The Relationship Between Mixing and Stratification Regime on the Phytoplankton of Lake Bosomtwe (Ghana), West Africa

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Abstract

The seasonal changes in the phytoplankton community in terms of biomass composition and associated physicochemical parameters of the Lake Bosomtwe (Ghana) located in West Africa were studied between 2004 and 2006 to assess the mixing and stratification regime of the lake on the phytoplankton dynamics. From water samples obtained from a central index station, biomass composition was assessed by converting phytoplankton counts to wet weights-based approximation into cell volume values; whiles mixed layer and euphotic depths were analyzed using temperature and light profiles of the lake respectively. Total phosphorus was estimated using the Ascorbic Acid Method. Results from the dataset showed that the phytoplankton biomass was dominated by the Cyanophyceae throughout the study period despite the seasonal changes associated with the mixing and stratification regimes. There were significant inter-annual differences in the mean values of the euphotic depth and the wet weight biomass ($P < 0.05$). However differences in the mean values of the mixed layer depth, the ratio of the mixed layer depth:euphotic depth, and total phosphorus concentration ($P > 0.05$) were insignificant. High variations in the mixed layer depth (CV > 34 %) and the euphotic depth (CV > 32) drive similarly high variations in the wet weight biomass (CV > 28) as is the case for many stratifying tropical lakes. However, both were poor predictors of the phytoplankton wet weight biomass behaviour (mixed layer depth, $r^2 = 0.1034$; euphotic depth, $r^2 = 0.0632$) though they were more important drivers of the biomass than nutrient concentrations (total phosphorus concentration, $r^2 = 0.0113$).

Introduction

Phytoplanktons are the key primary producers in pelagic zone of lakes, rivers and the oceans. They are important in fish yield and water quality assessments as well as useful paleolimnological tools (Melack, 1976). They can form harmful blooms that can be toxic to both domestic animals and humans that depend on water use from such sources for domestic and recreational purposes. In addition, they may cause massive fish kills in natural waters and commercial fish farms (Hallegraeff, 1995).

Not much is known about this important biological community of the Lake Bosomtwe since studies in the past have mostly focused

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on the origin of the crater which the lake occupies, aspects of its geology and paleolimnology, hydrologic and hydrographic features (Junner, 1937; Jones *et al*., 1981; Koeberl *et al*., 1998; Turner *et al*., 1996; Puckniak *et al*., 2009). Earlier studies have paid attention to the biological community of zooplankton and fish of the lake (Whyte, 1975; Post *et al*., 2008). Post *et al* (2008) also discussed their relation to mercury biomagnification in a phytoplanktivorous cichlid, *Sarotherodon multifasciatus* and other fishes.

By their nature, phytoplanktons are regulated by the physicochemical and biological environment and this affects nutrient and light availability as well as zooplankton grazing rates (Lewis, 1978; Huisman *et al*., 2004; Carpenter *et al*., 1987). In Lake Bosomtwe, nitrate and orthosphosphate concentrations are reported to be above the level of nitrogen and phosphorus famine (Karikari and Bosque-Hamilton, 2004). Thus, these major nutrients do not limit the growth of phytoplankton of the lake. Consequently, in a closed basin lake like the Lake Bosomtwe, meteorology and its associated effects on the physicochemical environment of the lake water is expected to be the primary driver of the phytoplankton dynamics. Somehow, because of their microscopic size, phytoplanktons are greatly affected by the depth of mixing of the water in which they inhabit. The thickness of the mixed layer is ecologically important because it influences, in part, the availability of photosynthetically available irradiance, the nutrient recycling efficiency, and the rate of zooplankton grazing on phytoplanktons (Fogg, 1991; Carpenter *et al*., 1987). Formed from the impact of the meteorite that created its basin, Lake Bosomtwe is sheltered by crater walls which rise to a minimum of about 210 m above the lake surface making wind mixing severely curtailed for most part of the year (Puchniak *et al.,* 2009). But, during certain brief periods in August and sometimes in January each year, the lake mixes as a result of the lowering of atmospheric temperatures that drive evaporative cooling of epilimnetic waters. On an annual cycle, Lake Bosomtwe is believed to be permanently hypoxic below 30 m and this depth is also believed to be the bottom of the mixed layer making it a meromictic lake (Puchniak *et al*., 2009). During such mixing periods, fish kills are observed as a result of the upwelling of hypoxic waters. But such mixing events are also expected to make available essential nutrients locked up in the hypolimnion over relatively long stratified periods which may consequently boost phytoplankton growth (Puchniak *et al*., 2009). Thus, for a meromictic lake like Bosomtwe, existence of phytoplanktons is unstable in a limited zone; between shortage of some essential nutrient of the surface waters because nutrients are usually locked up in deeper waters during long stratified periods, and, a lack of light in deeper waters if mixing is too deep especially in mixing periods (Fogg, 1991). Since these biological communities are controlled both by access to light, the distribution of nutrients, and to some extent the zooplankton grazing rates, factors which are regulated by the stratification and mixing regime, in such lakes, these factors become a vital and permeating influence on the life of phytoplanktons (Margalef, 1978; Melack, 1979; Archonditsis *et al.,* 2004). Consequently, the annual and seasonal dynamics of phytoplankton species in such lakes reflect changes in physical and chemical characteristics of the water body driven by the stratification and mixing regime which shows a predictable pattern of seasonality associated with regime conditions. With this view, this paperexamined the premise that the phytoplankton of Lake Bosomtwe will follow a similar yearly and seasonal pattern.

In this paper therefore, the annual and seasonal changes in the phytoplankton community wet weight biomass associated with the mixing and stratification regime of Lake Bosomtwe in Ghana, in West Africa were investigated over a two-year period between 2004 and 2006. Specifically, a temporal and seasonal signature of the phytoplankton community wet weight biomass composition and dynamics of the phytoplankton in relationship to mixing and stratification regimes are emphasized.

Materials and methods

Study area

The Lake Bosomtwe (located at 06°30'N and longitude 01°25'W) lies at an altitude of 99 m amsl in the south central part of Ghana in the Ashanti Region. This area potentially lies within the semi-deciduous forest/savanna zones of West Africa (Hall & Swaine, 1981). The catchment is both semi-forested and -cultivated and the average monthly temperature is about 26 °C while annual precipitation is about 1136 mm (Puchniak *et al.,* 2009). The lake occupies a drainage basin of 103.1 km2 and has a surface area of 48.6 km2 with maximum depth of 78 m. The lake is steep-sided with no outflows to make the inflowing water dilute compared to the concentrated soda lake (Whyte, 1975; Karikari & Bosque-Hamilton, 2004). Over 80 percent of the water into Lake Bosomtwe is through direct precipitation and water loss is principally through evaporation (Turner *et al.,* 1996). The major mineral constituents found in the lake are the bicarbonates and sulphates of sodium and potassium as well as essential nutrients, such as phosphates and nitrates which appear to be adequate for phytoplankton growth (McGregor, 1937; Karikari & Bosque-Hamilton, 2004). The Lake's water conductivity from 2004 to 2006 ranged from 1182 to 1283 μScm^{-1} while pH averaged 8.9 (Puchniak *et al*., 2009). The extant fish species of the lake are all cichlids which are known to be relatively tolerant of the hypoxic conditions which the lake experiences annually during the mixing period (Post *et al*., 2008).

Sampling and monitoring of physical parameters

A central index station located at latitude 6°30' 609''N and longitude 1°24' 671"W was chosen for bimonthly sampling and monitoring of both physicochemical conditions and phytoplankton over a period of two years, 2004–2006. The physical parameters measured included; (a) water temperature using a Hydrolab H_2O probe (Hydrolab Corporation, Austin, Texas, 1991), (b) water transparency using a 20 cm black and white Secchi disc, and (c) the extinction coefficient (k_{PAR}) with a flat-plate LI- COR quantum sensor (LI-COR Biosciences, Lincoln NB, USA) and subsequently from the relationship, k_{PAR}= 1.96* SD-1 - 0.4234 (r = 0.914; P < 0.01, n = 11). From the temperature-depth profiles obtained using the Hyrolab H_2O probe, the (d) mixed layer depth (Z_{mix}) was estimated whiles the (e) euphotic depth (Z_{eu}) was estimated from k_{PAR} on each occasion using the method of Talling (1986). Sampling periods were characterized using the first prominent break method of the temperature profiles of the lake water column into three seasons: (f) the stratified period – when the mixed layer was stable and shallow for a relatively long period; (g) the mixing period – when the mixed layer deepens after a relatively prolonged stratification (h) and restratifying period – period immediately following the mixing period during which stratification is re-established.

Collection and analyses of phytoplan-kton and phosphorus samples

For two years (2004–2006), the bimonthly water samples from the field were collected and immediately fixed with acid Lugol for phytoplankton studies. In the laboratory, the Lugol preserved water samples were settled, species identified and then counted using an inverted microscope (Utermohl, 1958). Counts of single cells, colonies and filaments done microscopically were then converted to wet weight biomasses by approximating their cell volume estimates. Cell volume estimation for each species was carried out by routine measurements of 20–30 cells of an individual species and application of the geometric formula that best fits the shape of the cell. Algal biomass for each species was then computed from cell counts and estimated cell volumes using the method of Rott (1981). Biomass was taken to include the space occupied by cell vacuoles assuming a specific gravity of 1.0.

Total phosphorus was also determined using some of the same water for phytoplankton biomass analysis; 20 ml glass vials were used to stake subsamples. In the laboratory, total phosphorus was analyzed using the phosphomolybdate colour development following spectrophotometric methods described in Stainton *et al.* (1977).

Statistical analysis

Statistical analysis of the data was carried out using SPSS (2001) computer-based software package to evaluate variations in the values of parameters measured. Independent student t-test, ANOVA, and the Tukey HSD were used to assess annual, inter-annual and seasonal variations in the physicochemical parameters and the phytoplankton wet weight biomass.

Results

Bimonthly variations

Bimonthly variations in the mixed layer depth (Z_{mix}) of the lake during the two years study; 2004–2006, are depicted in Fig. 1. Mean Z_{mix} recorded in the first year, 2004–2005, is 9.90 ± 1.24 m (n = 26) and that for the second year, 2005–2006, is 9.52 ± 0.65 m (n = 25). There was no significant difference in the mean Z_{mix} of the lake over the sampling period (Student t-test: 0.345, df = 2, 49; P > 0.05). However, a 15-fold coefficient of variance (CV) representing 63.9 % compared to 3-fold CV of 34.0 % was noted in the first and second years, respectively.

Bimonthly variations in the euphotic depth (Z_{eu}) of the lake during the two years study; 2004–2006, are depicted in Fig. 1. Mean Z_{eu} recorded in the first year, 2004–2005, is 6.63 ± 0.73 m (n = 26) and that for the second year, 2005–2006, is 4.73 ± 0.31 m (n = 25). There was significant difference in the mean Z_{eu} of the lake over the sampling period (Student t-test: 2.407, df =2, 49; P < 0.05). Also, a 10-fold CV representing 55.8% compared to 3-fold CV of 32.5% was noted in the first and second years, respectively.

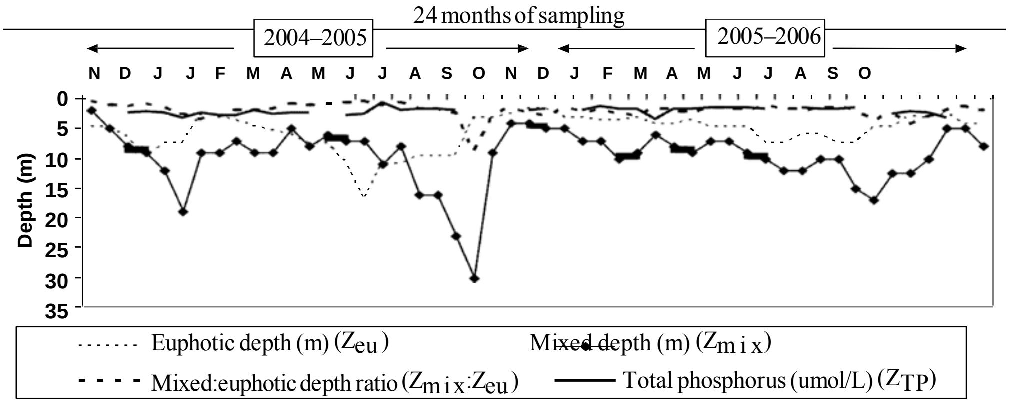

Fig. 1. Temporal variation in euphotic depth (Z_{eu}), mixed layer depth (Z_{mix}), mixed layer:euphotic depth ratio (Z_{mix}:Z_{eu}), and total phosphorus concentration (Z_{TP}) of Lake Bosomtwe (Ghana) from November 2004 to October 2006.

Bimonthly variations in the mixed layer to euphotic depth ratio (Z_{mix}:Z_{eu}) of the lake during the two years study; 2004–2006, are depicted in Fig. 1. Mean Z_{mix}:Z_{eu} recorded in the first year, 2004-2005, is 2.19 ± 0.33 m (*n* = 26) and that for the second year, 2005–2006, is 2.26 ± 0.15 m (*n* = 25). There was no significant difference in the mean Z_{mix}:Z_{eu} of the lake over the sampling period (Student t-test: 0.504, df = 2,49; $P > 0.05$). However, a 22-fold CV representing 86.7% compared to 3-fold CV of 35.6% was noted in the first and second years, respectively.

Bimonthly variations in the total phosphorus concentration (Z_{TP}) associated with varying lake water depth during the two years study; 2004–2006, are depicted in Fig. 1. Mean Z_{TP} recorded in the first year, 2004-2005, is 2.21 ± 0.12 ìmol L^{-1} (*n* = 21) and that for the second year, 2005–2006, is 1.9± 0.13 ìmol L^{-1} (*n* = 20). There was no significant difference in Z_{TP} of the lake over the sampling period (Student t-test: 1.706, df = 2, 39; $P > 0.05$). However, a 5-fold CV representing 24.0 % compared to 3-fold CV of 30.7 % was noted in the first and second years, respectively.

Seasonal variations

Mixed layer depth (Z_{mix}). The mean Z_{mix} compared to the bimonthly seasonal record for the two different years; 2004–2005 and 2005–2006 differed significantly. Here also, in the first year (2004–2005 sampling period), a higher mean seasonal mixing period depth of 17.70 ± 2.65 m (*n* = 7) compared to as low as 6.30 ± 0.96 m (*n* = 6) restratifying period depth was noted. Therefore, between the mixing and stratified periods on the one hand and the mixing and restratifying periods on the other hand, there were significant differences in the mean Z_{mix} of the lake at $P < 0.05$ (i.e. d.f = 2, 18 and d.f = 2, 11 respectively). But, no significant difference in the mean Z_{mix} of the water between the stratified and restratifying periods (d.f = 2, 17 at $P > 0.05$) as shown in Fig. 2 was noted.

In the second year (2005–2006), a higher mean Z_{mix} of 13.7 ± 1.01 m (*n* = 6) in the mixing period compared to a low of 7.5 ± 0.68 m (*n* = 8) in the restratifying period was noted. Similar to the 2004–2005 sampling period, there were significant differences in the mean Z_{mix} of the lake between the mixing and stratified periods on

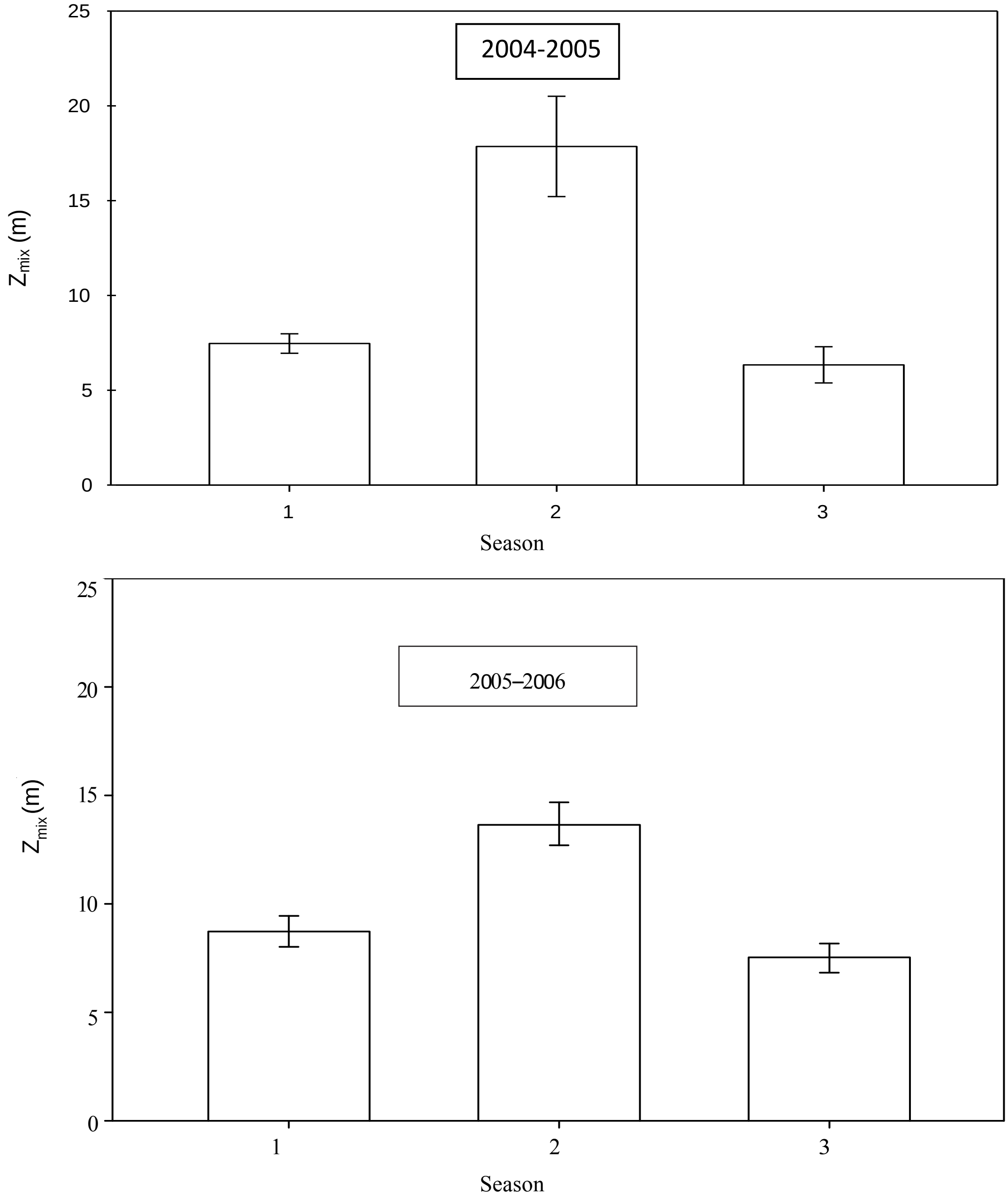

Fig. 2. Seasonal variation in depth of mixed water layer (Z_{mix}) (mean ± s.e) of Lake Bosomtwe (Ghana) from 2004-2005 and 2005-2006 sampling periods respectively. (1 = stratified period; 2 = mixing period; 3 = restratifying period).

the one hand and the mixing and restratifying period on the other hand at $P < 0.05$ (i.e. d.f = 2, 15 and d.f = 2, 13, respectively). Again, no significant difference in the mean Z_{mix} of the water occurred between the stratified and restratifying periods (d.f = 2, 17 at $P > 0.05$) as shown in Fig. 2.

Euphotic depth (Z_{eu})

The mean Z_{eu} compared to the bimonthly seasonal record for the first year, 2004–2005, also differed significantly but in the second year, 2005–2006, there was no significant difference (Fig. 3). In the first year (2004–2005 sampling period), a higher mean Z_{eu} of 8.2 ± 0.99 m ($n = 13$) in the stratified period compared to as low as 2.6 ± 0.35 m ($n = 6$) in the restratifying period was noted. Therefore, between the stratified and restratifying periods on the one hand and the mixing and restratifying periods on the other hand, there were significant differences in the mean Z_{eu} of the lake at $P < 0.05$ (i.e. d.f = 2, 19 and d.f = 2, 11, respectively). But, no significant difference in the mean Z_{eu} was found between the stratified and mixing periods (d.f = 2, 18 at $P > 0.05$) as shown in Fig 3.

Mean mixed layer to euphotic depth ratio (Z_{mix}:Z_{eu})

The mean Z_{mix}:Z_{eu} compared to the bimonthly seasonal record for the two different years; 2004–2005 and 2005–2006, differed significantly. In the first year (2004–2005 sampling period), a higher mean Z_{mix}:Z_{eu} in the mixing period of 3.2 ± 1.02 ($n = 7$) compared to a low of 1.20 ± 0.11 ($n = 13$) in the stratified period was noted. It differed significantly between the stratified and the mixing periods at $P < 0.05$ (d.f = 2, 18). But no significant differences were noted between the stratified and restratifying periods on the one hand and the restratifying and mixing periods on the other hand at $P > 0.05$ (i.e. d.f = 2, 19 and d.f = 2, 11 respectively) as shown in Fig. 4.

In the second year (2005–2006), a higher mean Z_{mix}:Z_{eu} of 3.13 ± 0.36 ($n = 6$) in the mixing period compared to a low of 1.67 ± 0.08 in the stratified period ($n = 11$) was noted (Fig. 4). There were significant differences in the Zmix:Zeu of the lake between the mixing and stratified periods on the one hand and the mixing and restratifying period on the other hand at $P < 0.05$ (i.e. d.f = 2, 15 and d.f = 2,10, respectively). But no significant difference in the Z_{mix}:Z_{eu} of the water was noted between the stratified and restratifying periods (d.f = 2, 17 at $P > 0.05$) as shown in Fig. 4.

Total phosphorus concentration (Z_{TP})

The mean Z_{TP} compared to the bimonthly seasonal record for the first year, 2004–2005, did not differ significantly but in the second study year, 2005–2006, it differed significantly (Fig 5). In the second year (2005–2006 sampling period), a higher mean Z_{TP} in the restratifying period of 2.27 ± 0.31 ìmol L^{-1} ($n = 7$) compared to a low of 1.60 ± 0.06 ìmol L^{-1} ($n = 13$) in the stratified period was noted.

It differed significantly between the stratified and restratifying periods at $P < 0.05$ (d.f = 2, 17). But no significant differences were noted between the mixing and stratified periods on the one hand and the mixing and restratifying periods on the other hand at $P > 0.05$ (i.e. d.f = 2, 15 and d.f = 2, 13, respectively) as shown in Fig. 5.

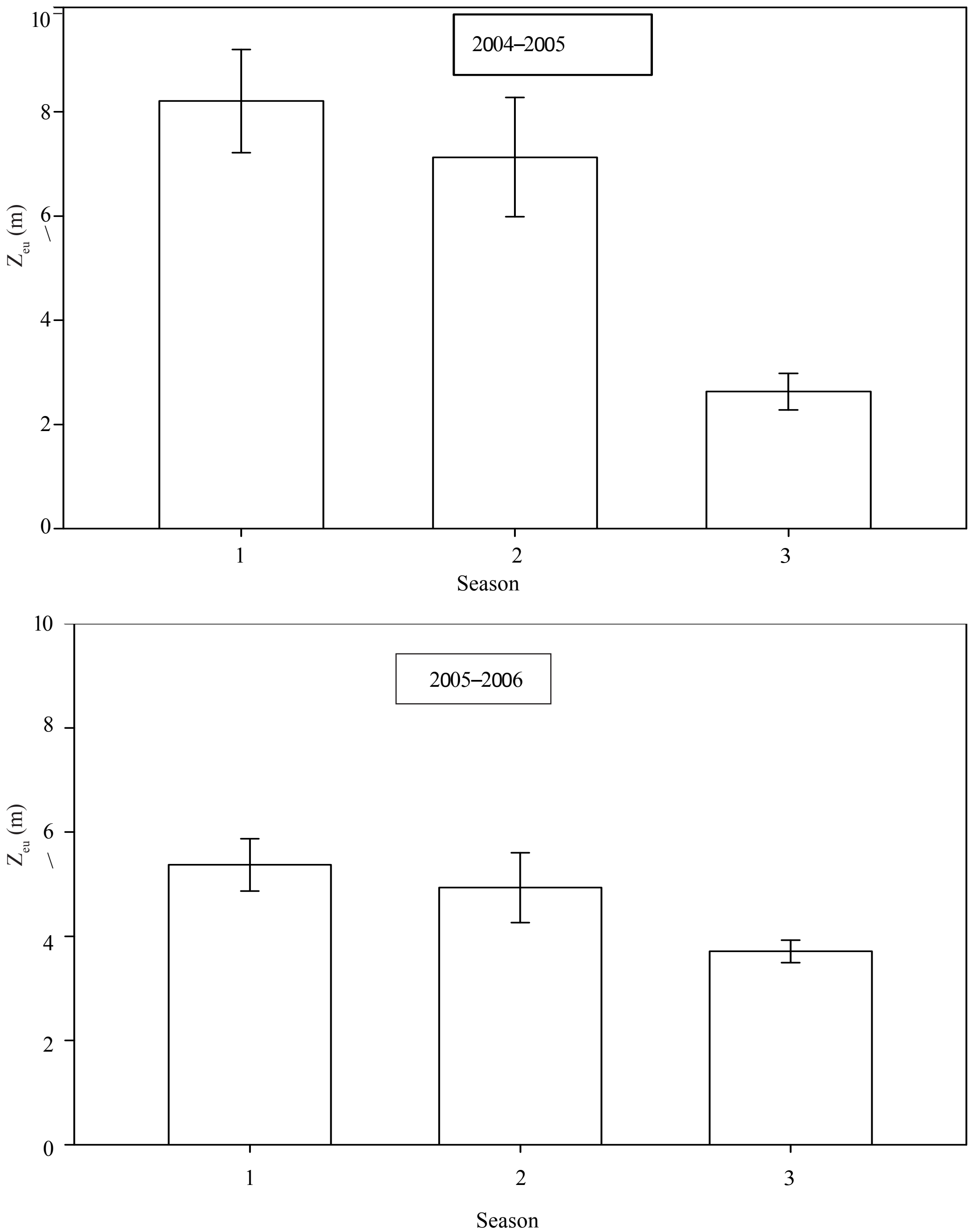

Fig. 3. Seasonal variation in the euphotic (Z_{eu}) (mean ± s.e) depth of Lake Bosomtwe (Ghana) from 2004-2005 and 2005-2006 sampling periods respectively. (1 = stratified period; 2 = mixing period; 3 = restratifying period).

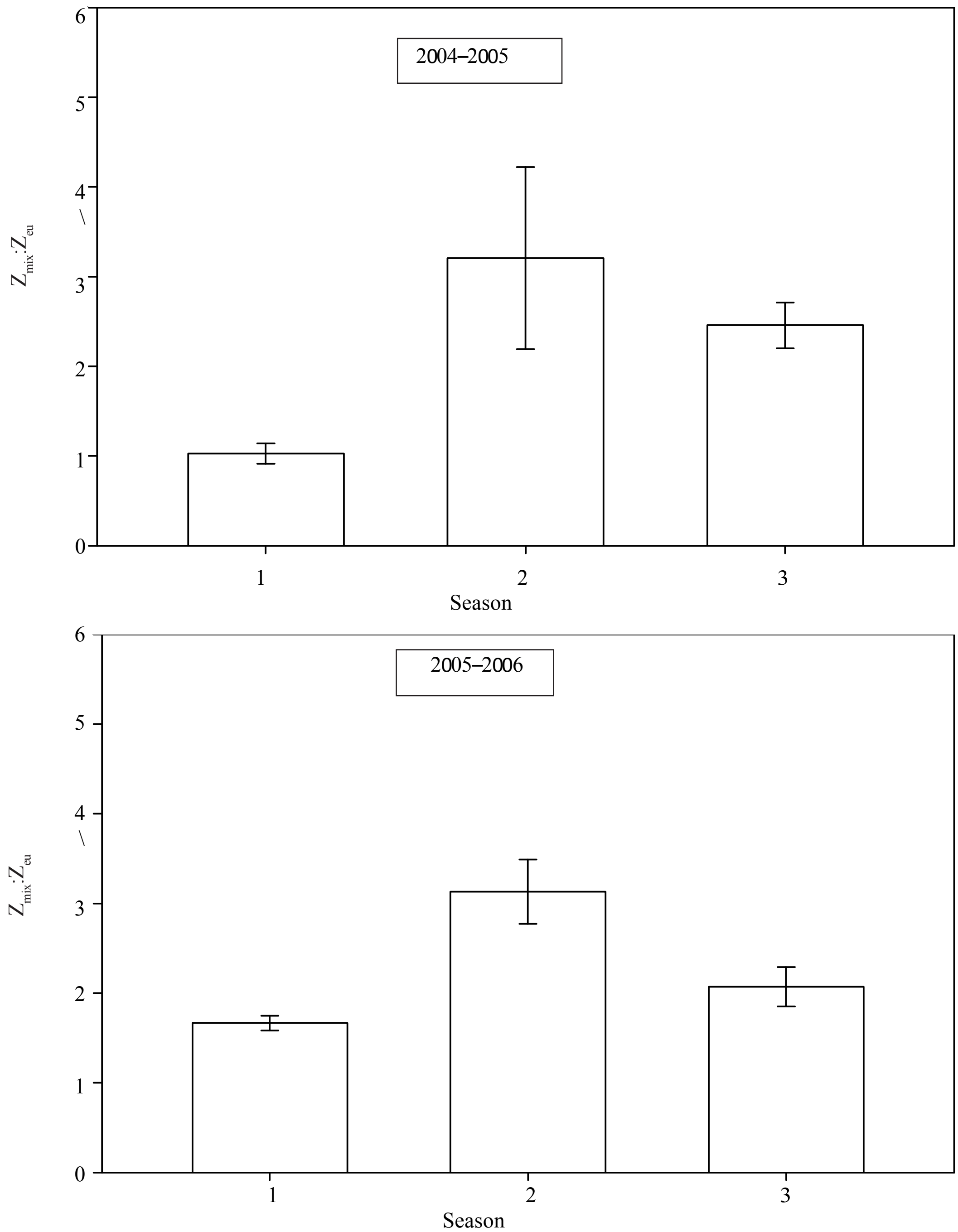

Fig. 4. Seasonal variation in the mixed layer:euphotic depth (Z_{mix}:Z_{eu}) (mean ± s.e) of Lake Bosomtwe mixing period; 3 = restratifying period).

Phytoplankton community biomass composition and variability

The bimonthly trends of the wet weight biomass of phytoplankton sampled for the 2 years are shown in Fig. 6. The Cyanophyceae dominated in both study years constituting 60% in the first year (2004–2005) and 51% of the biomass in the second year (2005–2006), respectively. The Bacillariophyceae and Cryptophyceae were prominent in the water only during the mixing and restratifying periods. However, together they constituted only 5% of the phytoplankton biomass in both the first year (2004–2005) and the second year (2005–2006) respectively. In the 2004–2005 period, during the prolonged stratified periods (November–December and March–June), phytoplankton biomass measure was low, 1337.75 mg m^{-3} (Fig 6). In the mixing periods (January, and July–August), biomass measure further declined to 1145.03 mg m^{-3}. However, during the restratifying periods(February, September–October), the biomass measure increased attaining a maximum measure of 2569.06 mg m-3 in October. In the 2005–2006 period, the peak biomass observed in October of the 2004–2005 period, declined to 2076.18 mg m^{-3} during the stratified periods (November – late December, March–July). Following this the biomass measured further decline to 1984.01 mg m^{-3} during the mixing periods (late December, August). However, the biomass increased to 2726.76 mg m^{-3} during the restratifying periods (January–February, September–October). In all the seasons, the phytoplankton biomass was dominated by the Cyanophyceae (Fig. 6).

Mean phytoplankton wet weight biomass during the entire study ranged from 311.4 mg m^{-3} in January 2005, a mixing period, to 4704.5 mg m^{-3} in October 2006, a restratifying period. Bimonthly variations in the phytoplankton wet weight biomass of the lake from 2004 to 2006 are depicted in Fig. 6. Mean phytoplankton wet weight biomass recorded in 2004-2005 is 1570.01 ± 242.86 m^{-3} (n = 26) and, 2005–2006, is 2262.30 ± 128.58 m^{-3} (n = 26). There was significant difference in phytoplankton wet weight biomass of the lake over the sampling period (Student t-test: 2.52, df = 2, 49; $P < 0.05$). Also, a 15-fold coefficient of variance (CV) representing 78.9 % compared to 3-fold CV of 28.4 % was noted in the first (2004–2005) and second (2005–2006) years, respectively.

The mean seasonal phytoplankton wet weight biomass for the first year, 2004–2005, did not differ significantly but in the second study year, 2005–2006, it differed significantly (Fig. 7). In the second year (2005–2006 sampling period), a higher mean phytoplankton wet weight biomass in the restratifying period of 2726.8 ± 153.40 mg m^{-3} (n = 8) compared to a low of 1984.1 ± 204.84 mg m^{-3} (n = 6) in the mixing period was noted. It differed significantly between the restratifying and the stratified periods on the one hand and the restratifying and the mixing periods on the other hand at $P < 0.05$ (i.e. d.f = 2, 17 and d.f = 2,13 respectively). But no significant difference was noted between the stratified and mixing periods at $P > 0.05$ (d.f =2, 17) as shown in Fig. 7.

Relationship between physico-chemical parameters and the phytoplankton

Both Z_{mix} and the Z_{eu} showed negative relationships with the phytoplankton wet weight biomass (Fig. 8 and 9, respectively). Similarly, the association of the Z_{mix}:Z_{eu} as well as Z_{TP} to phytoplankton wet weight biomass also showed negative relationships (Fig. 10 and 11 respectively). In all cases, $r2$

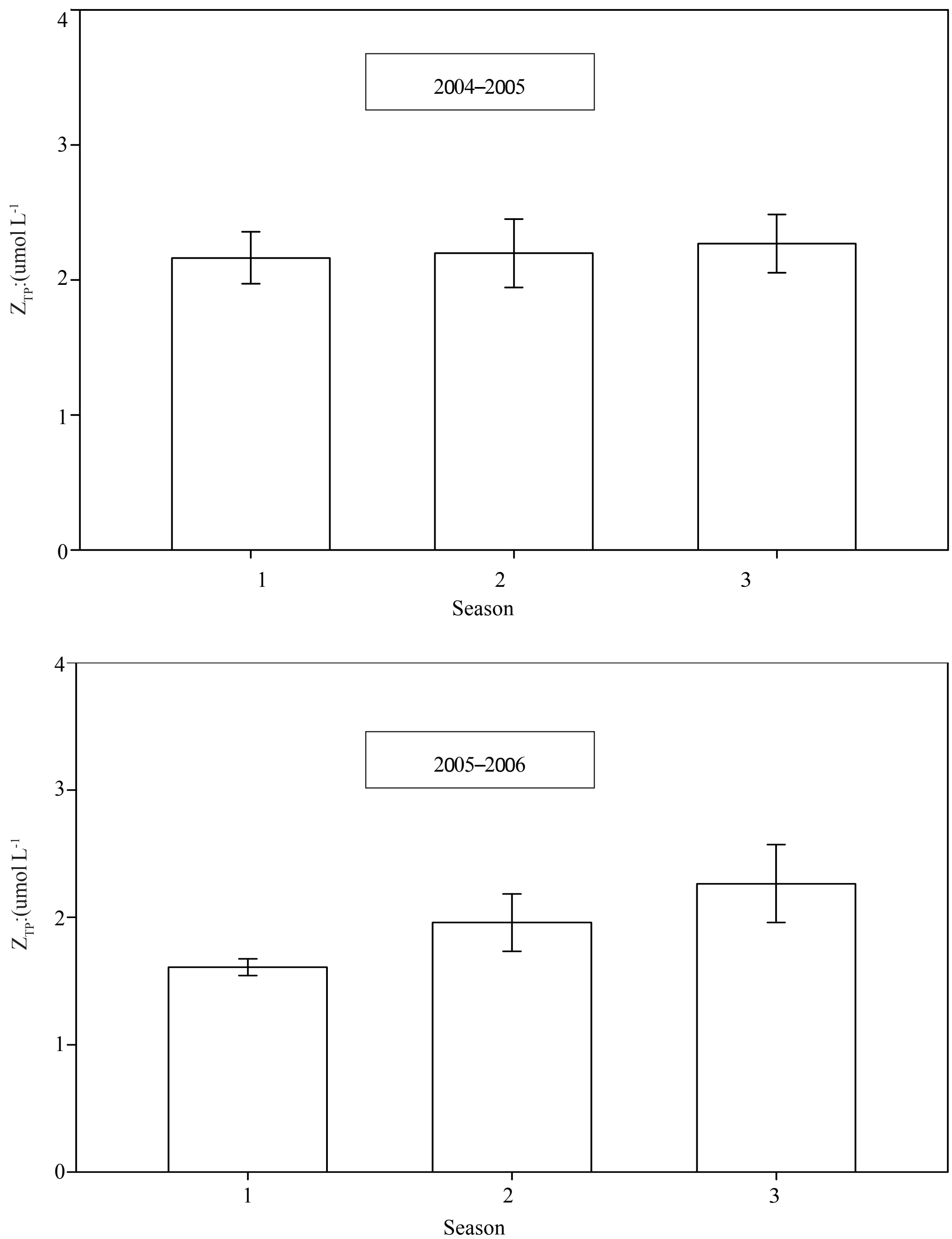

Fig. 5. Seasonal variation in the mixed layer:euphotic depth (Z_{mix}:Z_{eu}) (mean ± s.e) of Lake Bosomtwe mixing period; 3 = restratifying period).

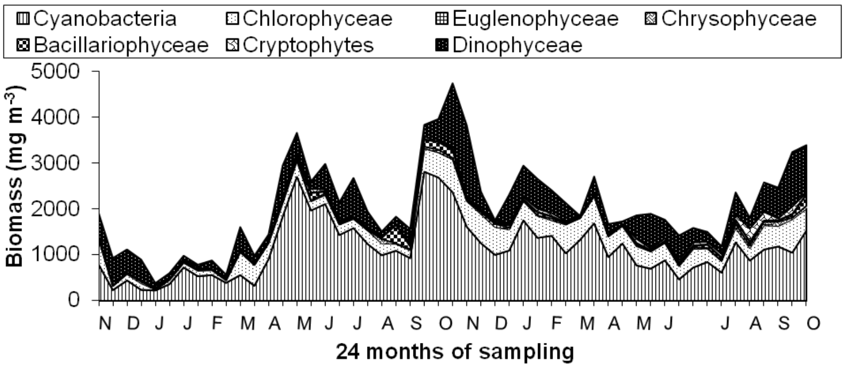

Fig. 6. Temporal variation in wet weight biomass of phytoplankton of Lake Bosomtwe (Ghana) showing the contribution of the different groups of phytoplankton from November 2004 to October 2006.

< 0.5, which implies that, both Z_{mix} and the associated physicochemical status did not significantly influence the biomass of the phytoplankton biomass measure.

Discussion

The dominance of the lake water by the Cyanophyceae in all the seasons of the two years' study suggests this to be the signature of the phytoplankton biomass of Lake Bosomtwe. This observation is common for stratifying tropical lakes (Kalff & Watson, 1986; Ganf, 1974) and could be attributable to a number of single factor determinants namely; considerable persistent stratification, high irradiance and high surface water temperatures, and long water residence times (Paerl, 1996; Sterner, 1989) which together are also characteristic of the Lake Bosomtwe (Turner *et al*., 1996; Puchniak *et al*., 2009). Under such conditions the ability of the Cyanophyceae to fix nitrogen, store nutrients especially nitrogen and phosphorus, regulate buoyancy, sequester important metals like iron and copper, produce mucilage sheaths to counter desiccation, photoprotect by production of carotenoid accessory pigments, and the production of toxins to reduce interspecific competition are some of the factors attributed to their success (Paerl, 1996; Zohary, 1989; Fogg, 1991; Ballot *et al*., 2005). Also, in the Lake Bosomtwe, the seeming adequacy of phosphorus (Karikari & Bosque-Hamilton, 2004) and the unpalatability of the Cyanophyceae to zooplanktons give them a clear advantage over the other phytoplankton groups of the lake. For instance mean total phosphorus concentration in the lake (18.91–109.45 mg m-3) is in the range of eutrophic to saline lakes (Reynolds, 2006; Karikari & Bosque-Hamilton, 2004). In lakeswhere Cyanophyceae are the dominant phytoplankton, they are usually displaced by other groups during the mixing season (Tilzer & Goldman, 1978) contrary to Lake Bosomtwe. The mixing period was too short to enable other phytoplankton groups adapted to the mixing conditions such as the Bacillariophyceae to displace the Cyanophyceae. Also, since the lake does not mix to the bottom the Bacillariophyceae which need occasional resuspension from the lake's sediments are not able to displace the Cyanophyceae (Fogg, 1991).

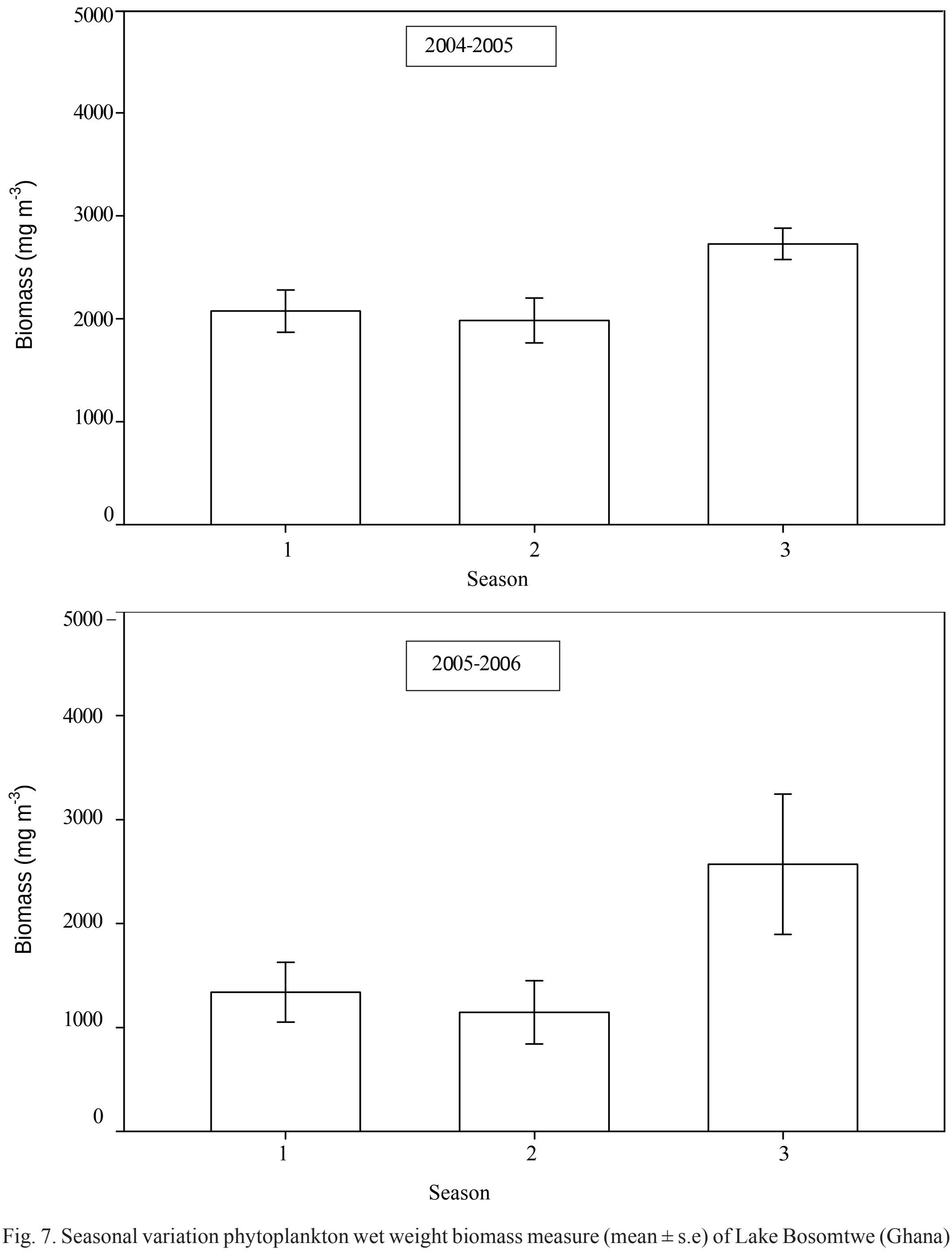

Fig. 7. Seasonal variation phytoplankton wet weight biomass measure (mean ± s.e) of Lake Bosomtwe (Ghana) from 2004-2005 and 2005-2006 sampling periods respectively. (1 = stratified period; 2 = mixing period; 3 = restratifying period).

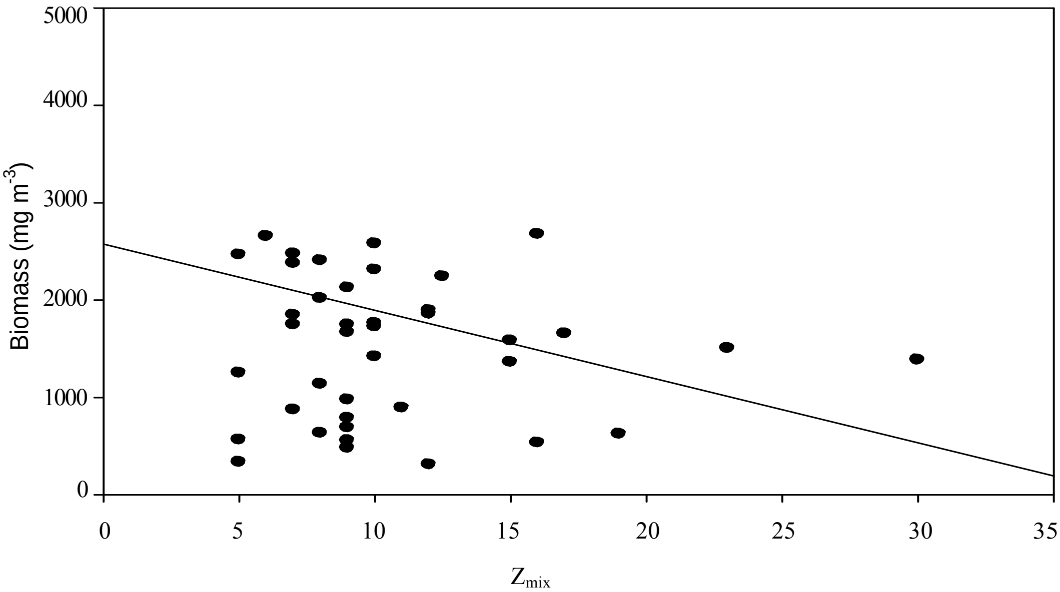

Fig. 8. Phytoplankton biomass as a function of variations in mixed layer depth (Z_{mix}) of Lake Bosomtwe (Ghana); November 2004 – October 2006.

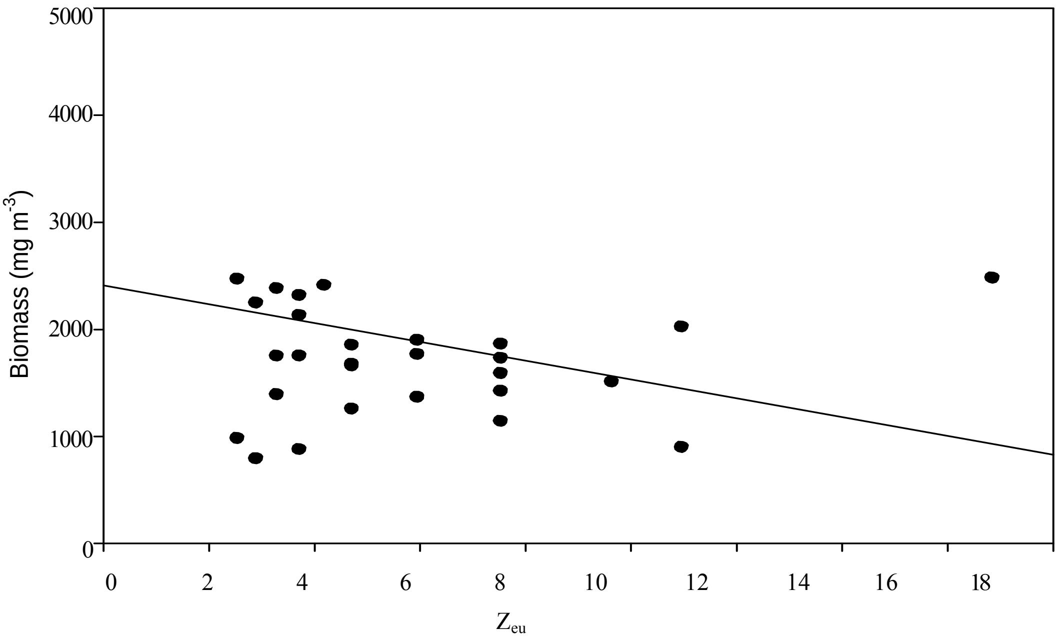

Fig. 9. Phytoplankton biomass as a function of variations in euphotic depth (Z_{eu}) of Lake Bosomtwe (Ghana); November 2004–October 2006.

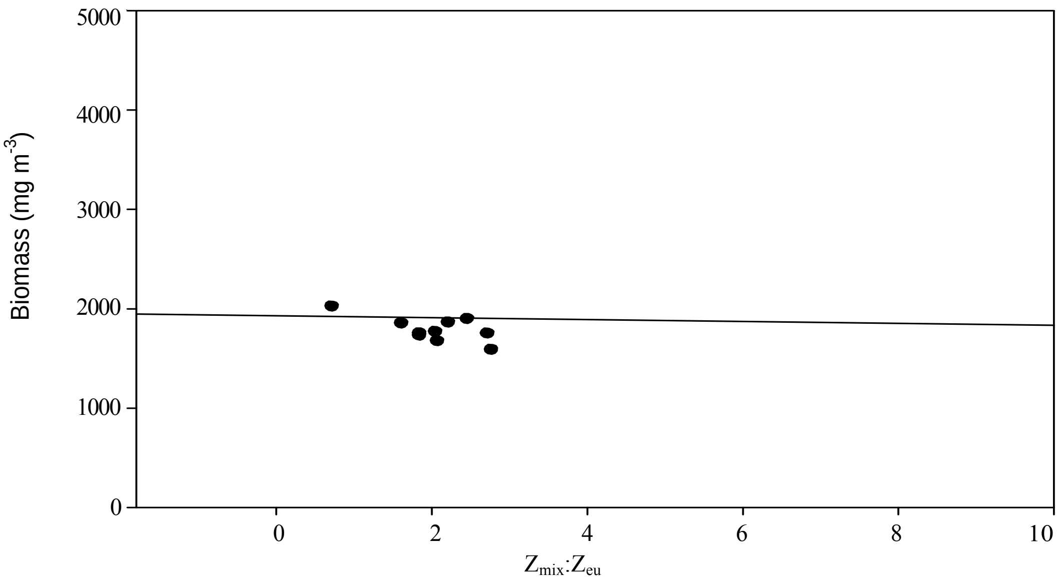

Fig. 10. Phytoplankton biomass as a function of variations in the mixed layer:euphotic depth ratio depth ($Z_{mix:}$ Z_{eu}) of Lake Bosomtwe (Ghana); November 2004 – October 2006.

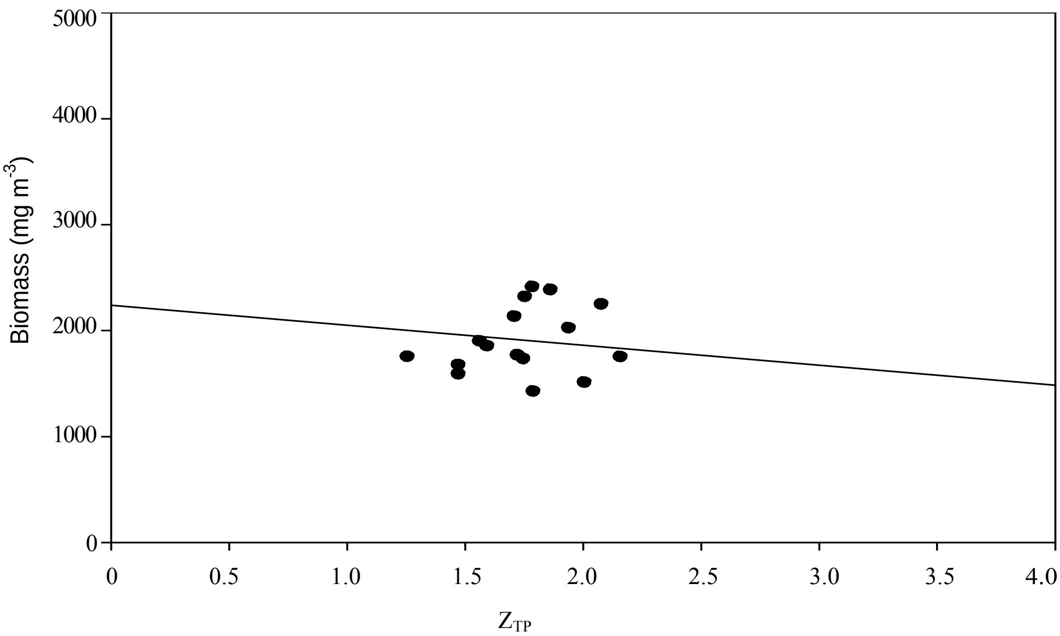

Fig. 11. Phytoplankton biomass as a function of variations in total phosphorus concentration (Z_{TP}) of Lake Bosomtwe (Ghana); November 2004 – October 2006.

The negative relation between the phytoplankton biomass and the Z_{mix} may be traceable to the fact that phytoplankton generally require light for photosynthesis so when taken below the euphotic depth as happens during the mixing periods, it reduces their photosynthetic activity and therefore biomass production (Tilzer & Goldman, 1978). Consequently, even though nutrients may be available in the mixing period as a result of upwelling from the hypolimnion, the phytoplankton in general may be unable to take advantage of it to increase their biomass as a result of light limitation leading to low biomass. Also, the dominance of the phytoplankton by the Cyanophyceae is partly explained by the negative relationship between the biomass and the mixed layer depth. This is because the Cyanophyceae are intolerant of mixing conditions (Paerl, 1996). The negative relationship between the higher Z_{eu} and the phytoplankton biomass can also be partly due to the prolonged stratified periods affecting nutrient availability. For instance, the lower phosphorus concentration during the stratified periods probably limited the growth of the phytoplankton leading to low biomass accumulation. Thus, the phytoplankton biomass may be adapting to such conditions by channeling most of their photosynthate to the production of non-chlorophyllous components with high energetic cost such as mucilage as well as the production of toxins to reduce inter-specific competition (Canfield *et al.*, 1985). Also during such periods, phytoplanktons have been observed to increase production of carotenoid-accessory pigments that do not transfer excitation energy to chlorophyll *a* and thus acting as photo- protective pigments, hence limiting biomass production (Paerl, 1996; Zohary, 1989; Fogg, 1991; Ballot *et al.*, 2005). On the other hand, the consistently higher biomass during the restratifying periods of both years can be attributed to high nutrient concentrations during such periods. This probably led to lower competition for nutrients and enabled all the phytoplankton groups to increase their biomass weight measures which generally led to the highest biomass production and accumulation. This may have eventually led to self-shading and the resultant decrease in the euphotic depth observed during this period.

The lack of a clear statistical relationship between the phytoplankton biomass and the Z_{mix}:Z_{eu} and the concentration of almost all the biomass below a ratio of less than 5 is indicative that the phytoplanktons could be responding to light-limitation. This is because when this ratio is 5 or more, the phytoplankton could largely be distributed in the aphotic zone and are likely to be light-limited even though nutrients may be available. This is corroborated by the low phytoplankton biomass during mixing periods. Indeed, several authors have suggested a critical value of this ratio between 4 and 5 beyond which light limitation is expected to prevail (Strickland, 1965; Wood *et al.*, 1978). In Lake Bosomtwe, the concentration of most phytoplankton biomass at or below a ratio of 5 seems to give some credence to this assertion.

Total phosphorus concentration could not be used as a predictive indicator of the behaviour of the phytoplankton biomass probably due to its seeming adequacy in the lake water. The earlier work of Karikari & Bosque-Hamilton (2004) has shown that nutrient concentrations especially phosphate and nitrate may not be limiting ingredients to phytoplankton growth in Lake Bosomtwe as levels of orthophosphate and nitrate concentrations were far above the levels of P- or N-famine for phytoplankton (Reynolds, 2007). This is confirmed by levels of total phosphorus in this study because mean total phosphorus levels were in the range of eutrophic to saline lakes (18-109.43 mg m-3) observed by Reynolds (2006). However, nitrogen limitation is suggestive from the continuous presence and dominance of heterocyst-bearing Cyanophyceae (Postgate, 1984) even though this was not measured. But nitrogen fixed by these nitrogen-fixing Cyanophyceae may be contributing to a reduction in nitrogen limitation in the lake thereby making it available to other phytoplankton groups. According to Graham & Wilcox (2000), 40–60% of fixed nitrogen by Cyanophyceae can be excreted from their cells into the open water, making it available to other phytoplankton groups. Thus, both phosphorus and nitrogen may not be important limiting factors of the phytoplankton of Lake Bosomtwe.

Annual variations of the mean biomasses expressed by the coefficient of variance indicate considerable variability for a tropical lake and are similar to that of tropical lakes which are subject to pronounced seasonal fluctuations associated with variations in vertical mixing, rainfall, or river discharges (Melack, 1979; Jassby *et al.,* 1990; Goldman *et al*., 1993). The similarly high coefficient of variances in the physico-chemical parameters monitored alongside phytoplankton during the study period therefore suggests this may be the case.

Conclusion

Lake Bosomtwe has a distinct mixing and stratification regime which affects light and nutrient availability and dictates the dynamics of the phytoplankton biomass. High inter-annual variations and differences in the seasonal variations of the mixed layer depth, euphotic depth, and the mixedlayer:euphotic depth ratio seem to be the more important drivers of the dynamics of the phytoplankton biomass than nutrient concentrations.

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