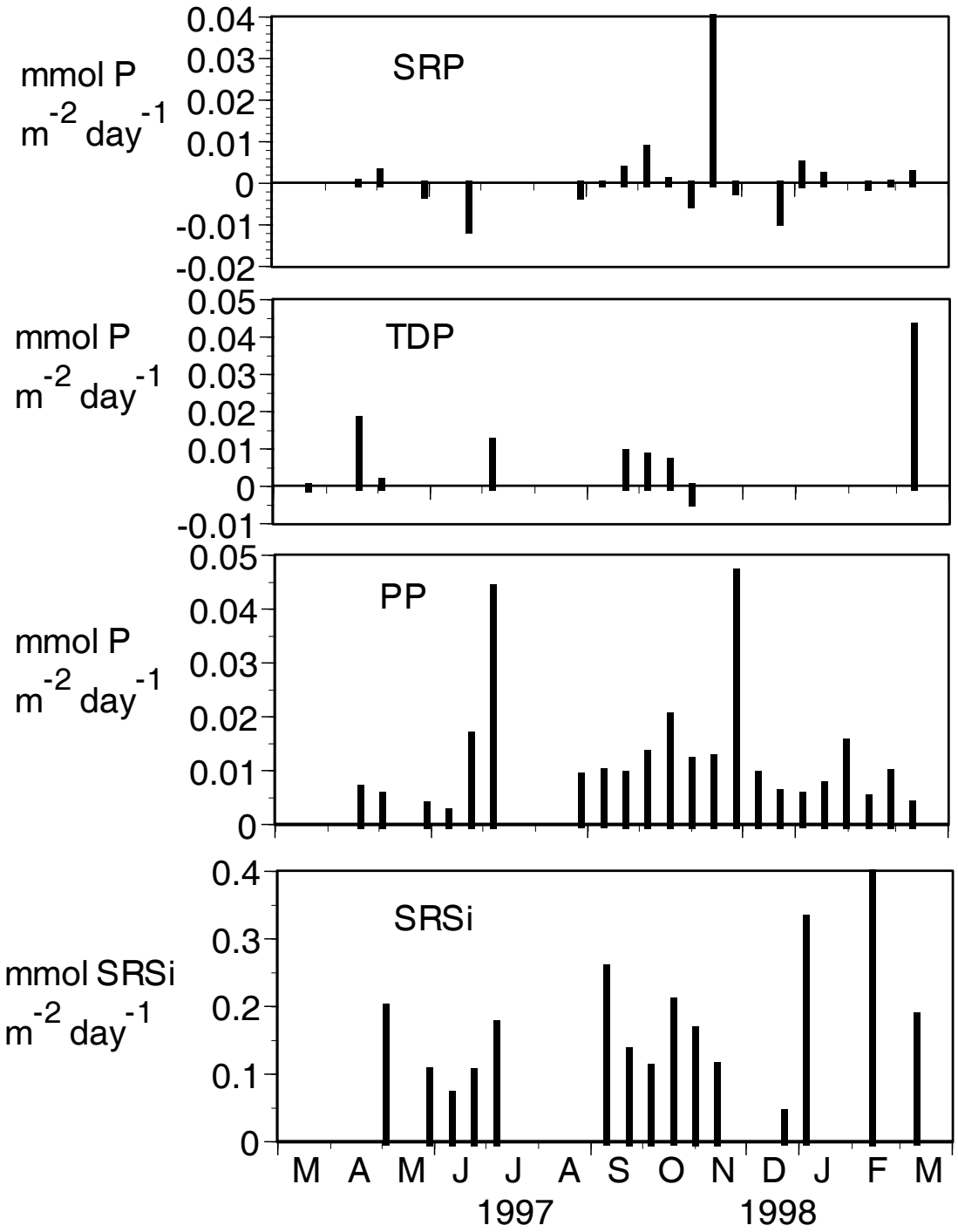


Fig. 3.13. Dry deposition of phosphorus and soluble reactive silica at Senga Bay.

Dry deposition rates of soluble reactive silica were always low, and showed no obvious seasonality (Fig. 3.13).

Dry deposition rates of particulate C, N and P were all significantly correlated to each other (Fig. 3.14). There was no correlation between dry particulate Si deposition and dry deposition of particulate C, N or P (although only 8 measurements of dry PSi deposition were made).

A summary of dry deposition measurements is presented in Table 3.4. Dry carbon deposition was primarily in the form of soluble organic carbon. Likewise, dry nitrogen deposition was dominated by soluble organic nitrogen (TDP minus $NO_3^-$ minus $NH_4^+$). Mean soluble organic phosphorus deposition (TDP minus SRP) was slightly less than particulate P deposition.

**Table 3.4**. Summary of measured dry deposition rates at Senga Bay. Mean units are µmol $m^{-2}$ $day^{-1}$. Total represents total of all deposition measurements (mmol $m^{-2}$). Days indicates the number of days for which measurements were made. Note that dry $SO_4^{2-}$ deposition was measured on one occasion only.

| | DOC | PC | $NO_3^-$ | $NH_4^+$ | TDN | PN | SRP | TDP | PP | SRSi | PSi | $SO_4^{2-}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 1727 | 842 | 99 | 7.0 | 343 | 112 | 1.7 | 10.5 | 12.5 | 103 | 52 | 174 |
| St.Dev. | 4309 | 400 | 283 | 12.8 | 510 | 51 | 10.3 | 14.0 | 11.6 | 199 | 43 | |
| Total | 38 | 19.4 | 1.97 | 0.13 | 3.09 | 2.57 | 0.032 | 0.094 | 0.276 | 1.96 | 0.42 | 0.174 |
| Days | 22 | 23 | 20 | 19 | 9 | 23 | 19 | 9 | 22 | 19 | 8 | 1 |

**Summary of Atmospheric Nutrient Deposition**. To estimate total annual wet and dry nutrient deposition, the following assumptions were made:

1. For nutrients that showed no positive correlation between deposition and rainfall amount, total measured wet deposition was factored to one rainy season by multiplying the total measured wet deposition (over two rainy seasons) by the ratio of the number of rain days in a season to the total number of rain days sampled. This is equivalent to multiplying the mean deposition rate per rain day by the number of rain days within a rainy season.
2. For nutrients that did show a positive correlation between deposition and rainfall amount, total measured wet deposition was factored to one rainy season by multiplying the total measured wet deposition by the ratio of total rainfall in a season to the total sampled rainfall. This approach accounts for the observation that a greater amount of rainfall results in a higher deposition rate of some nutrients (DOC, $SO_4^{2-}$, TDN and SRSi). By including the data from both rainy seasons in the factoring, interannual differences are averaged.
3. Dry deposition on rain days (when rainfall is greater than 0.5 mm) is accounted for in the measurement of wet deposition.
4. Annual dry deposition of a component was determined as the mean daily dry deposition times the total number of dry days per year.
5. Because there was a higher density of data following the 1996/97 rainy season, the period of May 1997 to the end of April 1998 was chosen to represent one annual cycle. During this period there were 81 rain days (with rainfall greater than 0.5 mm) and 284 dry days. Total rainfall at Senga Bay during this period was 1400 mm.

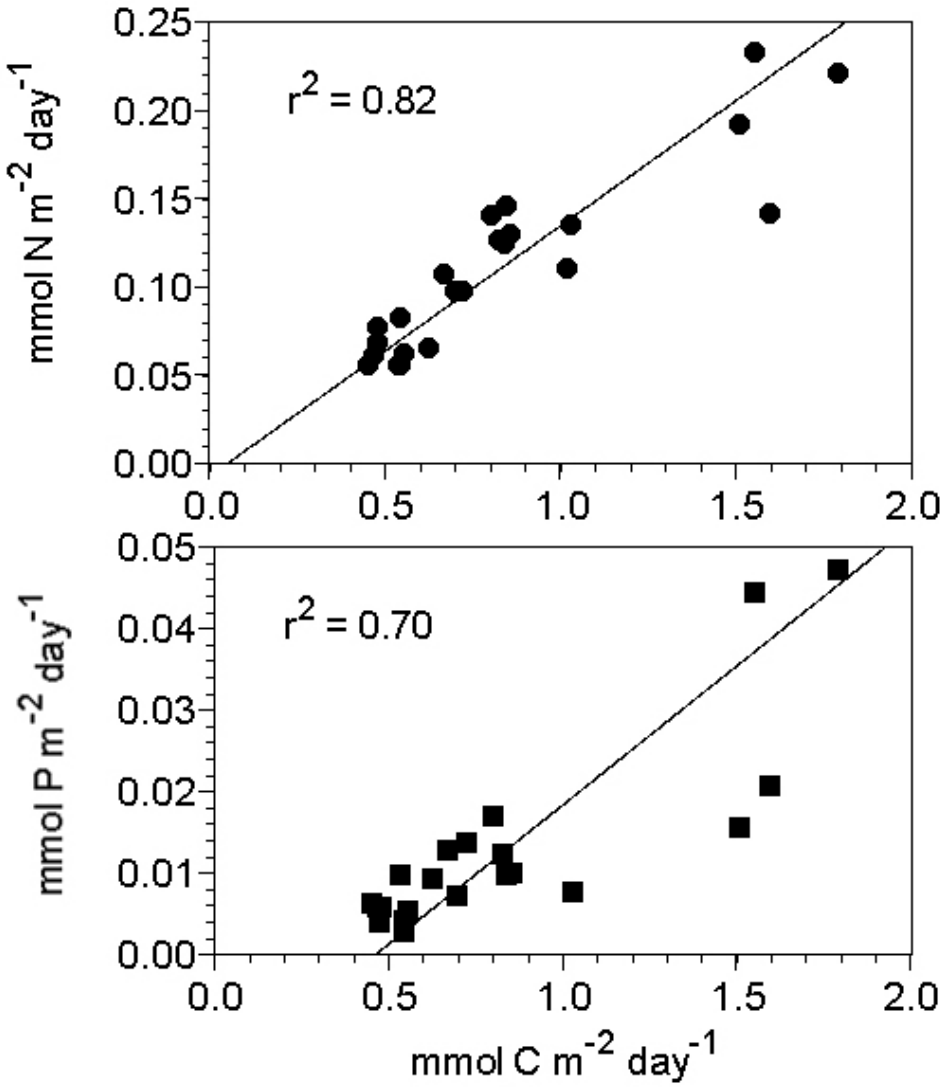


Figure 3.14 Relationship between dry deposition of various particulate nutrients.

(Table 3.5 is placed her in the chapter but can be located at the end of this file.)

A summary of wet and dry deposition rates, calculated based on the above criteria, is presented in Table 3.5. A comparison of the daily dry deposition rates in Table 3.5 with rain event deposition rates (Table 3.3) reveals that for $NO_3^-$, TDN, TDP and DOC, daily dry deposition was similar in magnitude to deposition during a rain event. In contrast, particulate C, N and P all exhibited much higher daily dry deposition rates than daily wet deposition rates. This may be due to less atmospheric suspension of particles during the rainy season, when the ground is wetter and there is greater vegetation cover. Daily wet deposition of $NH_4^+$ and SRP was greater than daily dry deposition.

If the various forms of C, N and P are added to determine total C, N and P deposition, then daily carbon and nitrogen deposition are quite similar in the rainy and dry seasons, while daily phosphorus deposition is almost two times greater in the dry season than in the rainy season (Table 3.6). This is due primarily to the greater daily particulate P deposition during the dry season, and the fact that particulate deposition is a larger proportion of total P deposition than C or N deposition, for which the soluble forms are more significant. Because the daily dry deposition rates of most measured components were similar to or greater than daily wet deposition rates, and because there are more dry days (approximately 3.5 times) than wet days, on an annual basis dry deposition is much greater than wet deposition.

## Conclusions

1. A large portion of atmospheric carbon and nitrogen deposition on the lake is in the form of soluble organic compounds. Soluble and particulate phosphorus deposition are similar in magnitude, with much of the soluble P being organic.
2. Atmospheric deposition of nutrients can vary significantly between years. Considering the relative ease with which an atmospheric deposition monitoring programme can be maintained, a long term monitoring programme is highly desirable.
3. Atmospheric deposition of nutrients on to the lake surface is primarily in the form of dry deposition.
4. While the concentration of solutes and particulates in rain near Lake Malawi/Nyasa are not particularly high relative to industrial regions or some other parts of Africa, higher than average $NH_4^+$:cation ratios, $NO_3^-$:anion ratios, and $K^+$ concentration suggest that burning is having a signifi-cant effect on atmospheric chemistry around the lake. High P deposition rates may also be linked to burning. Although, the direct effect of the deposition of these solutes on the lake may not be deleterious, the burning and soil exposure (as suggested by elevated $Ca^{2+}$ concentrations in rain) that these observations reflect may potentially result in detrimental impacts on the lake, such as siltation, accelerated flux of nutrients from soil to the lake, and a decreased and more variable water supply from rivers. In this regard, monitoring of atmospheric deposition is not only relevant to the study of lake nutrient cycles; it can also be used as an index of changes in land use around the lake.

**Table 3.6**. Comparison of daily dry deposition and wet deposition of carbon, nitrogen, phosphorus and silicon.

| | Total C | Total N | Total P | Total Si |
|---|---|---|---|---|
| Mean Wet Dep. ($\mu$mol $m^{-2}$ $event^{-1}$) (1997/98) | 2465 | 431 | 14.2 | 115 |
| Mean Dry Dep. ($\mu$mol $m^{-2}$ $day^{-1}$) | 2570 | 560 | 24.7 | 155 |

## References

Andreae, M.O. 1993. Global distribution of fires seen from space. EOS 74: 129-135.

Andreae, M.O., E.V. Browell, M. Garstang, G.L. Gregory, R.C. Hariss, G.F. Hill, D.J. Jacob, M.C. Pereira, G.W. Sachse, A.W. Setzer, P.L. Silva Dias, R.W. Talbot, A.L. Torres, and S.C. Wofsy. 1988. Biomass burning emissions and associated haze layers over Amazonia. Journal of Geophysical Research 93: 1509-1527.

Bennett, E.B. 1986. The nitrifying of Lake Superior. Ambio 15: 272-275.

Bootsma, H.A., M.J. Bootsma, and R.E. Hecky. 1996. The chemical composition of precipitation and its significance to the nutrient budget of Lake Malawi. Pages 251-265 *In* T.C. Johnson and E.O. Odada (eds.), The Limnology, Climatology and Paleoclimatology of the East African Lakes. Gordon and Breach, Toronto.

Bromfield, A.R. 1974. The deposition of sulphur in rainwater in Northern Nigeria. Tellus 26: 408-411.

Bromfield, A.R., D.F. Debenham, and I.R. Hancock. 1980. The deposition of sulphur in rainwater in central Kenya. Journal of Agricultural Science 94: 299-303.

Cole, J.J., N.F. Caraco, and G.E. Likens. 1990. Short-range atmospheric transport: A significant source of phosphorus to an oligotrophic lake. Limnology and Oceanography 35: 1230-1237.

Crutzen, P.J., and M.O. Andreae. 1990. Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. Science 250: 1669-1678.

Delmas, R. 1982. On the emission of caron, nitrogen and sulfur in the atmosphere during bushfires in intertropical savannah zones. Geophysical Research Letters 9: 761-764.

Galloway, J.N., G.E. Likens, W.C. Keene, and J.M. Miller. 1982. The composition of precipitation in remote areas of the world. Journal of Geophysical Research 87: 8771-8786.

Gaudet, J.J., and J.M. Melack. 1981. Major ion chemistry in a tropical African lake basin. Freshwater Biology 11: 309-333.

Jassby, A.D., J.E. Reuter, R.P. Axler, C.R. Goldman, and S.H. Hackley. 1994. Atmospheric deposition of nitrogen and phosphorus in the annual nutrient load of Lake Tahoe (California-Nevada). Water Resources Research 30: 2207-2216.

Kidd, C.H.R. 1983. A water resources evaluation of Lake Malawi and the Shire River. Malawi Technical Report (MLW/77/012), United Nations Development Programme, World Meteorological Organization. Geneva, Switzerland.

Lewis, W.M. Jr. 1981. Precipitation chemistry and nutrient loading by precipitation in a tropical watershed. Water Resources Research 17: 169-181.

Lewis, W.M. Jr. 1983. Collection of airborne materials by a water surface. Limnology and Oceanography 28: 1242-1246.

Linsey, G.A., D.W. Schindler, and M.P. Stainton. 1987. Atmospheric deposition of nutrients and major ions at the Experimental Lakes Area in northwestern Ontario, 1970 to 1982. Canadian Journal of Fisheries and Aquatic Science 44 (Suppl. 1): 206-214.

Manny, B.A., and R.W. Owens. 1983. Additions of nutients and major ions by the atmosphere and tributaries to nearshore waters of northwestern Lake Huron. Journal of Great Lakes Research 9:403-420.

Munger, J.W. 1982. Chemistry of atmospheric precipitation in the North-Central United States: Influence of sulfate, nitrate, ammonia and calcareous soil particles. Atmospheric Environment 16: 1633-1645.

Paerl, H.W. 1993. Emerging role of atmospheric nitrogen deposition in coastal eutrophication: Biogeochemical and trophic perspectives. Canadian Journal of Fisheries and Aquatic Science 50: 2254-2269.

Peierls, B.L, and H.W. Paerl. 1997. Bioavailability olf atmospheric organic nitrogen deposition to coastal phytoplankton. Limnology and Oceanography 42: 1819-1823.

Rodhe, H., E. Mukolwe, and R. Söderlund. 1981. Chemical composition of precipitation in East Africa. Kenya Journal of Science and Technology (Ser. A) 2: 3-11.

Scheider, W.A., W.R. Snyder, and B. Clark. 1979. Deposition of nutrients and major ioins by precipitation in South-Central Ontario. Water, Air and Soil Pollution 9: 309-314.

Schindler, D.W., R.W. Newbury, K.G. Beaty, and P. Campbell. 1976. Natural water and chemical budgets for a small precambrian lake basin in central Canada. Journal of the Fisheries Research Board of Canada 33: 2526-2543.

Visser, S. 1961. Chemical composition of rain water in Kampala, Uganda, and its relation to meteorological and topographical conditions. :Journal of Geophysical Research 66: 3759-3765.

Vollenweider, R.A. 1979. Das Nährstoffbelastungskonzept als Grundlage für den externen Eingriff in den Eutrophierungsprozess stehender Gewässer und Talsperren. Z. Wasser-u. Abwasser-Forschung 12: 46-56.

**Table 3.5**. Summary of wet and dry chemical deposition rates measured at Senga Bay. Annual deposition estimates are for the period May 1, 1997 to April 30, 1998.

| | | $NO_3^-$ | $NH_4^+$ | TDN | PN | SRP | TDP | PP | DOC | PC | SRSi | PSi | $SO_4^{2-}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WET | Total Rainfall Sampled (mm) | 1851 | 1667 | 524 | 1538 | 1776 | 488 | 1750 | 1698 | 1506 | 567 | 1170 | 731 |
| | Sampled Events, 1996/97 | 46 | 36 | 13 | 43 | 42 | 12 | 48 | 35 | 42 | 10 | 16 | 51 |
| | Sampled Events, 1997/98 | 52 | 46 | 11 | 42 | 51 | 13 | 45 | 48 | 42 | 16 | 30 | 0 |
| | Vol. Weighted Mean (μM) | 3.59 | 3.16 | 13.1 | 0.71 | 0.28 | 0.78 | 0.06 | 84 | 14.6 | 3.95 | 0.42 | 1.89 |
| | Total Measured Dep. (mmol $m^{-2}$) | 6.64 | 5.26 | 6.87 | 1.09 | 0.50 | 0.38 | 0.1 | 143 | 21.9 | 2.24 | 0.49 | 1.93 |
| | Annual Wet Dep. (mmol $m^{-2}$ $y^{-1}$) | 5.49 | 5.20 | 18.4 | 1.04 | 0.43 | 1.23 | 0.09 | 118 | 21.1 | 5.53 | 0.86 | 3.70 |
| DRY | Total Dry Days Sampled | 20 | 19 | 9 | 23 | 19 | 9 | 22 | 22 | 23 | 19 | 8 | 1 |
| | Mean Dep. (μmol $L^{-1}$ $day^{-1}$) | 98.7 | 7.0 | 343 | 112 | 1.70 | 10.5 | 12.6 | 1727 | 842 | 103 | 52 | 174 |
| | Total Measured Dep. (mmol $m^{-2}$) | 2.27 | 0.16 | 3.28 | 2.57 | 0.065 | 0.10 | 0.28 | 48 | 19.4 | 2.61 | 0.42 | 0.174 |
| | Annual Dry Dep. (mmol $m^{-2}$ $y^{-1}$) | 28 | 2.0 | 97 | 32 | 0.48 | 2.97 | 3.56 | 491 | 239 | 29 | 14.7 | 49 |
| TOTAL | Total Annual Dep. (mmol $m^{-2}$ $y^{-1}$) | 33.5 | 7.2 | 116 | 33 | 0.92 | 4.2 | 3.65 | 608 | 260 | 35 | 15.6 | 53 |

| | C | N | P | Si | $SO_4^{2-}$ |
|---|---|---|---|---|---|
| Total Annual Dep. (mmol $m^{-2}$ $y^{-1}$) | 869 | 149 | 7.84 | 50 | 53 |