

## CONDITIONS AND RESOURCE FACTORS ASSOCIATED WITH THE SPATIO-TEMPORAL VARIABILITY OF PHYTOPLANKTON COMMUNITY COMPOSITION AND ABUNDANCE IN THE TROPICAL MEROMICTIC LAKE BOSOMTWE (GHANA, WEST AFRICA)

Francis E. Awortwi<sup>1\*</sup> and Mark Osa Akrong<sup>2</sup>

<sup>1</sup>Department of Theoretical and Applied Biology, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

<sup>2</sup>Council for Scientific and Industrial Research, Water Research Institute, Accra, Ghana

\*Corresponding author: [awortwi8@gmail.com](mailto:awortwi8@gmail.com)

### ABSTRACT

*Phytoplankton community abundance and composition of Lake Bosomtwe (Ghana), West Africa, were investigated on spatio-temporal scales for two years from water samples obtained from a central index station and 12 other stations to determine their annual, seasonal, and spatial signature and to assess environmental conditions and resource factors which affect their natural variability. In the laboratory, phytoplankton were identified, counted, and analysed using an inverted microscope. Our study indicates seven phytoplankton groups with abundance dominated by the cyanobacteria composing at least 86% of it at all sampling times during the study. Mean cell abundance of  $59958 \pm 310406$  ( $n=51$ ;  $CV=62.74\%$ ) for temporal studies and  $16531 \pm 8734$  ( $n=26$ ;  $CV=52.84\%$ ) for spatial studies are consistent with other studies. Seasonally, mixed layer depth, euphotic depth, ratio of euphotic to mixed layer depths, water transparency, light intensity in mixed layer, extinction coefficient, surface temperature, total phosphorus, total nitrogen, ratio of total nitrogen to total phosphorus varied significantly ( $p<0.05$ ) with high variabilities. Phytoplankton abundance showed a clear seasonality associated with the mixing and stratification regime, with significant differences ( $p<0.05$ ) occurring during the temporal study specifically between the restratifying period and the stratified and mixing periods respectively, but not between the mixing and stratified periods. Variabilities of the meteorological factors showed no significant relationship with the abundance. Also, of the physicochemical and biological parameters, only variabilities in the ratio of euphotic to mixed layer depths ( $r^2=7.60\%$ ;  $n=51$ ), light intensity in the mixed layer ( $r^2=9.31\%$ ;  $n=51$ ), total phosphorus concentration ( $r^2=14.41\%$ ;  $n=43$ ) and the mixed layer depth ( $r^2=9.31\%$ ;  $n=51$ ) had a significant but weak relationship with the variabilities in the phytoplankton cell abundance at  $p<0.05$ . Our study indicates that the spatio-temporal variability of the phytoplankton abundance of Lake Bosomtwe is mostly affected by the variability in a mixture of hydrographic and nutrient factors.*

**Keywords:** Phytoplankton, spatio-temporal variability, abundance, tropical lake, Lake Bosomtwe.

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## **INTRODUCTION**

Phytoplankton, the major primary producers in lakes, are important in the evaluation of matter and energy along trophic webs (Melack, 1979), organic pollution, trophic state characterisation, water treatment, paleolimnological studies and oxygen production (Wehr and Sheath, 2000). But, their population blooms, crashes and decays result in significant fish kills due to oxygen depletion (Landsberg, 2002), create taste and odour problems in drinking water with substantial cost of removal (Wehr and Sheath, 2000), leads to reduction in system level productivity (Demott et al., 1991), produce toxins harmful to humans and livestock (Carmichael, 1997) and increases in some types such as cyanobacteria can destroy the potential of a lake for recreation (Landsberg, 2002). Thus, phytoplankton studies are of more than academic interest and many aspects of their community dynamics in lakes worldwide and the factors that affect them have received significant attention. Unlike terrestrial ecosystems, the nature of aquatic ecosystems at the autotrophic level is much more transitory and reliant on a diversity of varying conditions and resources at annual, inter-annual, and seasonal levels. Phytoplankton are quite sensitive to these variabilities, and their community dynamics develop due to their differing abilities to establish, grow, compete favourably, endure various conditions and resource constraints, and prevent losses, resulting in different communities in different environments (Cox, 1990). Different communities may also develop in the same habitat over time as the conditions and resources change (Awortwi et al., 2015). Again, the consolidated effects of the environment on the phytoplankton are only steady for a short period. A new situation begins to evolve while we are finding out what the conditions and resources are now (Lund, 1964). Thus, the consideration of the ecological signature of the phytoplankton dynamics of

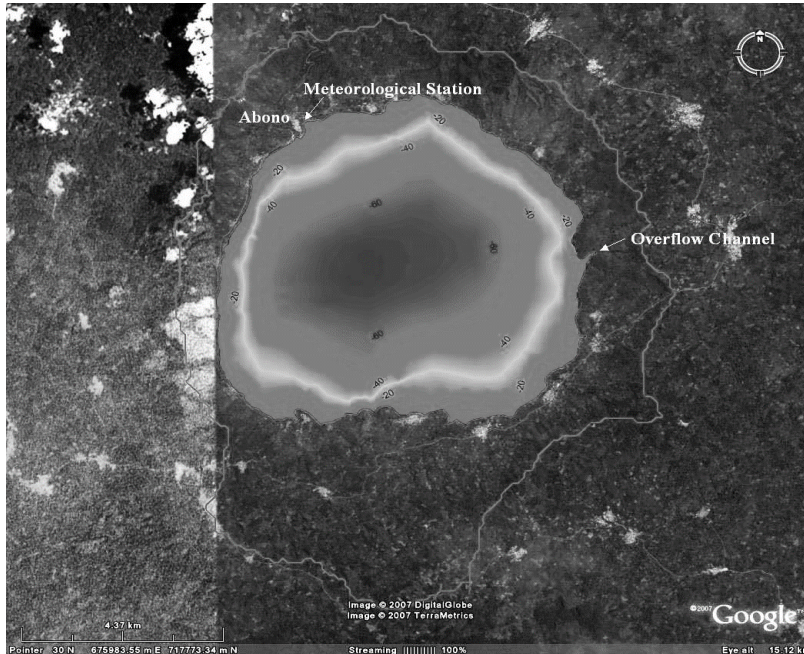
a lake needs to take into consideration the complex interplay between all of these factors. Aspects of phytoplankton of Lake Bosomtwe studied include temporal wet weight biomass (Awortwi et al., 2015); inshore diversity (Addico et al., 2018), seasonal productivity (Awortwi et al., 2018) and photosynthetic efficiency (Awortwi et al., 2022). Surrogates of phytoplankton abundance used in these studies include wet weight (Awortwi et al., 2015), and cell numbers (Addico et al., 2018), each with its own limitations. But, Vollenweider (1969) suggests cell numbers as the best quantitative expression of phytoplankton communities since counts can be directly linked to specific phytoplankton species, each organism is counted regardless of size, and biovolume changes do not affect. Also, most research in tropical lakes has short temporal periods and long sampling intervals at a few stations. Hence, in Lake Bosomtwe, the conceptualisation of phytoplankton dynamics in the spatio-temporal sense, which will provide a better understanding of the phytoplankton dynamics, is lacking. The objective of this study is to bridge this gap by looking at the phytoplankton community composition and abundance at temporal, spatial, and seasonal scales together with meteorological and physicochemical factors to achieve a comprehensive and better resolution of the phytoplankton dynamics of the lake and an understanding of the conditions and resource factors that affect them. Understanding the phytoplankton dynamics of the lake on a spatio-temporal scale is essential since it will help in improving our assessment of its fisheries and other biodiversity potential – activities which support the over 22 communities around the lake.

## MATERIALS AND METHODS

### Study area

Lake Bosomtwe is a natural meromictic lake which is stratified for most part of the year. It is located in the semi-deciduous forest/savanna potential zone at an altitude of 99 m above mean sea level (amsl) in the south-central part of Ghana. It lies in a one-million-year-old meteorite impact crater, a circular depression

of 11 km diameter with the lake itself having a diameter of 8 km, surface area of 48.6 km<sup>2</sup> and a radial drainage basin measuring 103.2 km<sup>2</sup>, completely divorced from the general drainage of the rest of Ghana due to its high crater rims despite an overflow event at 210 amsl in prehistoric times (Puckniak *et al.*, 2009; Koeberl *et al.*, 2007; Turner *et al.*, 1996; Fig. 1).



**Fig. 1:** A bathymetric map of Lake Bosomtwe (Ghana) showing the site of the meteorological station and the lake's catchment area (Puchniak *et al.*, 2009)

It responds to climatic variations by significant changes in lake level (Turner *et al.*, 1996), water chemistry (Talbot and Johannessen, 1992) and other hydrographic features (Puckniak *et al.*, 2009). The catchment is semi-cultivated and the average monthly atmospheric temperature is about 26 °C with an annual precipitation of about 1136 mm (Puckniak *et al.*, 2009). It is a closed-basin lake with over 37 mostly seasonal streams that flow into it, which are dilute compared to the lake water (Whyte, 1975). Annual inflow from rainfall and stream flow data is about 0.14027

km<sup>3</sup> (Amu Mensah *et al.*, 2019). Groundwater inflow is insignificant and hence, the lake obtains over 80% of its water input from direct precipitation and loses water mainly through evaporation (Turner *et al.*, 1996). The chief mineral constituents are the bicarbonates of sodium and potassium, and the essential nutrients, phosphorus and nitrogen, appear to be adequate for phytoplankton growth (Karikari and Bosque-Hamilton, 2004, Awortwi *et al.*, 2015). The Lake's water conductivity ranges from 1182 to 1283  $\mu\text{Scm}^{-1}$  while CO<sub>2</sub> and pH average 59  $\mu\text{molL}^{-1}$  and 8.9,

respectively (Puchniak *et al.*, 2009; Amankwaa *et al.*, 2020). Biological Oxygen Demand is low (2.0 to 4.1 mgL<sup>-1</sup>), indicating minimal allochthonous organic matter input and the support of Lake Bosomtwe’s biota mainly by in situ primary production (Mitra, 2017). The lake has high salinity and sodium hazards and is not suitable for irrigation since these high salinities reduce crop yields (Amankwaa *et al.*, 2020). Water quality based on physicochemical parameters (e.g. total phosphorus, total nitrogen, temperature, dissolved oxygen, sodium, potassium, etc) and bacteria loads indicate that they exceed permissible levels, which may require treatment before drinking (Karikari and Bosque-Hamilton, 2004). The lake also faces an ecological risk from the accidental introduction of the Nile tilapia, which is gradually becoming the dominant fish species (Obirikorang *et al.*, 2020) among the extant fishes of the lake which are all cichlids.

**Measurement of meteorological and physicochemical parameters**

Air temperature (°C), wind speed (ms<sup>-1</sup>), relative humidity (%), barometric pressure (mbar), and incidence irradiance were measured with weather condition sensors of a meteorological station near the lake shore (6°31.138''N, 1°25.665''W) at Abono (Fig. 1) from November 2004 to October 2006. These and some physicochemical factors have been published (Puchniak *et al.*, 2009) and are used here as independent variables to assess their effect on the phytoplankton cell abundance. A central index station (6°30' 609''N, 1°24' 671''W; Table 1) was used for bimonthly sampling of all physicochemical parameters and phytoplankton for two years (temporal studies) and at 13 stations (spatial studies) in 2006.

**Table 1. Sampling sites and respective maximum depths during spatial surveys in the Abono-Apewu/Asisiriwa-Dompa transects of Lake Bosomtwe in the Ashanti region of Ghana (West Africa) in the mixing (August) and stratified (November/December) periods of 2006**

Station	Latitude	Longitude	Maximum depth (m)
Stn 1	6°31938 N	1°25650 W	11.4
Stn 2	6°31595 N	1°25365 W	25.5
Stn 3	6°31147 N	1°25071 W	>50
Stn 4	6°29260 N	1°25449 W	>50
Stn 5	6°28664 N	1°26077 W	24
Stn 6	6°28620 N	1°26185 W	11.5
<sup>1</sup> Stn 7	6°30 609 N	1°24671 W	78
Stn 8	6°28891 N	1°26411 W	26.6
Stn 9	6°28976 N	1°26338 W	30.5
Stn 10	6°29453 N	1°25614 W	>50
Stn 11	6°31069 N	1°24094 W	>50
Stn 12	6°31530 N	1°23815 W	42.3
Stn 13	6°31884 N	1°23571 W	10.4

<sup>1</sup>stn 7 is also the central index station for temporal studies

Water temperature, dissolved oxygen, and electrical conductivity were measured in situ using a Hydrolab H<sub>2</sub>O probe (Hydrolab Corporation, Austin, Texas, 1991). Water transparency was measured with a Secchi disc, irradiance in the mixed layer according to Riley (1957), extinction coefficient ( $k_{PAR}$ ) LI-COR quantum sensor (LI-COR Biosciences, Lincoln NB, USA) and the euphotic depth was estimated from  $k_{PAR}$  (Talling, 1986). Mixed layer depth was estimated from temperature-depth profiles and was used to characterize three seasons: stratified, mixing, and restratifying periods, respectively. Water levels were measured using a gauge at Abono town.

#### **Collection and analysis of nutrient samples**

Concentrations of total phosphorus and total nitrogen were determined using unfiltered lake water collected initially with a 6-litre van-Dorn water sampler from discrete depths of the mixed layer and three subsamples at each depth were taken with 20 ml scintillation vials. Total phosphorus concentration was analysed using the ascorbic acid method after persulfate using the phosphomolybdate colour development (Havens et al. 2024). Concentrations of total nitrogen were determined using a reduction column of cadmium filings exposed to copper and the addition of a buffer solution (ammonium chloride, sodium tetraborate, and disodium dehydrate EDTA) and quantified by measuring absorption at 543 nm (Havens et al. 2024) using the equation:

$$C = A 543 - b/m$$

Where; C = concentration (mg L<sup>-1</sup>); m = slope of calibration curve; b = y-intercept

#### **Collection and analysis of phytoplankton and chlorophyll a samples**

From each of the discrete depths in the mixed layer, a 6-L van Dorn water sampler was used initially to collect water from which 20 ml samples were taken and fixed with Lugol's iodine in potassium iodide. In the lab, the bottles were shaken and three 2 ml subsamples were put into 2 ml settling chambers and left for 6 hours, after which the settled cells were identified (Prescott, 1962) and counted using an inverted microscope at a magnification of 400 following standard methods (Utermohl, 1958). At least 20 random fields were counted to ensure that the counts are representative of the phytoplankton population (Vollenweider et al., 1969). The total number of cells was then estimated by multiplying the number of cells counted by the ratio of the whole chamber area to that of the area from which cells were counted. Chlorophyll a concentrations were determined by filtering a measured 500 ml of lake water through a Whatman GF/F filter (0.7 µm pore size) at each discrete depth of the mixed layer and extracting pigments into acetone solvent. Fluorescence was measured by a Turner Designs Field Fluorometer 10-AU-005 (Sunnyvale, CA) set to deliver excitation of blue light (430-450 nm) and sense the emission of red light (650-675 nm). After the excitation was obtained, the sample was acidified with 3 drops of 1N HCl to denature the chlorophyll a porphyrin ring and re-measured. The difference was used to calculate the undegraded chlorophyll a concentrations removed from humic impurities and phaeophytin (Havens et al. 2024).

#### **Statistical analysis**

Statistical analysis of the data was done using SPSS (2001). Means and standard deviations were determined. Pooled sample t-test and One-way ANOVA were used to assess inter-annual differences and seasonal differences at  $p < 0.05$ . The Fisher LSD (least significant

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difference) was used to detect which periods differed significantly. Simple linear regression was used to assess the extent and nature of the relationship between the physicochemical parameters and the phytoplankton cell abundance at  $p < 0.05$ .

## RESULTS

### Annual variability of physicochemical and biological factors

Means of the physicochemical parameters are presented in Table 2. Only the euphotic depth ( $Z_{eu}$ ), ratio of euphotic to mixed layer depth ( $Z_{eu}:Z_{mix}$ ), light intensity ( $I_z$ ), total phosphorus (TP) and the conductivity in the mixed layer ( $C_z$ ) differed significantly between the two years ( $p < 0.05$ , t-test: Table 2).

**Table 2 Variability of physicochemical parameters in Lake Bosomtwe (Ghana, West Africa) from November 2004 to October 2006**

Parameter	Mean $\pm$ standard deviation	Minimum	Maximum	CV (%)	n
$Z_{mix}$ (m)	9.71 $\pm$ 5.00	2.00	30	51.56	51
$Z_{eu}$ (m)	5.69 $\pm$ 2.98	1.64	16.85	52.30	51
$Z_{eu}:Z_{mix}$	0.68 $\pm$ 0.46	0.11	2.41	66.79	51
SD (m)	1.66 $\pm$ 0.41	0.80	2.60	24.66	51
$I_z$ ( $\mu\text{Em}^{-2}\text{s}^{-1}$ )	130.00 $\pm$ 104.30	8.90	510.96	79.92	50
$k_{PAR}$ ( $\text{m}^{-1}$ )	0.83 $\pm$ 0.43	0.22	2.25	52.03	51
$T_o$ ( $^{\circ}\text{C}$ )	29.95 $\pm$ 1.54	24.72	32.10	5.14	45
$T_z$ ( $^{\circ}\text{C}$ )	29.28 $\pm$ 1.40	24.00	31.18	4.77	45
TP ( $\mu\text{g}\text{L}^{-1}$ )	64.31 $\pm$ 17.40	18.81	109.47	27.10	43
TN ( $\mu\text{g}\text{L}^{-1}$ )	140.58 $\pm$ 39.53	95.34	261.52	28.12	28
TNTP	4.51 $\pm$ 0.91	1.47	5.08	37.22	24
$C_o$ ( $\mu\text{Scm}^{-1}$ )	1184.10 $\pm$ 60.0	926.21	1284.10	5.10	45

( $Z_{mix}$  is the mixed layer depth;  $Z_{eu}$  is the euphotic depth;  $Z_{eu}:Z_{mix}$  is the ratio of euphotic depth to mixed layer depth; SD is the Secchi disc depth;  $I_z$  is light intensity within the mixed layer;  $k_{PAR}$  is extinction coefficient;  $T_o$  is temperature of surface water and  $T_z$  is temperature within the mixed layer; TP is total phosphorus concentration; TN is total nitrogen concentration; TN:TP is the ratio of total nitrogen to total phosphorus;  $C_o$  is electrical conductivity of surface water and  $C_z$  is electrical conductivity in the mixed layer; CV is the coefficient of variance in percentage; n is the number of samples)

**Temporal studies:** Phytoplankton cell abundance over the period ranged from 13532 to 142450, over 10-fold (CV = 62.74%) with a mean of  $50058 \pm 31405$  ( $n = 51$ ; Table 3). Mean cell numbers in the first year was  $65686 \pm 335184$  cells  $\text{ml}^{-1}$  (CV=53.57%;  $n = 26$ ) while

the mean in the second year was  $33805 \pm 15018$  cells  $\text{ml}^{-1}$  (CV=44.43%;  $n = 25$ ). There was a significant difference in the mean cell abundance between the two years (student's t-test: 4.178, df = 49;  $p < 0.05$ ).

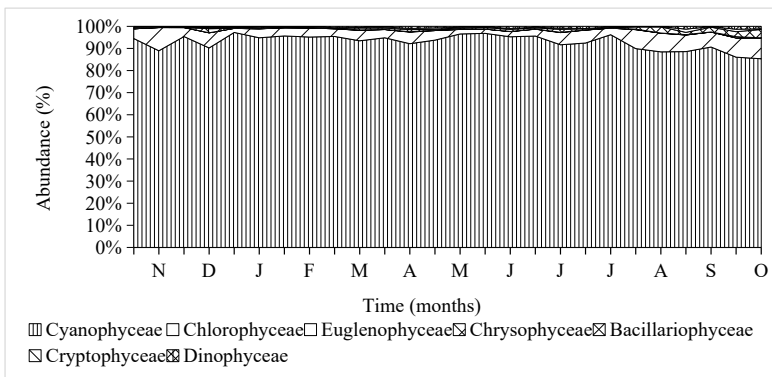
**Table 3** Variability of the phytoplankton abundance and related variables in Lake Bosomtwe (Ghana, West Africa) from November 2004 to October 2006

Parameter	Mean ± standard deviation	Minimum	Maximum	CV (%)	n
P <sub>b</sub> (cells mL <sup>-1</sup> )	59958 ± 31406	13532	142450	62.74	51
Chl <i>a</i> (µgL <sup>-1</sup> )	9.76 ± 4.38	1.79	25.15	44.84	33

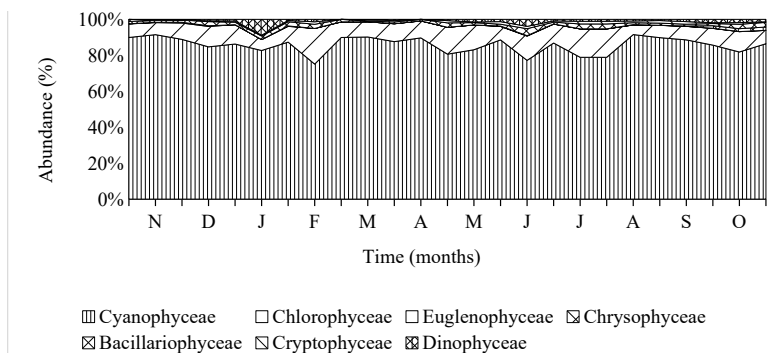
P<sub>b</sub> is phytoplankton abundance in the mixed layer; Chl *a* is chlorophyll *a* concentration in the mixed layer; CV is the coefficient of variance in percentage; n is the number of samples

In both years, phytoplankton abundance was dominated by the Cyanobacteria at all times (Figures. 2 and 3). In the first year the cell abundance was in the sequence Cyanobacteria (93.9%), Chlorophyceae (4.6%), Bacillariophyceae (0.71%), Dinophyceae (0.38%), Cryptophyceae (0.24%), Chrysophyceae (0.14%), and Euglenophyceae

(0.03%) respectively (Fig. 2). In the second year, the abundance was in the same sequence viz, Cyanobacteria (86.52%), Chlorophyceae (9.41%), Bacillariophyceae (1.61%), Dinophyceae (1.40%), Cryptophyceae (0.80%), Chrysophyceae (0.19%), and Euglenophyceae (0.07%) respectively (Fig. 3).



**Fig. 2:** Contribution of various classes of phytoplankton to cell abundance of Lake Bosomtwe, Ghana, during the first year (2004-2005). During the 2004-2005 year, July was sampled thrice instead of twice as was done in the 2005-2006 period. This accounts for the 3 Js here – two for June and one for July



**Figure 3:** Contribution of various classes of phytoplankton to the cell abundance of Lake Bosomtwe, Ghana, during the second year (2005-2006).

Mean chlorophyll a in the mixed layer ranged over 14-fold (CV = 44.84%) with a mean of  $9.76 \pm 4.38$  ( $n = 33$ ; Table 3). Means of the chlorophyll a in the first year ( $8.72 \pm 5.63 \mu\text{gL}^{-1}$ ;  $n=12$ ) and the second year ( $10.36 \pm 3.50 \mu\text{gL}^{-1}$ ;  $n=21$ ) did not differ significantly (t-test:

$1.034$ ,  $df = 31$ ;  $p > 0.05$ ). Seasonal variability of physicochemical and biological factors: The seasonal variability of physicochemical factors in the first and second years is shown in Tables 4 and 5.

**Table 4** Seasonal variability of physicochemical parameters in Lake Bosomtwe (Ghana, West Africa) from November 2004 to October 2005

Parameter	Mean $\pm$ standard deviation (n)			p-value
	Stratified Period	Mixing Period	Restratifying Period	
$Z_{\text{mix}}$ (m)	$7.10 \pm 2.35$ (12) <sup>a</sup>	$17.86 \pm 7.01$ (7) <sup>b</sup>	$6.71 \pm 2.36$ (7) <sup>a</sup>	0.000
$Z_{\text{eu}}$ (m)	$7.82 \pm 3.76$ (12) <sup>a</sup>	$8.14 \pm 2.35$ (7) <sup>a</sup>	$2.78 \pm 0.72$ (7) <sup>b</sup>	0.001
$Z_{\text{eu}}:Z_{\text{mix}}$	$1.24 \pm 0.64$ (12) <sup>a</sup>	$0.55 \pm 0.30$ (7) <sup>b</sup>	$0.43 \pm 0.13$ (7) <sup>a</sup>	0.001
SD (m)	$1.95 \pm 0.34$ (12) <sup>a</sup>	$2.01 \pm 0.33$ (7) <sup>a</sup>	$1.15 \pm 0.21$ (7) <sup>b</sup>	0.000
$I_z$ ( $\mu\text{Em}^{-2}\text{s}^{-1}$ )	$267.02 \pm 120.79$ (12) <sup>a</sup>	$80.39 \pm 65.22$ (7) <sup>b</sup>	$75.57 \pm 24.41$ (7) <sup>a</sup>	0.000
$k_{\text{PAR}}$ ( $\text{m}^{-1}$ )	$0.55 \pm 0.20$ (12) <sup>a</sup>	$0.52 \pm 0.27$ (7) <sup>a</sup>	$1.42 \pm 0.44$ (7) <sup>a</sup>	0.000
$T_o$ ( $^{\circ}\text{C}$ )	$31.37 \pm 0.80$ (10) <sup>a</sup>	$27.95 \pm 1.91$ (6) <sup>b</sup>	$29.82 \pm 1.57$ (7) <sup>b</sup>	0.020
$T_z$ ( $^{\circ}\text{C}$ )	$30.42 \pm 0.90$ (10) <sup>a</sup>	$27.50 \pm 2.02$ (6) <sup>b</sup>	$28.51 \pm 1.14$ (7) <sup>b</sup>	0.001
TP ( $\mu\text{gL}^{-1}$ )	$68.47 \pm 18.10$ (11) <sup>a</sup>	$67.66 \pm 15.69$ (6) <sup>a</sup>	$70.72 \pm 13.44$ (6) <sup>a</sup>	0.944
TN ( $\mu\text{gL}^{-1}$ ) <sup>†</sup>	$157.64 \pm 57.26$ (8) <sup>a</sup>	$122.01 \pm 51.76$ (4) <sup>a</sup>		0.210 <sup>†</sup>
TN:TP <sup>†</sup>	$2.740 \pm 1.41$ (8) <sup>a</sup>	$1.69 \pm 0.11$ (3) <sup>a</sup>		0.051 <sup>†</sup>
$C_o$ ( $\mu\text{Scm}^{-1}$ )	$1156.56 \pm 17.71$ (10) <sup>a</sup>	$970.68 \pm 447.87$ (6) <sup>a</sup>	$1160.17 \pm 17.33$ (7) <sup>a</sup>	0.276
$C_z$ ( $\mu\text{Scm}^{-1}$ )	$1154.87 \pm 11.22$ (10) <sup>a</sup>	$1119.00 \pm 99.66$ (6) <sup>a</sup>	$1155.75 \pm 12.43$ (7) <sup>a</sup>	0.325

Significance was tested at  $p < 0.05$ , means with different letters differed significantly; <sup>†</sup> represents t-tests due to batch sample loss otherwise, the test is a One-way ANOVA. ( $Z_{\text{mix}}$

is the mixed layer depth;  $Z_{eu}$  is the euphotic depth;  $Z_{eu}:Z_{mix}$  is the ratio of euphotic depth to mixed layer depth; SD is the secchi disc depth;  $I_z$  is light intensity within the mixed layer;  $k$  PAR is extinction coefficient;  $T_o$  is temperature of surface water;  $T_z$  is temperature within the mixed layer; TP is total phosphorus concentration; TN is total nitrogen concentration; TN:TP is the ratio of total nitrogen to total phosphorus;  $C_o$  is electrical conductivity of surface water and  $C_z$  is electrical conductivity in the mixed layer; n is number of samples)

Seasonally, only the means of mixed layer depth ( $Z_{mix}$ ), euphotic depth ( $Z_{eu}$ ), ratio of euphotic to mixed layer depth ( $Z_{eu}:Z_{mix}$ ), Secchi depth (SD), light intensity in the mixed layer ( $I_z$ ), extinction coefficient ( $k$  PAR), surface

temperature ( $T_o$ ), and mean temperature in the mixed layer ( $T_z$ ) differed significantly between seasons during the first year (2004-2005) at  $p < 0.05$  (Table 4).

**Table 5 Seasonal variability of physicochemical parameters in Lake Bosomtwe (Ghana, West Africa) from November 2005 to October 2006.**

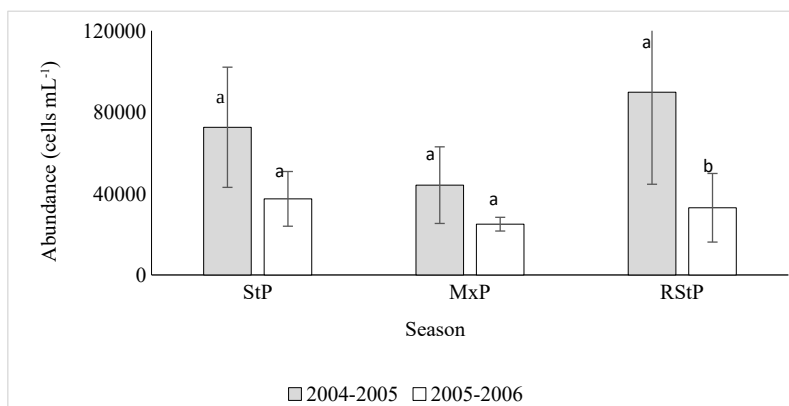
Parameter	Mean ± standard deviation (n)			p-value
	Stratified Period	Mixing Period	Restratifying Period	
$Z_{mix}$ (m)	7.29 ± 1.38 (7) <sup>a</sup>	12.08 ± 1.13 (12) <sup>b</sup>	7.00 ± 2.00 (6) <sup>a</sup>	0.000
$Z_{eu}$ (m)	3.92 ± 0.65 (7) <sup>a</sup>	5.99 ± 1.74 (12) <sup>b</sup>	4.20 ± 0.70 (6) <sup>a</sup>	0.013
$Z_{eu}:Z_{mix}$	0.57 ± 0.11 (7) <sup>a</sup>	0.51 ± 0.00 (12) <sup>a</sup>	0.61 ± 0.18 (6) <sup>a</sup>	0.400
SD (m)	1.43 ± 0.14 (7) <sup>a</sup>	1.71 ± 0.07 (12) <sup>b</sup>	1.50 ± 0.17 (6) <sup>a</sup>	0.021
$I_z$ ( $\mu\text{Em}^{-2}\text{s}^{-1}$ )	131.21 ± 28.44 (7) <sup>a</sup>	79.44 ± 41.83 (12) <sup>b</sup>	71.44 ± 43.23 (6) <sup>b</sup>	0.020
$k$ PAR ( $\text{m}^{-1}$ )	0.94 ± 0.15 (7) <sup>a</sup>	0.73 ± 0.09 (12) <sup>a</sup>	1.0 ± 0.23 (5) <sup>b</sup>	0.042
$T_o$ (°C)	30.67 ± 0.61 (5) <sup>a</sup>	30.15 ± 0.50 (12) <sup>a</sup>	29.45 ± 0.94 (5) <sup>a</sup>	0.272
$T_z$ (°C)	30.02 ± 0.23 (5) <sup>a</sup>	29.55 ± 0.58 (12) <sup>a</sup>	29.29 ± 0.53 (5) <sup>a</sup>	0.151
TP ( $\mu\text{gL}^{-1}$ )	48.30 ± 6.62 (6) <sup>a</sup>	56.20 ± 2.11 (9) <sup>a</sup>	82.43 ± 26.70 (5) <sup>b</sup>	0.020
TN ( $\mu\text{gL}^{-1}$ )	137.11 ± 10.29 (4) <sup>a</sup>	139.66 ± 32.73 (11) <sup>a</sup>	138.53 ± 34.55 (2) <sup>a</sup>	0.935
TN:TP	2.80 ± 0.15 (4) <sup>a</sup>	2.64 ± 0.50 (7) <sup>a</sup>	1.77 ± 0.40 (2) <sup>b</sup>	0.036
$C_s$ ( $\mu\text{Scm}^{-1}$ )	1200.25 ± 35.07 (5) <sup>a</sup>	1140.90 ± 2.83 (12) <sup>a</sup>	1222.50 ± 369.64 (5) <sup>a</sup>	0.750
$C_z$ ( $\mu\text{Scm}^{-1}$ )	1203.15 ± 2.24 (5) <sup>a</sup>	1217.22 ± 3.73 (12) <sup>a</sup>	1215.02 ± 41.26 (5) <sup>a</sup>	0.396

Significance was tested at  $p < 0.05$ , means with different letters differed significantly;  $Z_{mix}$  is the mixed layer depth;  $Z_{eu}$  is the euphotic depth;  $Z_{eu}:Z_{mix}$  is the ratio of euphotic depth to mixed layer depth; SD is the secchi disc depth;  $I_z$  is light intensity within the mixed layer;  $k$  PAR is extinction coefficient;  $T_o$  is temperature of surface water;  $T_z$  is temperature within the mixed layer; TP is total phosphorus concentration; TN is total nitrogen concentration; TN:TP is the ratio of total nitrogen to total phosphorus;  $C_o$  is electrical conductivity of surface water and  $C_z$  is electrical conductivity in the mixed layer; n is the number of samples

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In the second year (2005-2006), seasonal means of the mixed layer depth ( $Z_{mix}$ ), euphotic depth ( $Z_{eu}$ ), Secchi depth (SD), light intensity in the mixed layer ( $I_z$ ), extinction coefficient ( $k_{PAR}$ ), total phosphorus concentration (TP), and the Total nitrogen: total phosphorus ratio (TN:TP) differed significantly between at  $p < 0.05$  (Table 5). The rest of the variables did not differ significantly between seasons

during this season (Tables 4 and 5). Seasonally, mean phytoplankton cell abundance ranged from a minimum value of  $44125 \pm 18819$  ( $n=7$ ;  $CV=42.65\%$ ) in the mixing period to a maximum value of  $83036 \pm 44953$  ( $n=7$ ;  $CV=54.14\%$ ) in the restratifying period during the first year (2004-2005), but it did not differ significantly ( $p > 0.05$ ; Figure. 4).



**Fig. 4** Seasonal variation of phytoplankton abundance (cells mL<sup>-1</sup>) of Lake Bosomtwe, Ghana during the first (2004-2005) and second (2005-2006) years; StP = stratified Period; MxP = mixing Period, and RStP = Restratifying Period. Error bars represent standard deviation.

In the second year (2005-2006), it ranged from a low of  $26344 \pm 8568$  ( $n=12$ ;  $CV=42.52\%$ ) in the mixing period to a high of  $46487 \pm 16848$  ( $n=6$ ;  $CV=36.24\%$ ) in the restratifying period and differed significantly among the seasons at  $p < 0.05$  (Fig. 4) between the stratified and restratifying periods ( $df=11$ ) and also between the mixing and restratifying periods ( $df=16$ ; Fig. 4) but not between the stratified and mixing periods ( $df= 17$ ; Fig. 4).

### **Spatial variability of physicochemical and biological factors**

Variations in the physicochemical parameters at the various stations during the spatial surveys are depicted in Table 6. Only the means of the SD,  $T_o$ , and DO differed significantly at  $p < 0.05$  (Table 6).

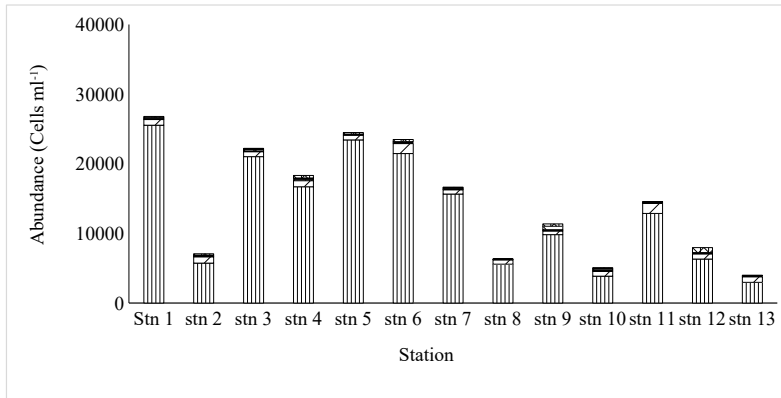
**Table 6 Spatial variability of physicochemical parameters at a central index station and 12 other stations in Lake Bosomtwe (Ghana, West Africa) in November and December 2006 (stratified period) and August 2006 (mixing period)**

Parameter	Mean ± stdev (n)	Minimum	Maximum	CV (%)
<b>Stratified Period</b>				
SD (m)*	1.60 ± 0.11 (13)	1.50	1.80	7.07
T <sub>o</sub> (°C) *	30.12± 0.23 (13)	29.73	30.37	0.77
DO (%)*	67.74± 16.00 (8)	50.96	86.10	23.62
C <sub>s</sub> (µScm <sup>-1</sup> )	1293.18±30.74 (8)	1218.33	1312.88	2.38
<b>Mixing Period</b>				
SD (m)	1.34± 0.13 (13)	1.10	1.60	9.90
T <sub>o</sub> (°C)	27.91± 0.17 (13)	27.55	28.10	0.59
DO (%)	56.11± 4.90 (13)	56.11± 4.90 (13)	47.19	72.35
C <sub>s</sub> (µScm <sup>-1</sup> )	1268.80± 52.71 (13)	1106.40	1307.82	4.15

\*indicates significant differences between seasons at p<0.05; (SD is the Secchi disc depth; T<sub>o</sub> is the surface temperature; DO is dissolved oxygen concentration measured as % saturation, and C<sub>s</sub> is the electrical conductivity of surface water; n is the number of samples; CV is the coefficient of variance in percentage)

Phytoplankton abundance ranged from a low of 3996 cells ml<sup>-1</sup> to a high of 26796 cells ml<sup>-1</sup> in the stratified period with a mean of 14482 ± 8084 ml<sup>-1</sup> (n=13; Fig. 5). During this period, the abundance (%) across stations

was in the sequence Cyanobacteria (90.76%), Chlorophyceae (5.78%), Dinophyceae (1.43%), Cryptophyceae (0.89%), Chrysophyceae (0.65%), Bacillariophyceae (0.48%), Euglenophyceae (0.01%; Fig. 5).

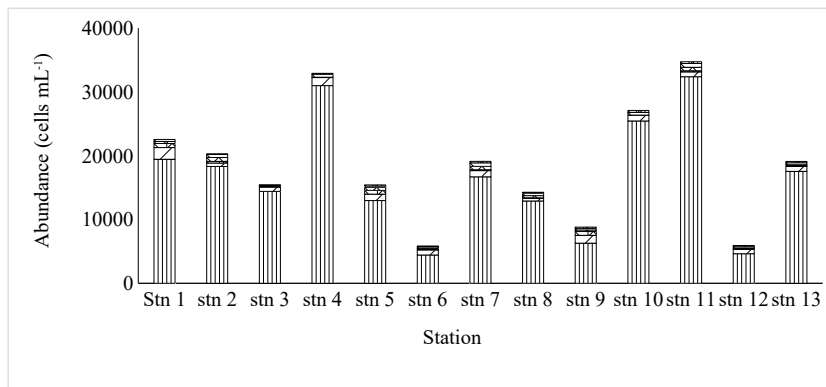


**Fig. 5** Spatial variability in the phytoplankton cell abundance and community composition of Lake Bosomtwe, Ghana, at different stations during the stratified period (November/December, 2006) at the Abono-Apewu-Asiriwa-Dompa transect.

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In the mixing period, cell abundance ranged from a minimum value of 5855 cells ml<sup>-1</sup> to a maximum value of 34727 cells ml<sup>-1</sup> with a mean of 18581 ± 9191 ml<sup>-1</sup> (n=13; Fig. 6). During this period, the percentage of

abundance across stations was in the sequence Cyanobacteria (89.63%), Chlorophyceae (4.91%), Cryptophyceae, Bacillariophyceae (1.48%), Chrysophyceae (1.15%), Dinophyceae (0.89%), and Euglenophyceae (0.06%).



**Fig. 6** Spatial variability in the phytoplankton cell abundance and community composition of Lake Bosomtwe, Ghana at different stations during the mixing period (August, 2006) at the Abono-Apewu-Asiriwa-Dompa transect

Mean cell abundance across sites did not differ significantly between the stratified and mixing periods (student's t-test: 1.207, df= 2, 24, p>0.05) and the cyanobacteria dominated the cell abundance at all stations and in both seasons (Figures. 5 and 6).

### **Relationship between meteorological, physicochemical variables and phytoplankton abundance**

Increases in the meteorological parameters viz; atmospheric temperature, wind speed, and solar radiation, led to an increase in the phytoplankton abundance, but none of these parameters was significantly related to the phytoplankton cell abundance (p>0.05, Table 7). Similarly, increases in atmospheric pressure and relative humidity led to a decrease in the phytoplankton abundance and none of these parameters was significantly related to it at p>0.05 (Table 7).

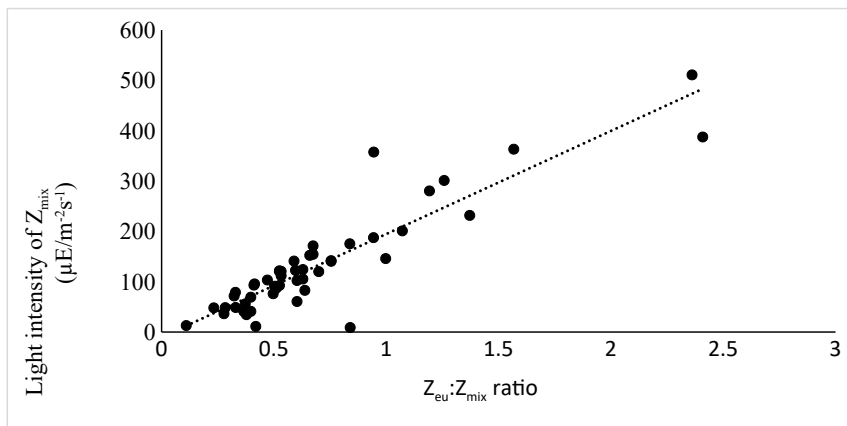
**Table 7. Relationship between phytoplankton abundance (PB) and some meteorological, physicochemical and biological factors in Lake Bosomtwe (Ghana, W/A) from November 2004 to October 2006**

Parameters	r2 (%)	Relationship	n	p-value
$P_B$ vs $I_o$	5.54	$P_B = 131.57 * I_s + 27812$	50	0.10
$P_B$ vs $P_s$	4.30	$P_B = -451.73 * WS + 86655$	50	0.15
$P_B$ vs RH	2.51	$P_B = -285.92 * P_s + 86655$	50	0.27
$P_B$ vs $W_L$	1.99	$P_B = -370.78 * WL + 59604$	50	0.32
$P_B$ vs $Z_{mix}$	9.31	$P_B = -1914.5 * Z_{mix} + 68640$	51	0.03
$P_B$ vs $Z_{eu}$	0.69	$P_B = -873.74 * Z_{eu} + 55038$	51	0.56
$P_B$ vs $Z_{eu} : Z_{mix}$	7.60	$P_B = 18947 * Z_{eu} : Z_{mix} + 37108$	51	0.05
$P_B$ vs SD	1.52	$P_B = -8831.5 * SD + 64708$	51	0.42
$P_B$ vs $I_z$	9.31	$P_B = 92.308 * I_z + 37564$	51	0.03
$P_B$ vs $k_{PAR}$	1.52	$P_B = 8977.3 * K_{PAR} + 42611$	51	0.39
$P_B$ vs $T_o$	3.10	$P_B = 3434 * T_o - 54516$	45	0.25
$P_B$ vs TP	14.41	$P_B = 715.52 * TP + 5589.1$	43	0.01
$P_B$ vs TN	1.99	$P_B = 79.284 * TN + 27003$	28	0.47
PB vs TN:TP	2.42	$P_B = 3816.4 * TN:TP + 31368$	24	0.47
$P_B$ vs $C_z$	7.74	$P_B = -139.51 * C_z + 213549$	45	0.05
$P_B$ vs Chl a	5.31	$P_B = -1090.86 * Chl a + 4953.2$	33	0.20

Significance was tested at  $p < 0.05$ ;  $T_s$  is atmospheric temperature ( $^{\circ}C$ );  $WS$  is wind speed ( $ms^{-1}$ );  $I_o$  is light intensity at the lake water surface ( $Wm^{-2}$ );  $P_s$  is atmospheric pressure (mbars);  $W_L$  is water level (cm);  $Z_{mix}$  is the mixed layer depth (m);  $Z_{eu}$  is the euphotic depth (m);  $Z_{eu} : Z_{mix}$  is the ratio of euphotic depth to mixed layer depth;  $SD$  is the secchi disc depth;  $I_z$  is mean light intensity within the mixed layer;  $k_{PAR}$  is extinction coefficient ( $m^{-1}$ );  $T_o$  is temperature of surface water;  $TP$  is total phosphorus concentration ( $\mu g L^{-1}$ );  $TN$  is total nitrogen concentration ( $\mu g L^{-1}$ );  $TN:TP$  is the ratio of total nitrogen to total phosphorus;  $C_z$  is electrical conductivity in the mixed layer ( $\mu S cm^{-1}$ ) and  $T_o$  surface temperature ( $^{\circ}C$ );  $r^2$  is the coefficient of determination;  $n$  is the number of samples

Increases in the physicochemical parameters; surface water temperature, the extinction coefficient, the ratio of euphotic depth to mixed layer depth, and the mean irradiance in the mixed layer led to an increase in the phytoplankton abundance (Table 7) but only the ratio of mean euphotic depth to mean mixed layer depth and the mean irradiance in the mixed layer were significantly related to it at  $p < 0.05$ . Generally, the strength of the relationships was weak even when they were significant.

Also, a strong positive and significant relationship was found between the ratio of the euphotic depth to the depth of the mixed layer and the mean light intensity in the mixed layer at  $p < 0.05$  ( $r^2 = 81.83\%$ ; Fig. 7).



**Fig. 7** Light intensity in the mixed layer depth as a function of the variability in the ratio of the euphotic depth to the mixed layer depth of Lake Bosomtwe (Ghana, W/A) from 2004 to 2006

But increases in mixed layer depth, euphotic depth, secchi disc depth, and water level led to a decrease in the phytoplankton cell abundance (Table 7), with only the variability in the mixed layer depth being significantly related to the phytoplankton cell abundance at  $p < 0.05$ . Increases in total phosphorus, total nitrogen, and the ratio of total nitrogen to total phosphorus all led to an increase in the phytoplankton cell abundance (Table 7), but only the mean total phosphorus in the mixed layer was significantly but weakly related to the phytoplankton cell abundance at  $p < 0.05$ . An increase in the mean conductivity in the mixed layer led to a decrease in the mean cell abundance (Table 7) but did not significantly vary with it at  $p < 0.05$ .

## DISCUSSION

### Phytoplankton community composition and cell abundance

The dominance of the cell abundance by the cyanobacteria for both the spatial and temporal studies is a common observation in stratifying tropical lakes (Kalff and Watson, 1986; Ganf, 1974) and is consistent with the observation of Addico *et al.*, (2018). A number of single- factor theories have been used to

explain this observation. These include high temperature and light intensity, efficient light harvesting, low  $Z_{eu}:Z_{mix}$  ratio, buoyancy regulation, favourable energy balance, high nutrient affinity, high phosphorus storage capacity, low TN:TP, slow growth rate, population stability, amongst others. For instance, temperatures observed in the lake are within that required for optimum growth of most cyanobacteria, i.e. above 25 °C (Bartram *et al.*, 1999), giving the cyanobacteria an advantage over many of the other groups. Also, they possess accessory pigments that enable them to adapt to both high light intensities typical of tropical lakes and low light intensities when shaded by others or mixed below the euphotic depth. These pigments enable them to efficiently harvest light in almost the entire range of the visible spectrum (Cohen-Bazir and Bryant, 1982). Again, in Lake Bosomtwe, mean light intensity in the mixed layer of 130  $\mu E m^{-2} s^{-1}$  does not reach photo- inhibitory onset levels of above 200  $\mu E m^{-2} s^{-1}$  for the cyanobacteria (Horne and Goldman, 1994). The high variability in the light intensity of the water column also indicates that cyanobacteria are not exposed to lethal levels of over 320  $\mu E m^{-2} s^{-1}$  for long periods (Van Liere and Mur, 1980). The low  $Z_{eu}:Z_{mix}$  ratio of the lake also favours

the cyanobacteria (Bartram *et al.*, 1999). At such low levels, the phytoplankton spend a considerable part of the daylight below the euphotic depth with low light intensity and quality, which can adversely affect them. The cyanobacteria are the phytoplankton adapted to such low light intensity and spectral quality due to their ability to harvest almost all the visible wavelengths of light (Van Liere and Mur, 1980). The high correlation between the  $Z_{eu}:Z_{mix}$  ratio and the mean light intensity in the mixed layer supports the assertion that the  $Z_{eu}:Z_{mix}$  ratio is a good estimate of the underwater light climate of lakes (Wood *et al.*, 1978; Awortwi *et al.*, 2022). In addition, the cyanobacteria are known to have a low maintenance cost requiring little energy to maintain cell function and structure (Van Liere *et al.*, 1979; Horne and Goldman, 1994), which is an added advantage over other phytoplankton. Furthermore, studies suggest that the cyanobacteria have a higher affinity for the key nutrients; phosphorus and nitrogen compared to other microalgae (Bartram *et al.*, 1999) and often outcompete other groups when these nutrients are limited. But levels of total phosphorus in this study are in the range of eutrophic to saline water bodies (Whitaker and Likens, 1975; Reynolds, 2006) and are unlikely to limit phytoplankton growth. Some studies have suggested that the high levels of phosphorus in the lake to inputs from anthropogenic activities such as fertiliser leachate, organic pollution by livestock, and domestic waste water input from surrounding communities. Our study supports this assertion. In addition, cyanobacteria are known to have high phosphorus storage capacity, enough to perform up to four cell divisions compared to other phytoplankton (Bartram *et al.*, 1999). Horne and Commis (1987), suggest that total nitrogen should be lower than 50 to 100  $\mu\text{gL}^{-1}$  to induce nitrogen fixation in cyanobacteria. In Lake Bosomtwe, on average, total nitrogen concentration is above 140  $\mu\text{gL}^{-1}$  consistent with Addico *et*

*al.* (2018) and Amo-Mensah *et al.*, (2014) and hence the lake phytoplankton may not be nitrogen-limited. But the continuous presence of heterocyst-bearing nitrogen-fixing cyanobacteria such as *Aphanizomenon*, *Anabaenopsis*, and *Cylindrospermopsis* in the lake suggests otherwise, since the process is an energetically expensive one (Postgate, 1984; Awortwi, 2009). However, others suggest that heterocyst production is an indication of ammonium nitrogen and not total nitrogen limitation (Reynolds, 2006). But nitrogen-fixing cyanobacteria may be contributing to a reduction in nitrogen limitation of other phytoplankton groups in the lake since about 40-60% of fixed nitrogen is observed to be released into open waters (Graham and Wilcox, 2000), implying that total nitrogen may be adequate for the phytoplankton. Moreover, lower ratios of TN:TP are known to favour the dominance of the cyanobacteria due to their lower optimum values of TN:TP compared to other phytoplankton (Schreurs, 1992). Addico *et al.* (2018) also found similarly low TN:TP ratios in the lake, an indication of the abundance of phosphorus in the lake (Chapman, 1996). In addition, the ability to regulate their position in the water column between nutrient-depleted, light-sufficient surface and light-attenuated nutrient-abundant deep waters enables them to avoid both light and nutrient limitation (Bartram *et al.*, 1999).

Again, the cyanobacteria have few natural enemies due to the production of toxins reducing their edibility (Bartram *et al.*, 1999). This together with their buoyancy regulation which prevents sedimentation helps to reduce their loss rates. Hence, the slow growth rates of the cyanobacteria are compensated for by population stability once they have been established (Bartram *et al.*, 1999) as we have seen in this study. On the other hand, the low cell numbers of the Chlorophyceae, Bacillariophyceae, and Cryptophyceae is attributed to higher grazing

rates by the zooplankton and herbivorous fishes (Addico *et al.*, 2018; Carpenter *et al.*, 1987). For the Chrysophyceae, the high pH, nutrients, and conductivities in the lake are believed to restrict their growth (Sandgren, 1988; Jensen *et al.*, 1994; Reynolds, 2006) while the Euglenophyceae are more notable in organic matter-enriched zones and littoral areas (Oliveira and Calheiros, 2000). The high variabilities in the phytoplankton cell abundance indicated by the coefficient of variance are not unexpected even for a tropical lake which is subjected to the pronounced annual and seasonal variabilities in the physicochemical factors observed in this study which seem to drive it (Melack, 1979; Jassby *et al.*, 1990; Goldman *et al.*, 1993).

#### **Seasonal variability of the phytoplankton abundance**

Generally, the seasonal variability of the phytoplankton abundance seems to be driven by the variabilities in light and light-related factors and nutrient factors especially total phosphorus associated with the stratification and mixing regime of the lake. The relatively low abundance of the phytoplankton during the stratified period may be attributed to the relatively high irradiances and unfavourable light climate compared to other periods. During such periods, phytoplankton may be channelling excitation energy to other pigments such as carotenoids which do not transfer it to chlorophyll *a* but rather act as a screen to protect them from photodamage (Fogg, 1991). These conditions, coupled with the high temperatures of tropical lakes which result in high respiration rates (Sternler, 1989; Awortwi *et al.*, 2018), often lead to low photosynthetic efficiency (Awortwi *et al.*, 2022), low growth rate (Awortwi *et al.*, 2018), and thus low abundance, as was observed during this period. The low nutrient levels during the stratified period may also have adversely contributed to the low abundance observed during this period. The cyanobacteria

dominated the abundance during this period partly because they are adapted to the stable conditions of the stratified period due to their low growth rates (Bartram *et al.*, 1999). In addition, the ability to regulate their position in the water column (Reynolds, 2006) gives them better access to the required light and nutrient levels during this period compared to the other phytoplankton and to outcompete them. Also, their ability to fix atmospheric nitrogen using their heterocyst is an added advantage during the low nutrient levels of the stratified period (Bartram *et al.*, 1999). On the other hand, the lowest abundance that occurred during the mixing period may be attributed to the dominance of the phytoplankton by the cyanobacteria which require less turbulent conditions due to their low growth rates (Bartram *et al.*, 1999). Nutrient levels at this period are favourable, and so phytoplankton are more likely to be limited by relatively unfavourable light conditions, which can lead to low growth rates compared to other periods (Awortwi *et al.*, 2018) and hence, to the lowest abundance observed during this study. In temperate and relatively shallow tropical lakes, cyanobacteria are often displaced by other phytoplankton groups, especially the Bacillariophyceae during this period due to high silica availability, the material needed to construct their cell walls (Tilzer and Goldman, 1978; Nixdorf, 1994) compared to other periods. But this was not observed in Lake Bosomtwe. It may be that mixing in the lake is not deep enough to cause a substantial increase in silica levels and to resuspend sedimented forms. Thus, contrary to the cyanobacteria, the Bacillariophyceae require relatively turbulent mixing conditions (Kalff and Watson, 1986), mostly to keep them suspended since their heavy silica cell walls tend to cause them to sediment out of the water column during the stable conditions of the stratified periods. Nevertheless, the increase in abundance of the Bacillariophyceae in the mixing period is consistent with other

studies and current ecological principles of life cycle adaptation to environmental variability which characterise the Bacillariophyceae as being meroplanktonic (Kalff and Watson, 1989; Lewis, 1978). The increase in their abundance during this period may also be due to reduced zooplankton grazing, which is known to be relatively high during stratified periods (Carpenter *et al.*, 1987). They share this trait with the Cryptophyceae (Carpenter *et al.*, 1987) which also increased their abundance during this period. In addition, the Bacillariophyceae are known to be good competitors of the scarce light typical of mixing periods (Willen, 1991). The occurrence of the highest abundance in the restratifying period can be attributed to the slowing down or a halt in turbulent mixing conditions, which favour the cyanobacteria (Bartram *et al.*, 1999), the dominant phytoplankton in the lake namely. This, coupled with the consistently high nutrient levels and the high variability in the irradiance and light conditions favoured the cyanobacteria which have very efficient light-harvesting mechanisms (Cohen-Bazir and Bryant, 1982) to counter these variabilities. These factors may have led to the observed high abundance during this period compared to the others. Also, Awortwi *et al.* (2018) observed the lowest community respiration in the lake and the highest net primary productivity, as well as the highest growth rate of the phytoplankton during this period. This period also has relatively moderate photosynthetic efficiency (Awortwi *et al.*, 2022). These conditions naturally lead to an increase in abundance of the phytoplankton as was observed during this study and others (Awortwi *et al.*, 2015; 2018).

#### **Relationships between abundance and environmental conditions and resource factors**

The positive relationship between the mean light intensity of the mixed layer and the  $Z_{eu}:Z_{mix}$  ratio, both of which are indications of the light climate of a lake, with the phytoplankton abundance implies that increasing light levels in the lake mostly did not exceed intensities

which can cause photoinhibition and reduce the growth rate and abundance of the phytoplankton. This is because increases in these parameters tend to reduce light utilisation efficiency due to light inhibition (Wood *et al.*, 1978; Awortwi *et al.*, 2022). But the mean light intensity of the mixed layer in the lake ( $130 \mu\text{Em}^{-2}\text{s}^{-1}$ ) and the  $Z_{eu}:Z_{mix}$  ratio of 0.68 in this study, did not reach levels which would lead to light limitation of the phytoplankton (Grobellar, 1985; Cloern, 1999; Goldman, 1994) and hence, light may not adversely affect the phytoplankton. The light intensities encountered in the mixed layer of the lake were mostly within those typically expected in the mixed layer of lakes, which are usually conducive for the phytoplankton (Horne and Goldman, 1994). Increases in total phosphorus, are generally known to boost phytoplankton growth and abundance (Kalff, 2002) as was observed in this study. Though Lake Bosomtwe appears to have an adequate total phosphorus concentration and therefore the phytoplankton is not limited by it, it is the factor that led to the highest variation in the abundance of the phytoplankton during the study, as it had the highest coefficient of determination. Phosphorus is considered the scarcest nutrient among those absolutely required by photoautotrophs (Kalff, 2002) and also a reasonable measure of the fertility of a water body (Moss, 1979). Though several studies (Brylinsky and Mann, 1973; Awortwi *et al.*, 2018; Marzetz *et al.*, 2020) suggest that in nutrient-sufficient water bodies such as Lake Bosomtwe, energy and energy-related factors have a greater effect on the variability of the phytoplankton, it seems that variabilities in phosphorus play a key role in the phytoplankton cell abundance of the lake.

#### **CONCLUSIONS**

The mean cell abundance of Lake Bosomtwe during the study period from 2004 to 2006 is high and shows significant inter-annual differences but it is similar to other observations in tropical lakes. It also showed a clear seasonal signature associated with the mixing-stratification regime of the lake,

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which is consistent with current ecological hypotheses despite the continuous dominance of the cyanobacteria throughout all stations at all seasons of the study.

Overall, there is evidence to suggest that the variabilities in the phytoplankton abundance of Lake Bosomtwe are weakly regulated by a mixture of hydrographic or water column characteristics such as the mixed layer depth, ratio of euphotic to mixed layer depth, light intensity in the mixed layer, as well as nutrient factors, especially total phosphorus concentration. The high variabilities in the cell abundance of the phytoplankton seem to be associated with the similarly high variabilities in the physicochemical factors observed during the study.

## **ACKNOWLEDGEMENT**

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