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Temporal changes in the community structure and photosynthetic production of phytoplankton in Lake Babogaya, Ethiopia

By

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Table of contents

pages

List of Tables

List of Figures

List of Appendices

ABSTRACT

The temporal variations in the taxonomic composition, biomass and photosynthetic production of phytoplankton in Lake Bishoftu-Guda were investigated for a period of one year, from November, 2004 to October, 2005. Concurrently changes in some physico-chemical environmental variables were studied. Temporal variations in inorganic nutrients were observed with the maximum values coinciding with a period of relatively high rainfall at both stations. Lake's transparency was always high (Z_{SD} > 1m). Since the lake was transparent due to low phytoplankton biomass and suspended inorganic particles throughout the study period, the extinction of underwater light was low. The phytoplankton community of this nutrient-poor and deep lake was dominated by dinoflagllates during the dry and short rain periods before a shift in dominance to diatoms occurred during the long rainy period. Phytoplankton biomass of Lake Bishoftu-Guda was found to vary from 4 to 20 (mean=10.8) mg Chl a m^{-3} at the central station and from 3.96 to 24.2 (mean=10. 2) mg Chl a m^{-3} at the near-shore station. The depth-profiles of gross photosynthetic activity were of a typical pattern for phytoplankton with light-inhibition at the surface and with light-saturated rates generally occurring at a depth of 0.9 m of the water column on all sampling dates. The light-saturated rates of photosynthesis (A_{max}) ranged from 106 to 407 mg O_2 (~33.1 to 127 mg C) m^{-3} h^{-1}. A strong and positive correlation (r=0.76, p=0.000) was found between A_{max} and phytoplankton biomass. Biomass-specific rate of photosynthetic production at light-saturation (P_{max}) ranged from 19 to 29 mg O_2 (mg chl a)$^{-1}$ h^{-1} and was inversely related to phytoplankton biomass. Hourly integral photosynthesis ($\sum A$, g O^2 m^{-2} h^{-1}), which was obtained by the Grid Enumeration Analysis ranged from 0.112 to 0.66 g O_2 (~0.03 to 0.21 g C) m^{-2} h^{-1}. There was a positive but weak correlation (0.36), P=0.000) between phytoplankton biomass and hourly integral photosynthesis, while the correlation between $\sum A$ and A_{max} was 0.83. Daily production rates per unit area ($\sum\sum A$, g O^2 m^{-2} d^{-1}), were estimated from hourly integrated rates and the calculated daily integral production values ranged from 1.01 to 5.98 g O_2 (~0.32 to 1.87 g C) m^{-2} d^{-1}. The temporal variations in species composition, biomass and photosynthetic production of phytoplankton are discussed in relation to physico-chemical factors.

1. Introduction

World human population increases from year to year at an alarming rate. Food production must keep pace with the increasing number of people living on this planet. This cannot be achieved through conventional agriculture alone. An alternative approach should be sought for in order to provide adequate and high quality food for the ever-increasing human population. Aquatic ecosystems can make a unique contribution to nutrition by virtue of their extremely high productivity and importance as actual and potential sources of food for humans. Therefore, biological productivity should be studied at all levels of the food chains of aquatic ecosystems.

Investigations geared towards generating baseline of information about energy transfer within aquatic ecosystems involve measurements of primary production of phytoplankton and the environmental factors, which limit this production. In addition Melack (1976), Oglesby (1977) and Downing *et al.* (1990) also argue that primary production by phytoplankton is a better predictor of fish yield in lakes.

Limnological investigations on East African lakes date back to 1890s (Talling, 1995). However, studies on photosynthetic production of tropical phytoplankton started about 70 years ago (Talling and Lemoalle, 1998), with the application of the method to assess production rates per unit area waiting until 1950s (Prowse and Talling, 1958). Nowadays, the literature on the community structure and primary production of phytoplankton in relation to physicochemical environmental variables in African lakes is voluminous (see the review by Talling and Lemoalle, 1998).

Volcanic crater lakes are well represented in Africa. Several of them occur in Uganda (Beadle, 1966; Melack, 1978; Kizito *et al.,* 1993), Ethiopia (Baxter, 2002), Tanzania (Hecky, 1971; Kilham, 1971), Kenya (Melack, 1979b; MacIntyre and Melack, 1982) and Cameroon (Kling, 1988). The crater lakes in Ethiopia may provide admirable opportunities for comparative limnological studies owing to the considerable variations in their morphometric, physical and chemical features. Among these are the Bishoftu lakes, which form an extensive series of volcanic explosion craters in the vicinity of the town of Bishoftu (Debre Zeit).

Some crater lakes, particularly the alkaline saline lakes of East Africa including those in Ethiopia are of particular ecological interest because some of the highest recorded values of gross primary production and biomass of phytoplankton for any natural aquatic ecosystem have been measured in them (Talling *et al.,* 1973; Melack and Kilham, 1974). For example, Lakes Chitu, Hora-Hoda (Arenguade) and Hora-Kilole in Ethiopia (Talling *et al.,* 1973) and Lake Simbi in Kenya (Melack, 1979c) are among the world's most productive ecosystems with exceptionally high photosynthetic rates and algal biomass.

Primary production by planktonic algae is the fundamental biological process that sustains life in the aquatic environment as the primary producers form the basis of the aquatic food chain, which end in fish production. Photosynthetic production of phytoplankton also generates some 70% of the world's atmospheric oxygen supply (Reynolds, 1984). Study on primary production and the standing stock of phytoplankton in lakes also provides base-line data, which are essential for their optimum utilization and proper management. The assessment of the productive status and ecological health of lakes also necessitates a detailed study on primary production and standing stock of phytoplankton in lakes.

Temporal variations in the abundance, biomass and photosynthetic activity of phytoplankton are important and familiar features of East African lakes (Symoens *et al.,* 1981). Several studies (e.g. Talling, 1966, 1987; Melack and Kilham, 1974; Melack, 1979b; Kalff and Watson, 1986; Elizabeth Kebede and Amha Belay, 1994, see also Talling and Lemoalle, 1998) have documented seasonal variations in abundance, standing stock and production of phytoplankton in East African lakes. However, there is very little on record about temporal and spatial variations in algal biomass and photosynthetic activity of phytoplankton for Ethiopian lakes. The first studies made on the primary production of phytoplankton in Ethiopian Rift Valley and Bishoftu Crater Lakes are those of Amha Belay and Wood (1984) and Talling *et al.,* (1973) respectively. However, the only studies carried out on the temporal and spatial variations of phytoplankton production in relation to some physical and chemical variables over an extended period of time are those of Demeke Kifle (1985), and Demeke Kifle and Amha Belay (1990) on Lake Awassa, Girma Tilahun (1988) on Lake Ziway and Eyasu Shumulo (2004) on Lake Chamo.

Although the Bishoftu crater lakes have been the subjects of many limnological investigations, some dating as far back to the early 1930's (cited in Prosser *et al.,* 1968), published information on the community structure and photosynthetic production of phytoplankton in Lake Bishoftu-Guda (Babogaya or Pawlo) is non-existent. Moreover, there is a need to update the database on the physico-chemical and biological aspects of Lake Bishoftu-Guda over an extended period of time owing to possible water quality changes, which generally originate from the rapid growth of human population, urbanization coupled with agricultural development (Zinabu Gebre-Mariam, 2002).

The purpose of the present study was, therefore, to investigate the temporal changes in the community structure and primary production of phytoplankton in relation to some physico-chemical variables in Lake Bishoftu-Guda.

2. Description of the study lake

Lake Bishoftu-Guda (Babogaya or Pawlo, Fig. 1), is one of the Bishoftu explosion crater lakes found in and around Bishoftu (formerly known as Debre Zeit), a town situated 47km South East of Addis Ababa. Some morphometric and physico-chemical features of the lake are given in Table 1.

Previous limnological studies made on Lake Bishoftu-Guda described bathymetry (Prosser *et al.*, 1968), water chemistry (Prosser *et al.*, 1968; Wood *et al.*, 1984; Rippey and Wood, 1985; Zinabu Gebre-Mariam, 1994; Baxter, 2002; Zinabu Gebre-Mariam *et al.*, 2002), thermal stratification and mixing (Baxter and Wood, 1965; Baxter *et al.*, 1965; Wood *et al.*, 1976; 1984), chlorophyll *a* and phytoplankton (Wood and Talling, 1988; Zinabu Gebre-Mariam, 1994; Zinabu Gebre-Mariam and Taylor, 1997), bacterial abundance (Zinabu Gebre-Mariam and Taylor, 1997) and zooplankton associations (Green, 1986).

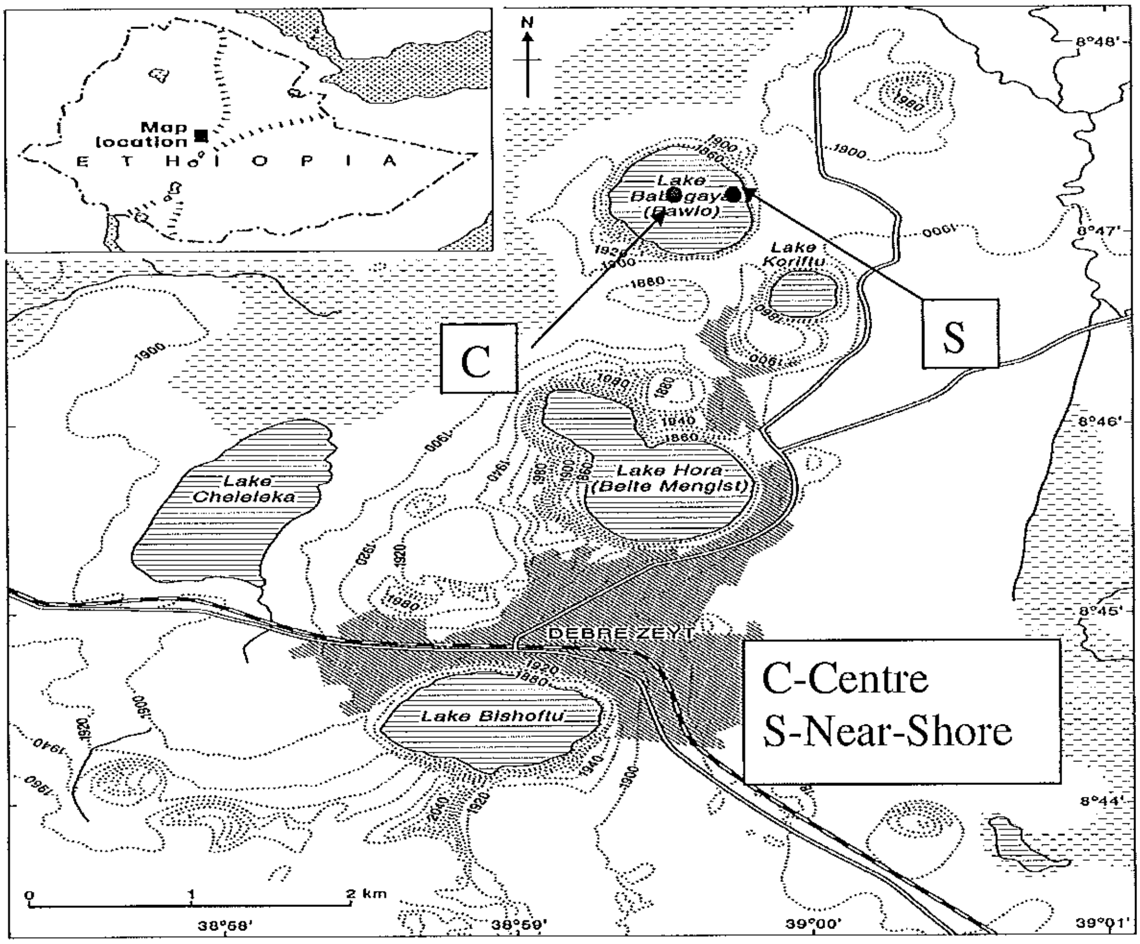

Fig.1. Location of the study Lake Bishoftu-Guda (Pawlo) in relation to other Bishoftu Crater Lakes.

Lake Bishoftu-Guda is a small, roughly circular and fairly deep lake found at an altitude of 1870 m and at about 9^0N and 39^0E latitude (Prosser, *et al.,* 1968; Wood, *et al.*, 1984). It is a closed system, surrounded by very steep and rocky hills. The vertical distance from the lake's surface to the crater rim is 20 m and affords moderate protection from wind (Baxter, 2002) The lake is fed primarily by precipitation falling directly on its surface and run-off from its small catchment area (Prosser *et al.*,1968), which was formed from volcanic rocks of basalt, rhyolite and tuff (Mohr, 1961). The lake's region is characterized by moderate rainfall, varying around about 850 mm per annum (Rippey and Wood, 1985), high incident solar radiation and low relative humidity. The region has two rainy periods, the minor one extending roughly from February to April and the major one beginning in June and ending in September.

Table 1. Some morphometric and physico-chemical features of Lake Bishoftu-Guda. (Source: morphometric data from Prosser *et al.*, 1968;Chemical data from Wood and Talling, 1988 unless otherwise stated)

Altitude (m)	1870
Surface Area (km^2)	0.58
Maximum depth (m)	(71[a]) 65
Mean depth (m)	38
Volume (Km^3)	0.022
Salinity (ppt)	0.928
Conductivity (K_{25}, $\mu S\ cm^{-1}$)	900[b]
Alkalinity ($meq\ l^{-1}$)	10.80
pH	9.20
Na^+ ($meq\ l^{-1}$)	5.50
Cl^- ($meq\ l^{-1}$)	0.90
Sum of cations ($meq\ l^{-1}$)	11.70
Sum of anions ($meq\ l^{-1}$)	11.40

[a]This study

[b]from Zinabu Gebre-Mariam (1994)

The temperature of its surface water was frequently found to be about 22^{0}C with a maximum of 24.5 and a minimum of 19.2^{0}C, while the bottom temperature was almost constant (19.2^{0}C-19.4^{0}C) (Wood, *et al.*, 1976). Through their studies over extended periods, Baxter *et al* (1965) and Wood *et al.* (1976) have shown the frequent occurrence of pronounced and deep-seated thermal stratification, with a consequent stratification of various chemical species in Lake Bishoftu-Guda (Wood *et al.*, 1984).

Lake Bishoftu-Guda is a dilute lake with Na^+ as the dominant cation and carbonate-bicarbonate as the dominant anion. The lake water is alkaline, with the erosion of basaltic and hyper-alkaline rocks surrounding the lake playing an important role in increasing the alkalinity of the water (Wood and Talling, 1988).

The phytoplankton community is dominated by blue-green algae, particularly *Microcystis aeruginosa* (Kutz.) Kutz. (Wood and Talling, 1988), while the zooplankton is composed of copepods [*Afrocyclops gibsoni* (Brady), *Lovenula africana* Daday], rotifers [*Asplancha sieboldi* (Leydig), *Brachionus calyciflorus* Pallas and *Hexarthra jenkinae* de Beachump (Green, 1986) and cladocera (Seyoum Mengistou, personal communication).

There is a small fishery based on tilapia (*Oreochromis niloticus* L.) and catfish (*Clarias gariepinus* Burchell) (Brook Lemma, personal communication) but fishing activities are not commonly observed.

Meteorological Data

The temporal variations in mean monthly maximum and minimum air temperature, monthly rainfall and wind speed of the lake region, obtained from Addis Ababa, Bole International Airport Weather Station are shown in Fig. 2 (see also Appendix 1).

Mean monthly minimum air temperature ranged from 7.3 to 13.6 ^{0}C, while the maximum mean monthly air temperature varied from 24 to 29 ^{0}C.

Monthly rainfall varied from 10.3 mm of November, 2004 to 225.2 mm of February, 2005. Although the region was described by Baxter *et al.* (1965) as having two rainy periods, the minor one extending roughly from February to April and the major one beginning in June and ending in September, appreciable quantities of rainfall were recorded throughout the period extending from February to September, 2005, with the highest peak in February. Rippey and Wood (1985) also documented that the lake area has moderate rainfall, varying around about 850 mm per annum. The present meteorological data, however, show an annual rainfall of about 1150 mm.

Wind Speed (in m s^{-1}) of the sampling dates ranged from 0.86 in July, 2005 to 2.74 in February, 2005.The weekly average wind speed of the days preceeding sampling days varied from 1.09 in September to 2.63 in May, 2005.

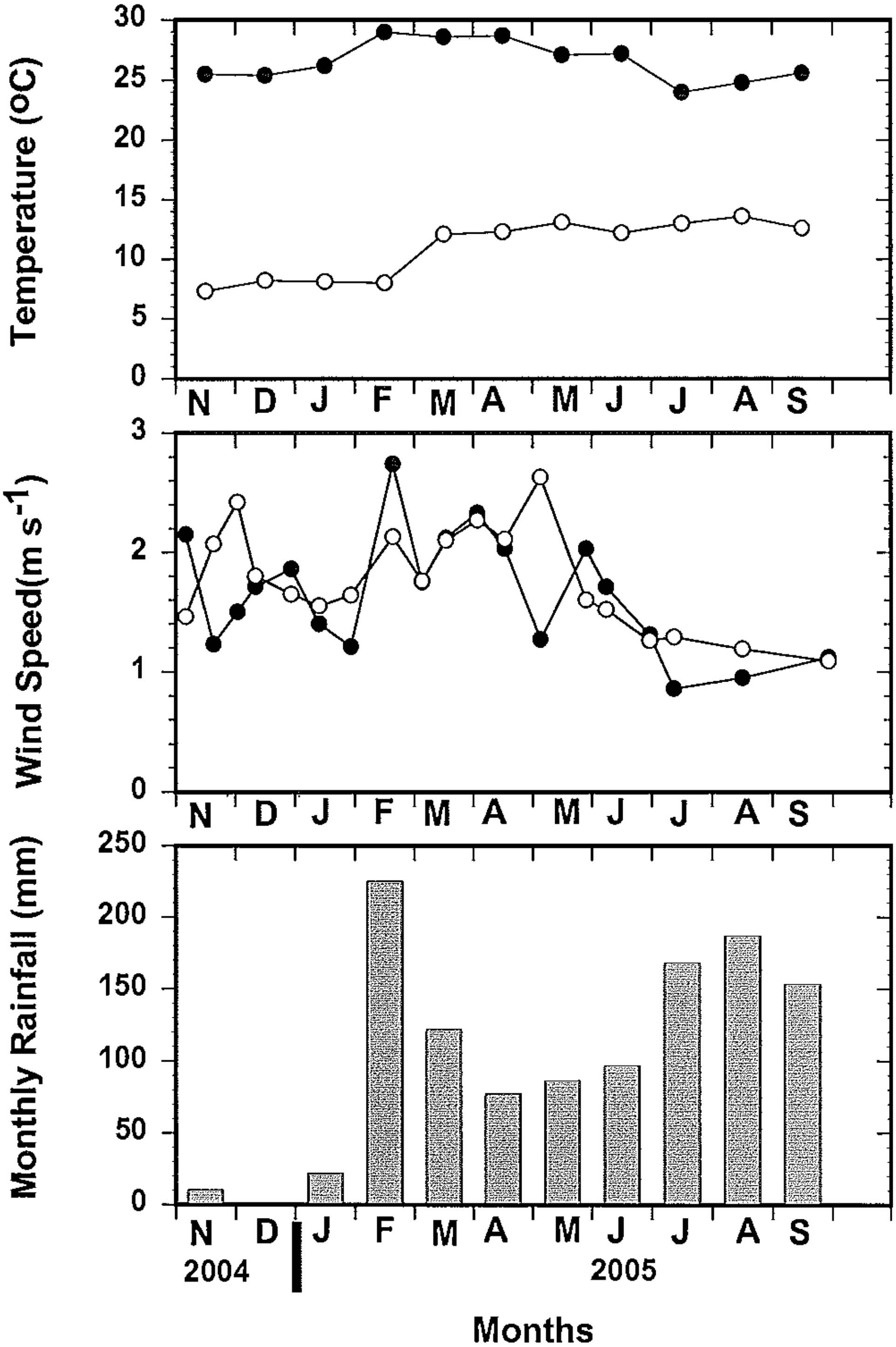

Fig. 2. Meteorological data of Lake Bishoftu Guda: mean maximum (●) and minimum (o) air temperature, wind speed on the sampling days(●) and mean of the preceding seven days(o) and monthly rainfall. (Source: Debre zeit Air force)

3. MATERIALS AND METHODS

3.1. Sampling Protocol

Two sampling stations-one central (~71 m deep) and another near-shore (5 m deep) were selected for the present study. These stations were sampled about every two weeks from November, 2004 through October, 2005.

Water samples were collected with a bottle sampler (Ruttner) from selected depths of the lake. These samples were used for the estimation of the biomass (as chlorophyll *a* concentration) and photosynthetic production of phytoplankton and for the analyses of inorganic nutrients.

3.2. *In-situ* measurements

Lake water transparency (vertical visibility) was estimated using a standard Secchi disc of 20 cm diameter. Dissolved oxygen and water temperature were measured at different depths of the upper part of water column (0 - 3.5 m) using a digital oxygen meter (Hanna 9143) while the determination of electrical conductivity and salinity was made with a digital S-C-T meter (YSI model 30). pH of surface water was measured with a portable digital pH meter (Hanna 9024).

3.3. Chemical Analyses

Carbonate-bicarbonate alkalinity was determined within a few hours of sample collection by titration with 0.1N HCl to a pH of 4.5 using unaltered samples.

Samples filtered through glass fiber filters (GF/C) were used for the analyses of various chemical parameters except alkalinity. Nitrate and Sulphate (SO_4^{2-}) were determined using a Hach Kit (DR/4000 spectrophotometer) at Water Works Design and Supervision Enterprise Water Laboratory. The methods used for the measurement of Nitrate, Sulphate (SO_4^{2-}), and Chloride (Cl^-), were the Cadmium Reduction Method (Wetzel and Likens, 2000), sulfa Ver 4 method and with mercuric nitrate method respectively. Calcium and Magnesium were analysed by EDTA titrametric method whereas the measurement of Potassium and Sodium was made by flame photometry.

For the analyses of the various chemical parameters (except for, NO_3-N) the procedures outlined in APHA *et al.*, (1999) were followed. The Ascorbic Acid and Molybdosilicate methods were used to measure orthophosphate and silica respectively.

3. 4. Identification of phytoplankton taxa and estimation of their relative abundance.

For the taxonomic analysis of phytoplankton and determination of their relative importance of different algal groups to the total phytoplankton abundance, samples collected with 10 and 25 μm plankton nets were used. The results presented here are based on samples collected with 25 μm plankton net as the 10 μm net was disrupted after the first 2 samplings. The phytoplankton samples were preserved with Lugol's iodine.

Identification of phytoplankton to genus or species level was made on the basis of various taxonomic literature available on phytoplankton including Whitford and Schumacher (1973); Jeeji-Bai, (1977); Durand and Leveque (1980); Gasse (1986); Talling (1987); Rot and Lenzenwger (1994); Komarek and Komarokova (2002) and John *et al.* (2002). To facilitate identification, fresh (unpreserved) samples were also examined microscopically.

Counting of phytoplankton was made in a Sedgwick-Rafter cell under an inverted microscope (Model-Nikon) following the procedures outlined in Hotzel G. and Croome (1999).

3.5. Estimation of phytoplankton biomass

Phytoplankton biomass was estimated as Chlorophyll *a* concentration. Samples collected from discrete depths distributed within the euphotic zone (approximated as Z_{SD} x 3) and mixed in equal proportions were used to produce composite samples. Appropriate volumes of these composite samples (in duplicate), depending on the presumed density of phytoplankton, were filtered onto glass fiber filters (Whatman GF/C) and pigments were extracted in 90% cold acetone. The filters were manually ground in a test tube with a glass rod in a small volume of 90% cold acetone to enhance extraction of pigments. After grinding, the algal material was placed in a parafilm-covered centrifuge tube and centrifuged at 3000 rpm for 10 minutes. The extract was then decanted into a 10 volumetric flask and made up to the mark with 90% acetone. The absorbance of centrifuged pigment extracts was measured spectrophotometrically at 665 and 750nm and the concentration of chlorophyll *a* was estimated using the approximate equation of Talling and Driver (1963).

3.6. *In situ* measurements of Primary Production

Primary production of phytoplankton was measured by the Light and Dark bottle Technique and the Winkler method of oxygen determination (Mackereth *et al.,* 1978) using the composite samples described under section 3.5. The composite samples were siphoned into 250 ml Pyrex light (clear) and dark (covered with cloth tape) glass bottles under reduced light conditions. The light bottles (in duplicate) were attached to a suspension line prepared for this purpose, at the following depths (in m): 0.00, 0.45, 0.90, 1.80, 2.70, 3.60, 4.50 and 5.40. Dark bottles were incubated at 0.0 and 5.40 m. On all sampling dates, the bottles were incubated for a period of three to four hours around mid-day (between 10:00 a.m. - 2:00 p.m.). Oxygen concentration was determined by titration with standardized thiosulphate solution using starch as indicator (Macereth *et al.,* 1978).

Explanations of symbols used throughout this thesis are given below.

Z_{SD} ....Secchi depth (in m)

Z_{eu} ....Depth of the euphotic zone (in m)

K_{25}............................Conductivity (Specific conductance) (in μS cm^{-1}) at 25^0C

K_d ....Mean vertical extinction coefficient of down welling irradiance (in units m^{-1})

B ....phytoplankton biomass (in mg Chl *a* m^{-3})

A ....Rate of gross photosynthesis per unit water volume, in mg O_2 m^{-3} h^{-1}

A_{max} ....light-saturated rate of gross photosynthesis, in mg O_2 m^{-3} h^{-1}

P (Φ, A/B)................. (=A/B) Specific rate of gross photosynthesis per unit biomass, mg O_2 (mg Chl *a*)$^{-1}$ h^{-1}

P_{max} (Φ_{max}, A_{max}/B) ..Specific rate of gross photosynthesis per unit biomass at light-saturation, mg O_2 (mg Chl *a*)$^{-1}$ h^{-1}

ΣA ....Hourly rate of gross photosynthesis per unit area, g O_2 m^{-2} h^{-1}

$\Sigma\Sigma$A ....Daily rate of gross photosynthesis per unit area, g O_2 m^{-2} d^{-1}

Ph.AR ....Photosynthetically Active Radiation in μE m^{-2} h^{-1} and E m^{-2} h^{-1}

4. RESULTS AND DISCUSSION

4.1. Physico-chemical parameters

Physical parameters

Surface water temperature, surface dissolved oxygen, Z_{SD}, K_d and Z_{eu} of the present sampling stations in Lake Bishoftu-Guda are presented in Table 2. The surface water temperatures of Lake Bishoftu-Guda ranged from a low value of 22.3 ^{0}C at the central station at the end of December, 2004 to a high value of 26.8 ^{0}C at the near-shore station in March, 2005 and varied directly with air temperature. On all sampling dates of the present study, the surface water temperatures of Lake Bishoftu-Guda increased slightly from the central station to the near-shore station. This variation was probably due to the difference in the time of measurement as the temperature measurements of the central station were made a little bit earlier than that of the near-shore station. Wood, *et al.* (1976) reported surface water temperatures that ranged from 19.2 to 24.5^{0}C, with most values about 22^{0}C for the same lake.

The surface water temperatures of Lake Bishoftu-Guda are closer to those recorded for most Ethiopian crater and Rift Valley Lakes (see Appendix 10) including Lake Hora-Hoda (Wood *et al.*, 1976), Lake Awassa (Demeke Kifle, 1985), Lake Ziway (Girma Tilahun, 1988) and Lakes Abijata and Langano (Kassahun Wodajo, 1982). They are, however, slightly lower than those reported by Eyasu Shumbulo (2004) for Lake Chamo, Ethiopia, Ganf and Horne (1975) for Lake George, Uganda and Lake Turkana (see Appendix 10). The higher surface water temperature of lakes like Chamo is obviously related to their location at considerably lower altitudes and the shallowness of the lake (Z_{max}=13 m).

The depth profiles of temperature measured at the central station are shown in Appendix 2. The water temperature was above 22^{0}C throughout the 0-3.5 column of water on all days of measurement, with vertical temperature difference of less than 0.5 ^{0}C between surface and the deepest depth of measurement on most sampling dates.

The Secchi depth (Z_{SD}), an estimator of lake transparency, was always high ranging from 1.48 to 4.46 m at the central station and from 1.39 to 4.66 m at the near-shore station with most values above 2 m (see Table 2). The possible explanations for the high Z_{SD} of Lake Bishoftu-Guda include the low phytoplankton biomass, which the lake supports and the presumed low concentration of suspended solids. In light of the fact that the surrounding vegetation and the crater wall give moderate protection from wind, and the lake is deep, resuspension of sediments in the water column as a result of mixing does not seem to be a common phenomenon in Lake Bishoftu-Guda.

In Crater lakes of East Africa including those in Ethiopia (Wood *et al.*, 1976, 1984), Kenya (Melack, 1981) and Uganda (Melack, 1978), seasonal stratification of different magnitude may occur depending on the extent of protection from wind, which is afforded by their crater walls (Wood *et al.,* 1976, 1984). The Bishoftu crater lakes are small (surface area < 1.1 Km^2), have steep-sided basin, and often lie in depressions likely to provide shelter from wind action. Variation among these lakes in the extent of deep circulation seems to be related to the variation in the depth and degree of exposure to wind (Baxter *et al.*, 1965; Wood *et al.*, 1976, 1984). In Lake Bishoftu-Guda, which is the second deepest lake (~71m deep) among these crater lakes, frequent and complete mixing is not to be expected. In their studies on African lakes, Baxter *et al.* (1965) also noted that complete mixing is normally frequent in lakes with a maximum depth (Z_{max}) of less than about 15-30 m and that thermal stratification is diurnal.

The maximum transparencies of 4.46 m at the central station and of 4.66 m at the near-shore station were observed in July, 2005 and seem to have resulted from an increase in lake volume with a consequent reduction in the concentration of suspended sediments. An increase in water transparency was also observed from October to December and from April to May, which coincided with low phytoplankton biomass. The decline in Secchi depth readings to below 2 m from January to the beginning of April was generally associated with increased biomass.

The Secchi depths of Lake Bishoftu-Guda are much higher than those recorded for most Ethiopian crater and Rift Valley Lakes (see Appendix 11) including Lakes Abaya, Langano, Koka and Ziway (Elizabeth Kebede, *et al.*,1994) and Lake Chamo (Eyasu Shumbulo, 2004).

Table 2. Surface water temperature, surface dissolved oxygen (DO), Z_{SD}, K_d and Z_{eu} at the central (C) and near-shore (S) stations of Lake Bishoftu-Guda.

Sampling Date	Station	Temp. (^{0}C)	DO (mg l^{-1})	Z_{SD} (m)	K_d (Units m^{-1})	Z_{eu}(m)
11/5/2004	C	23.4	7.66	3.78	0.38	12
	S	23.9	7.52	3.82	0.38	12
19/11/2004	C	23.1	6.61	3.98	0.36	13
	S	23.5	6.43	4.10	0.35	13
1/12/2004	C	23.4	7.12	3.28	0.44	10
	S	24.8	7.00	3.27	0.44	10
10/12/2004	C	22.7	7.94	2.23	0.65	7
	S	23	7.82	2.28	0.63	7
28/12/2004	C	22.3	12.34	2.26	0.64	7
	S	22.6	12.37	2.28	0.63	7
11/1/2005	C	22.4	2.75	1.72	0.84	5
	S	22.9	2.86	1.86	0.77	6
27/1/2005	C	23.9	15.8	1.66	0.87	5
	S	24.2	15.73	1.55	0.93	5
17/2/2005	C	23.3	12.64	1.51	0.95	5
	S	23.5	12.67	1.39	1.04	4
4/3/2005	C	26.3	13.75	1.48	0.97	5
	S	26.5	13.63	1.60	0.90	5
16/3/2005	C	26.6	_	1.55	0.93	5
	S	26.8	_	1.65	0.87	5
1/4/2005	C	25.1	6.42	1.67	0.86	5
	S	25.4	6.33	1.73	0.83	6
15/4/2005	C	24.8	8.56	3.28	0.44	10
	S	25	8.61	3.36	0.43	11
3/5/2005	C	25.8	9.62	2.19	0.66	7
	S	26	9.78	2.31	0.62	7
28/5/2005	C	24.9	7.38	3.42	0.42	11
	S	25.2	7.45	3.50	0.41	11
7/6/2005	C	26.3	_	3.33	0.43	11
	S	26.5	_	2.95	0.49	9
29/6/2005	C	23.7	8.42	2.33	0.62	7
	S	23.8	8.37	2.64	0.55	8
11/7/2005	C	24.3	_	4.46	0.32	14
	S	24.5	_	4.66	0.31	15
15/8/2005	C	24.3	7.58	2.12	0.68	7
	S	24.9	7.64	2.23	0.65	7

Table 2. contd.

Sampling Date	Station	Temp. (^{0}C)	DO (mg l^{-1})	Z_{sd} (m)	K_d (Units m^{-1})	Z_{eu}(m)
27/9/2005	C	26.4	5.77	2.47	0.58	8
	S	26.7	5.65	2.29	0.63	7
31/10/2005	C	24.1	9.34	2.82	0.51	9
	S	24.6	8.1	2.77	0.52	9

Lake's transparency (vertical visibility) showed an inverse, but weak relationship ($r= -0.41$, $p=0.076$) with Chl *a*. Linear regression of vertical visibility on phytoplankton biomass seems to suggest that a small fraction (<20%, see Appendix 9) of the variation in Z_{SD} was due to Chl *a*. This means that abiogenic turbidity is of over-riding importance in determining the photic conditions in the water column of Lake Bishoftu-Guda.

Mean vertical extinction coefficient of down-welling irradiance (K_d), which was estimated from Secchi depths, according to Holmes (1970) ranged from 0.32 to 0.97 at the central and from 0.31 to 1.04 in units m^{-1} at the near-shore stations (see Table 2).

The lower limits of the trophogenic zone, Euphotic depths (Z_{eu}), were also approximated as being equal to 4.6/ K_d (Kalff, 2002) and the values ranged from 5 to 14 m at the central station and from 4 to 15 m at the near-shore station (see Table 2).

The calculated Euphotic depths (Z_{eu}) of Lake Bishoftu-Guda are much deeper than those of most Ethiopian crater and Rift Valley Lakes (see Appendix 12) including Lakes Hora-Kilole and Hora-Hoda (Talling *et al.*, 1973), Lake Ziway (Girma Tilahun, 1988), Lake

Awassa (Demeke Kifle and Amha Belay, 1990) and Lake Chamo (Eyasu Shumbulo, 2004). The shallowness of the euphotic depths in the first two crater lakes was the result of biogenic turbidity, which emanated from their superabundant phytoplankton (Talling *et al.*, 1973), a situation which contrasts with those of Lakes Abaya and Langano (Wood *et al.*, 1978; Elizabeth Kebede *et al.*, 1994) in which the vertical extent of the trophogenic zone is almost exclusively of stable suspension of silt.

The only Ethiopian lakes with records of euphotic depths that approach at least some of the euphotic depth values estimated for Lake Bishoftu-Guda are the oligotrophic alkaline saline lake, Shalla (Amha and Wood, 1984) and the former oligotrophic Lakes Ardibo and Hayq (Baxter and Golobistch, 1970; Elizabeth Kebede *et al.*, 1992) (see Appendix 12).

Chemical parameters

Dissolved oxygen (DO) concentrations at the surface of Lake Bishoftu-Guda ranged from a minimum of 2.75 to a maximum of 15.8 mg l^{-1} at central station and from a minimum of 2.86 to a maximum of 15.73 mg l^{-1}, with corresponding saturation values at the prevailing temperature of about 32 and 184 % and 29 and 181% respectively. The concentration of oxygen reached its seasonal maximum at the end of January, 2005 and remained at high levels before its sudden drop to a much lower value (6.4 mg l^{-1}) in April, 2005.

The concentration of dissolved oxygen was below 8 mg l^{-1} for most of the rest of the study period. The minimum dissolved oxygen concentration was observed in mid-January, 2005. There were no incidents of hypoxia (< 2 mg O_2 l^{-1}) although there is anecdotal evidence of fishkill in the years preceding the study period in Lake Bishoftu-Guda, which coincided with an offensive odour of the lake water. This probably resulted from mixing of the water column after prolonged period of thermal stratification and associated deoxygenation of the water column.

According to the observations made on the thermal characteristics of Lake Bishoftu-Guda from April, 1964 to September, 1966 (Wood *et al.*, 1976) and reviewed recently by Baxter (2002), the lake stratifies during most of the time of the year with occasional occurrence of multiple thermoclines. Although the weather condition throughout the country may vary from year to year and hence the thermal stratification pattern of Ethiopian lakes, the near-complete destratification of the water column in Lake Bishoftu-Guda was observed during the coldest and driest period extending from November to February, as a result of the physical conditions that resulted from a combination of low minimum temperatures and high rates of evaporative cooling and that favour downward mixing of the epilimnion (Baxter, 2002). During a brief period of this nearly isothermal condition, oxygen was absent almost throughout the water column (Wood *et al.*, 1976; Baxter, 2002).

Depth profiles of dissolved oxygen measured down to a depth of 3.5 at the central station are shown in Appendix 2. In most depth profiles, the concentration of oxygen throughout the 0-3.5 column of water was between 7 and 8 mg l^{-1} and the vertical distribution was more or less even. Concentrations of dissolved oxygen in excess of 12 mg l^{-1}

were recorded at the end of January, 2005, mid-February, and early-March, 2005, coincident with high phytoplankton biomass. The difference between the lowest and highest values of dissolved oxygen concentration measured within each depth profile was always less than 1 mg l^{-1} except in early-March, mid-August, end of September and October, when differences ranged from 1.47 to 2.45 mg l^{-1}.

pH, Total alkalinity, Electrical conductivity and concentration of major ions of the surface water in Lake Bishoftu-Guda measured over the study period are shown in Table 3. Electrical conductivity (K_{25}) of the surface water of Lake Bishoftu-Guda ranged from 793 to 808 μS cm^{-1} in the central and from 803 and 804 μS cm^{-1} in near-shore stations. These results are comparable to the values previously recorded by Prosser *et al.* (1968) for the same lake (see Appendix 6). The lake was characterized by very low salinity of about 0.4 g l^{-1} at both stations, which is closer to 0.3 g l^{-1} recorded in 1963 by Prosser *et al.* (1968) for the same lake. The salinity of Lake Bishoftu-Guda is broadly similar to those reported by Wood and Talling (1988) for East African lakes (see Appendix 13) including Lake Koka and Lake Ziway both in Ethiopia, Lake George, Uganda and Naivasha, Kenya. They are, however, lower than those observed in the other Bishoftu crater lakes, Lakes Hora-Hoda (Prosser *et al.,* 1968), and Bishoftu (Prosser *et al.,* 1968), and the crater lake in the Ethiopian Rift Valley, Lake Chitu, (Elizabeth Kebde *et al.*, 1994). The present observations on K_{25} and salinity of Lake Bishoftu-Guda are very close to those measured in 1963 (Prosser, *et al.,* 1968), showing that small changes in chemical composition of the lake water have occurred after 1963.

Table 3. pH, Total alkalinity (TA), Conductivity (K_{25}), and concentration of major cations and anions at the central (C) and near-shore (S) stations of L. Bishoftu-Guda. Units are meq l^{-1} unless otherwise indicated.

Sampling	Station	pH	TA	K_{25} ($\mu S\ cm^{-1}$)	Na	K	Ca	Mg	Cl	SO_4
5/11/2004	C	9.03	12.1	800	0.8	1.6	1.24	1.3	1.4	0.01
	S	9.05		804	–	–	–	–	–	–
19/11/2004	C	8.64	6.8	793	1.72	0.54	1.1	0.38	0.44	0.024
	S	9.04		801	–	–	–	–	–	–
1/12/2004	C	8.48	6.4	793	1.96	0.62	0.78	0.58	0.48	0.016
	S	8.58		803						
10/12/2004	C	8.82	7.15	888	1.98	0.6	0.9	0.64	0.48	0.022
	S	8.66		888	–	–	–	–	–	–
28/12/2004	C	9.08	11.6	888	–	–	–	–	–	–
	S	8.98		888	–	–	–	–	–	–
11/1/2005	C	8.65	10	–	–	–	–	–	–	–
	S	8.96		–	–	–	–	–	–	
27/1/2005	C	8.98	9.7	–	2	0.62	1.24	0.44	0.48	0.0264
	S	8.99		–						
17/2/2005	C	8.95	10.1	–	1.9	0.62	0.72	0.74	0.56	0.016
	S	8.97		–	–	–	–	–	–	–
4/3/2005	C	9.09	9.6	–	–	–	–	–	–	–
	S	9.05		–	–	–	–	–	–	–
16/3/2005	C	–	9.7	–	2.06	0.64	0.92	0.72	0.5	0.016
	S	–		–						
1/4/2005	C	9	8.4	–	1.94	0.6	0.94	0.62	0.48	0.016
	S	9.01		–						
15/4/2005	C	8.85	9.2	–	2.02	0.6	1.06	0.48	0.52	0.016
	S	8.87		–	–	–	–	–	–	–
3/5/2005	C	8.95	10.3	–	–	–	–	–	–	–
	S	8.96		–	–	–	–	–	–	–
28/5/2005	C	8.89	10.3	–	–	–	–	–	–	–
	S	8.91		–	–	–	–	–	–	–

Table 5 contd.

Sampling	Station	pH	TA	K_{25} ($\mu S\ cm^{-1}$)	Na	K	Ca	Mg	Cl	SO_4
7/6/2005	C	8.87	10.1	_	_	_	_	_	_	_
	S	8.84		_	_	_	_	_	_	_
29/6/2005	C	8.88	10.03	_	_	_	_	_	_	_
	S	8.85		_	_	_	_	_	_	_
11/7/2005	C	8.95	11.15	_	_	_	_	_	_	_
	S	8.96		_	_	_	_	_	_	_
15/8/2005	C	8.98	9.6	_	_	_	_	_	_	_
	S	8.95		_	_	_	_	_	_	_
27/9/2005	C	9.09	10.6	_	_	_	_	_	_	_
	S	9.03		_	_	_	_	_	_	_
31/10/2005	C	8.93	10.3	_	_	_	_	_	_	_
	S	8.96		_	_	_	_	_	_	_

'-' no datum is available

Carbonate-bicarbonate alkalinity determined over the study period ranged from 6.4 to 12.1 meq l^{-1}. The alkalinity of Lake Bishoftu-Guda is constituted largely by bicarbonate-carbonate ion. The alkalinity values reported by Prosser *et al.* (1968) and Zinabu Gebre-Mariam (1994) (see Appendix 6) are within the range of the present study. The pH of the surface water ranged from 8.48 to 9.09 at the central station and from 8.58 to 9.05 at the near-shore station. Similar pH values, were reported by Prosser *et al.* (1968) for the same lake (see Appendix 6). The high pH values were generally associated with increased productivity and/or biomass. According to Maberly (1996) high rates of primary production allow large daytime CO_2 and HCO_3^- withdrawal resulting in a large rise in pH. A positive and fairly strong (r=0.69) correlation (see Appendix 9) between alkalinity and pH was observed for Lake Bishoftu-Guda although in such bicarbonate-type lakes the correlation between these chemical parameters have been found to be quite high (Talling and Talling, 1965; Wood and Talling, 1988).

As in other East African lakes (Talling and Talling, 1965; Wood and Talling, 1988), the ionic composition of Lake Babogay was dominated by sodium and bicarbonate-carbonate.

The ranges of concentrations of the major cations (in meq l^{-1}) in Lake Bishoftu-Guda were from 0.8 to 2.06 for Na^{+}, 0.54 to 1.6 for K^{+}, 0.72 to 1.24 for Ca^{2+} and 0.38 to 1.3 for Mg^{2+}, while those for the major anions were from 0.44 to 1.4 meq l^{-1} for Cl^{-} and 0.01 to 0.026 meq l^{-1} for SO_4^{2-}. The cationic proportions in Lake Bishoftu-Guda followed the order $Na^{+}>Ca^{2+}>K^{+}>Mg^{2+}$, similar to that of Lake Cheleklaka (Getachew Teffera, 1980) but different from that reported by Prosser *et al.* (1968) for Lake Bishoftu-Guda and in which the concentration of Mg^{2+} was much higher than those of Ca^{2+} and K^{+}. The anionic proportion followed the order $HCO_3^{-}+CO_3^{2-}>Cl^{-}>SO_4^{2-}$, which is a common feature of a large number of East African lakes including those in Ethiopia (Talling and Talling, 1965; Wood and Talling, 1988).

Inorganic nutrients

The temporal variations in the concentration of inorganic nutrients in relation to phytoplankton biomass in composite samples collected from the central and near-shore stations in Lake Bishoftu-Guda are shown in Fig. 3.

Nitrate-N varied from near the lower limit of its delectability to 31µg l^{-1} at both central and near-shore stations (See Appendix 4). Nitrate peaked at the beginning of December, 2004 at both stations before it declined to a low value around mid-December. Thereafter, it almost consistently increased to another peak at the beginning of March at both stations and remained at high levels until it dropped to its seasonal minimum in Mid-April, 2005 at both stations. Its concentrations remained at relatively low levels throughout the rest of the study period. High levels of nitrate-nitrogen were often associated with relatively high algal biomass and the correlation between the two was positive but fairly strong (r=0.5) (see Appendix 9).

Although the generally low levels of nitrate-nitrogen observed in the present study and documented by Wood *et al.* (1984) suggest the likelihood of nitrogen limitation in Lake Bishoftu-Guda, this may not occur as ammonium-nitrogen was found to be the dominant form of inorganic nitrogen at all depths of the water column in Lake Bishoftu-Guda investigated over several years by Wood *et al.* (1976).

Soluble reactive phosphate (SRP) of Lake Bishoftu-Guda varied from below 1 μg l^{-1} at both stations to 11 μg l^{-1} at the central station and to about 13 μg l^{-1} at the near-shore station (see Appendix 4). The maximum values were registered in August, 2005 at both stations, which could be due to the heavy rains at this time of the year that may have brought phosphorus into the lake from the catchments through runoff. The concentration of phosphorus remained below 5 μg l^{-1} for most of the study period. The lowest concentrations of phosphate in July coincided with one of the large peaks of Chl *a* at the central and near-shore stations.

The observed low concentrations of phosphate are comparable to those previously reported by Prosser *et al.* (1968) for Lakes Bishoftu-Guda, Hora and Bishoftu although they are considerably lower than the values registered for all the crater lakes at Bishoftu by Zinabu Gebre-Mariam (1994) and the Rift Valley Lakes, including Lakes Awassa (Demeke Kifle and Amha Belay, 1990), Chamo (Eyasu Shubulo, 2004) and Ziway (Getachew Beneberu, 2004) (see Appendix 15). Much higher concentrations of SRP have been registered from crater lakes of Ethiopia, such as Lakes Hora-Hoda and Hora-Kilole by Prosser, *et al.* (1968) and Lake Chitu by Elizabeth Kebede, *et al.* (1994) and Lake Simbi in Kenya by Melack (1979c).

As indicated in the foregoing paragraphs, although phosphorus concentrations in African waters, particularly in alkaline soda lakes of East Africa, are generally higher than elsewhere (Talling and Talling, 1965), they were very low with most values below 5 μg l^{-1} in Lake Bishoftu-Guda. The persistent and more or less complete plant cover on almost all sides of the lake and the great depth of the lake are contributory factors to the observed low level of phosphorus.

Contrary to nitrate and phosphate, molybdate reactive silica was found at concentrations above 10 mg l^{-1} at both stations throughout the study period as it is usually in East African lakes including those in Ethiopia (Talling and Talling, 1965; Wood and Talling, 1988; Talling and Lemoalle, 1998). Concentration of silica varied from 11 at both stations to 58 mg l^{-1} at the central station and to 54 mg l^{-1} at the near-shore station (see Appendix 4). Silica peaked in mid–December and January, early May and mid-July with abrupt drops in concentration in between at both stations. Maximum values of silica concentration were observed in July, 2005 at both stations. The marked drop in silica concentration from the seasonal maximum values in July to low values of the period from August to October, 2005 at both stations could be explained by the higher demand for this nutrient by diatoms, which dominated the planktonic algae at this time of the year. Most of the low values occurred during the period extending from August to October, 2005 at both stations. However, concentration of silica limiting to diatom growth was never approached. Prosser *et al.* (1968) and Zinabu Gebre-Mariam (1994) reported molybdate reactive silica concentrations of 25 and 45 mg l^{-1}, respectively for surface water of Lake Bishoftu-Guda, which are within the range of values recorded in the present study.

The concentrations of silica, in mg l^{-1}, recorded for Lake Bishoftu-Guda in this study are comparable to those reported by Wood and Talling (1988) for Lakes Koka, Ziway, Abaya and Langano and by Prosser *et al.* (1968) for Lakes Hora, Hora-Hoda and Bishoftu (see Appendix 16). Much higher values of silica concentration were, however documented by Wood and Talling, (1988) for the alkaline Crater Lake Chitu.

Although all inorganic nutrients exhibited spatial variations, both horizontally and vertically variations, no significant differences in the concentration of nutrients between the two stations were observed as the T-test values (T-Value = 0.45 for nitrate, 0.97 for phosphate and 0.79 for silica, conducted at p = 0.05) indicate (see Appendix 9).

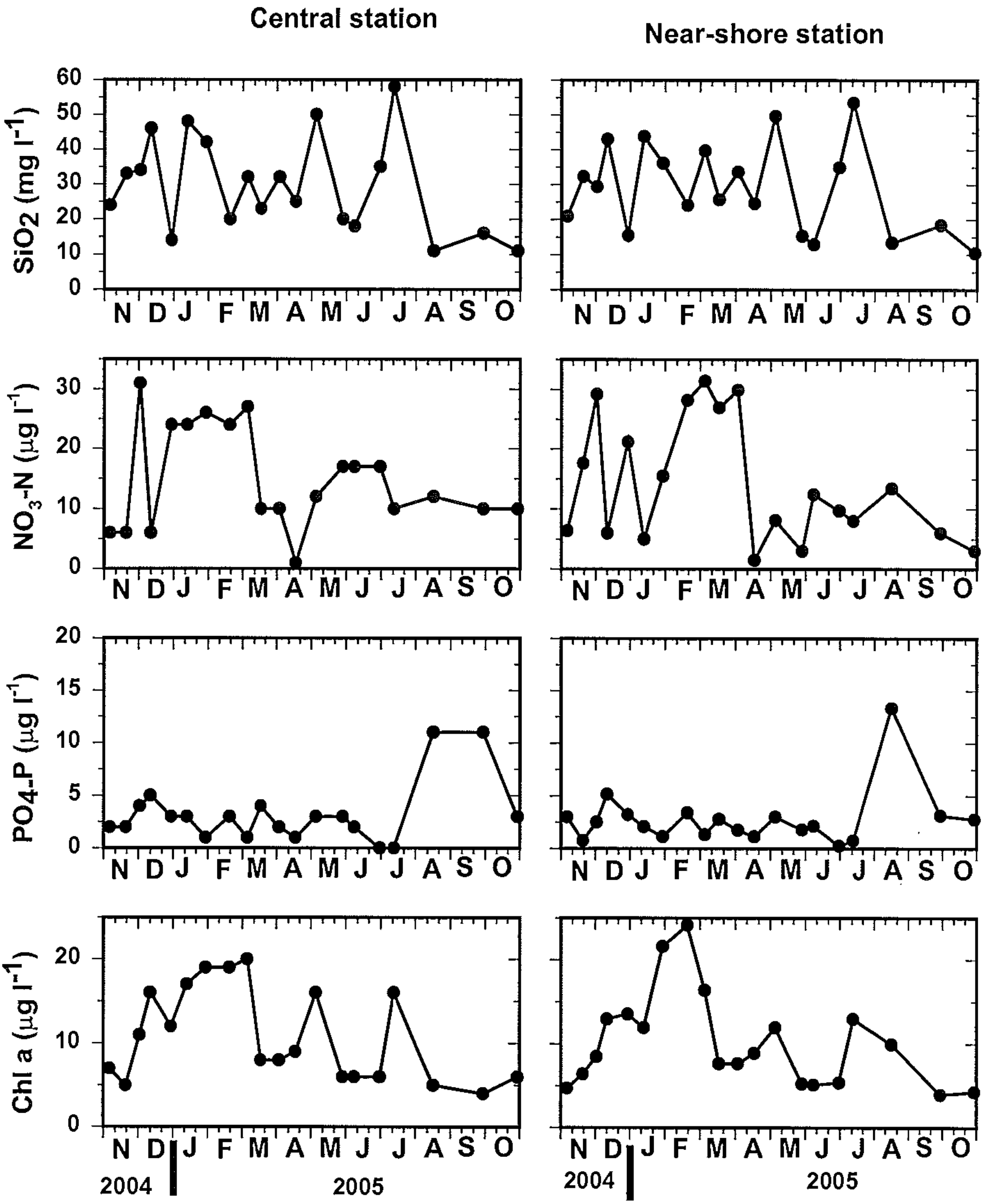

Fig. 3. Temporal changes in the concentration of inorganic nutrients in relation to phytoplankton biomass measured as chl a at the central and near-shore stations in Lake Bishoftu Guda.

The vertical distributions of NO_3-N, PO_4-P and SiO_2 in relation to phytoplankton biomass measured as chlorophyll *a* concentration on some sampling dates of the present study are presented in Fig. 4. Although no regular pattern was evident, all nutrients and phytoplankton biomass exhibited vertical stratifications, suggesting the absence of frequent mixing of the epilimnetic waters in Lake Bishoftu-Guda. Phytoplankton biomass exhibited a more or less uniform distribution down the upper part of the water column in September, 2005, despite the marked vertical variations in the concentrations of inorganic nutrients.

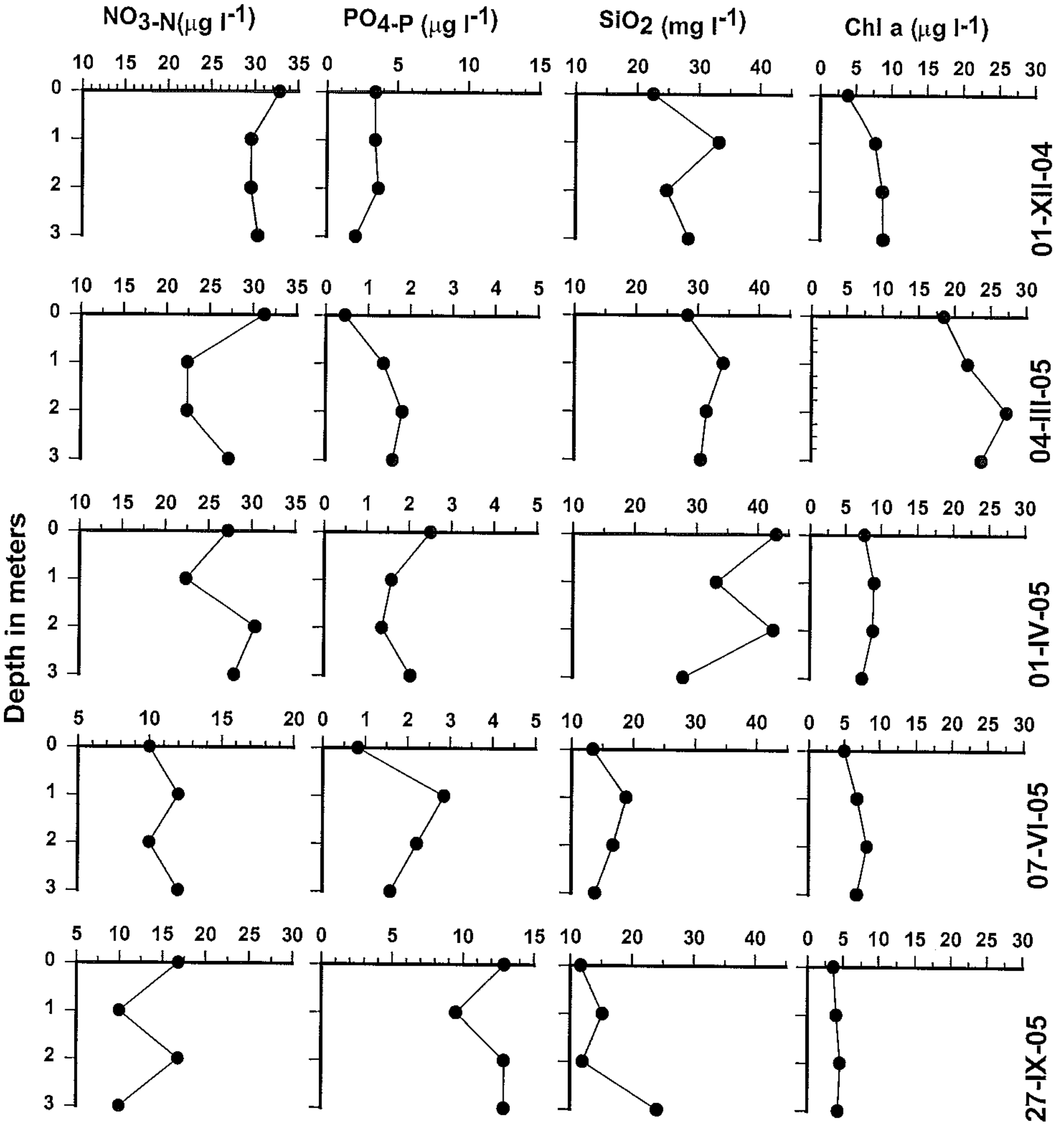

Fig. 4. Depth-profiles of inorganic nutrients in relation to chlorophyll a concentration on some sampling dates at the central station in Lake Bishoftu Guda.

4.2. Biological features of the lake

4.2.1. Taxonomic Composition of phytoplankton

Table 4 presents a list of major phytoplankton species identified in samples collected over the study period. A total number of 32 species /taxa of phytoplankton were recorded during the present study period. The identified species belonged to seven algal classes and twenty-three genera.

Table 4. List of phytoplankton species/taxa identified in samples collected from Lake Bishoftu-Guda.

***Bacillariophyceae* (diatoms)**

Cyclotella planctonica Brunthaler
Cymbella cistula (Hemp.) Grun.
Fragilaria capucina Desm.
F. ulna
Nitzschia nyassensis O. Muller
N. vermicularis (Kutz.) Grun.
Surirella linearis var. spendid (Ehr.) Var Huerck
Synedra dorsiventralis O. Muller

Haptophyceae (haptophytes)
(Marss.) Skuja
Chrysochromulina cf. parva Lack.

Cyanophyceae (blue-green algae)
Chroococcus limneticus Lemm.

C. turgidus (Kutz.) Näg.
Cylinrospermopsis sp.
Microcystis aeruginosa (Kutz.) Kutz.)
Merismopedia glauca (Eher.) Näg.
Rhaphidiopsis mediterraneae Skuja

Euglenophyceae (euglenoids)
Euglena cf. deses Ehr.
Lepocinclis cf. striata (Hubner) Skuja

***Chlorophyceae* (green algae)**

Cosmarium depressum (Nag.) Lund.
Pediastrum duplex Meyen.
Pediastrum cf. integrum
Tetraedron minimum (A.Br.) Hansg.
T. triangulare Korsch.
Tetrastrum hetercanthum Nordst.

Cryptophyceae (cryptomonads)
Cryptomonas marssonii

C. obovata Skuja

C. ovata Ehr.

Dinophyceae (dinoflagellates)

Gymnodinium aeruginosum Stein.
G. limneticus Lackey
Peridinium aciculiferum Lemm.
Peridinium bipes stein
Pyrophacus sp.
Ceratium carolineanum (Bailey) Jörgensen

Acknowledging the fact that plankton nets are not recommended for the quantitative assessment of phytoplankton, we used net samples for the estimation of the relative seasonal importance of the different algal groups as all algal units with dimensions greater than the mesh size of the net have equal probability of being retained. The contributions of the different algal groups to the abundance of total phytoplankton are expressed as percentage of the total number of phytoplankton.

The temporal variations in the relative importance (in terms of number of algal units relative to the total number of phytoplankton) of the different algal groups are shown in Fig. 5. The phytoplankton community of Lake Bishoftu-Guda was dominated by two classes of algae- namely *Dinophyceae* (dinoflagellates) (annual mean = 52%) and *Bacillariophyceae* (diatoms) (annual mean = 32%). This is inconsistent with the findings of Wood and Talling (1988), indicated the dominance of blue-green algae, particularly of *Microcystis aeruginosa* in Lake Bishoftu-Guda. The most important species of *Dinophyceae* were *Peridinium aciculiferum* and *P. bipes* whereas the most important species of the class *Bacillariophyceae* were *Nitzschia vermicularis* and *N. nyassensis*. Others, which were present in the phytoplankton community of Lake Bishoftu-Guda, although often rare, included blue-green algae (*Cyanophyceae*), green algae (*Chlorophyceae*) and euglenoids (*Euglenophyceae*).

Temporal changes in the dominance of algal groups were observed in the phytoplankton community of Lake Bishoftu-Guda Fig. 5. From November, 2004 to July, 2005, the dinoflagellates were more important in their contribution to the total phytoplankton abundance (43-78%) than all other algal groups, while the contribution of the other dominant group- diatoms- decreased from 28 to 7%. The contribution of green algae and euglenoids was small throughout the year, although the species of green algae *Tetraedron minimum* (5%), *Tetraedron triangulare* (10%) and *Tetrastrum hetercanthium* (3%) showed an increase between January and March, which was a period of high algal biomass.

In August, there was a shift in dominance from dinoflagellates (12-23%) to diatoms (60-80%), which coincided with a decline in silica concentration.

In dimictic lakes of the temperate latitudes, temporal changes in dominant species, biomass and abundance of phytoplankton are correlated with the strong seasonality in temperature and irradiance (Wetzel, 2001). In tropical lakes, where the variations imposed at higher latitudes by the seasonality of light and temperature are reduced (Lewis, 2000), temporal changes in species composition and biomass are best linked to hydrographic and hydrological changes (Talling, 1986; Talling and Lemoalle, 1998).

The dominance of dinoflagellates in Lake Bishoftu-Guda over an extended period of time seems to be linked to the water column stability in the lake. Lake Bishoftu-Guda is a deep lake, which is moderately protected from wind by crater walls and natural as well as managed vegetation. Previous reports (Baxter *et al.*, 1965; Wood *et al.,* 1976, 1984) as well as the heterogenous vertical distributions of chemical and biological parameters observed in the present study to compete with other phytoplankton (Pollingher, 1987; 1988), which include luxury consumption of phosphorus (Serruya and Berman, 1975) and nitrogen (Bhovichitra and Swift, 1977; Chapman and Pfiester, 1995), vertical migration which maximizes nutrient uptake from nutrient-replete hypolimnetic waters (Cullen and Horrigan, 1981; James *et al.*, 1992) and reduces sinking losses (Levandowsky and Kaneta, 1987). Many species are capable of mixotrophic nutrition (Gaines and Elbrachter, 1987) while the large-sized dinoflagellates experience low grazing losses (Pollingher, 1987). The ability of dinoflagellates to migrate vertically to great depths is of immense competitive importance in lakes like Bishoftu-Guda, where epilimnetic waters are nutrient-poor and in which deep parts of the water column may have as high concentrations of phosphorus as over 800 µg l^{-1} (Wood *et al.*, 1984). It is this nutrient-acquisition ability, which allows dinoflagellates to occupy notoriously nutrient-poor tropical and sub-tropical open-ocean waters (Graham and Wilcox, 2000).

The dominance of diatoms during the period of heavy precipitation seems to be related to a change in the thermal stability and nutrient-status of the water column. Heavy rainfalls thicken the mixed layer depth by eroding at least the upper part of the metalimnetic region and inject nutrients into the water column (Talling and Lemoalle, 1998) although they reduce light penetration by introducing silt through runoff if the surroundings of the lake lack plant cover. The importance of mixing, to the dynamics of phytoplankton in tropical African lakes has been emphasized by Talling (1966; 1969; 1986) and Hecky and Kling (1981; 1987). Diatoms are planktonic algae, whose maintenance in suspension depends on turbulence (Reynolds, 1984) and which are able to exploit temporarily favourable conditions and build up their populations because of their intrinsically high growth rates (Paasche, 1975).

4.2.2. Phytoplankton biomass

Temporal changes in phytoplankton biomass, measured as chlorophyll *a* concentration in composite samples collected from both stations, are shown in Fig. 3 (see also Appendix 4).

Phytoplankton biomass of Lake Bishoftu-Guda was found to vary from 4 to 20 (mean=10.8) mg Chl *a* m^{-3} at the central station and from 3.96 to 24.2 (mean=10.2) mg Chl *a* m^{-3} at the near-shore station. The highest biomass values (in mg Chl *a* m^{-3}) recorded in this study are lower than those reported for samples collected in 1990 (37), 1991 (29) and 1992 (33) from the same lake by Zinabu Gebre-Mariam and Taylor (1997). The low biomass values recorded for Lake Bishoftu-Guda in this study are comparable to those reported for Lakes Shalla and Langano, during 1966 (Wood *et al.*, 1978) and Lake Tanganyika during 2003 (Chale, 2004) while the high biomass values are closer to those reported for Lake Abaya (Elizabeth Kebede *et al.*, 1994), Koka (Elizabeth Kebede and Willen 1998) and Lake Awassa (Tadesse Fetahi, 2004) all in Ethiopia and Lake Naivasha in Kenya (Kalff and Watson, 1986). However, much higher algal biomasses are prevalent in shallower basins within a deeper lake (e.g. Lake Victoria's Winam Gulf, Talling, 1965; Melack, 1979b). Very dense phytoplankton, dominated by the cyanobacterium *Spirulina platensis* (*Arthospira fusiformis*) and associated with exceptionally high algal biomass, are also known from deeper (> 20 m) phosphorus-rich saline lakes, such as Lake

Hora-Hoda in Ethiopia (Talling *et al.*, 1973) and Lake Simbi, in Kenya (Melack, 1979c) (see Appendix 17)

Although marked changes in phytoplankton biomass with time were observed, a consistent pattern in the spatial variation of phytoplankton biomass was not apparent. Phytoplankton biomass varied irregularly at both stations with peaks in March, May and July, 2005 at the central station and in February, May and July, 2005 at the near-shore station, with the highest concentration of chlorophyll *a* (24.2 mg Chl *a* m^{-3}) observed in the near -shore station in February, 2005.

A positive but fairly strong correlation between phytoplankton biomass in the composite samples and nitrate-nitrogen ($r = 0.5$) and silica ($r=0.6$) was found while its correlation with phosphate was positive, but weak ($r = 0.35$) (see Appendix 9). A linear regression of biomass on inorganic nutrients (see Appendix 9) showed that about 25, 12 and 36% of the variation in biomass can be accounted for by the variation in nitrate-nitrogen, phosphate and silica, respectively. Despite the fact that the dependence of phytoplankton biomass on phosphorus (Dillon and Rigler, 1974; Schindler, 1977, 1978; Peters, 1986 and references therein) is remarkably common in lakes, the correlation between chlorophyll *a* and phosphorus is poor for Lake Bishoftu-Guda probably corroborating the assertion that nitrogen-limitation is more likely than phosphorus-limitation in tropical lakes (Talling and Talling, 1965; Elizabeth Kebede and Willen, 1998; Wood and Talling, 1998).

In light of the differences in the biomass values observed between the two stations, a t-test was conducted to determine if the horizontal variation was significant. The t-test conducted for the biomass values of the two stations showed no significant variation. (see Appendix 9).

4.2.3. Photosynthetic production

4.2.3.1. Depth profiles of photosynthesis

In situ experimental measurements of rates of gross photosynthesis per unit water volume (A, mg O_2 m^{-3} h^{-1}) are shown in Fig. 6 (see also Appendix 7).

Since the same composite samples were incubated at different depths, the variations in photosynthetic rates with depth were related to differing responses of uniform algal biomass to different level of irradiance. The depth profiles of gross photosynthesis per unit volume usually had maximum rates at a depth of 0.9 m and gradually declined with increasing depth due to light limitation.

The depth-profiles of gross photosynthesis exhibited reduced rates at the surface of the water column due to photoinhibition, which is a typical pattern for phytoplankton. Talling and Lemoalle (1998) argued that depression of production rates at a lake's surface is a common feature of profiles of photosynthesis in tropical waters as it is of temperate. Depressed photosynthetic rates at the surface of water columns have been reported from many African lakes including those in Ethiopia (Talling *et al.,* 1973; Amha Belay and Wood, 1984; Girma Tilahun, 1988; Demeke Kifle and Amha Belay, 1990), Chad

(Lemoalle, 1983), Kenya (Talling, 1965; Melack, 1979b, 1981; Vareschi, 1982) and Tanzania (Melack and Kilham, 1974).

Photoinhibition is associated with excess of photons that are not dissipated by photosynthetic carbon fixation when light exceeds physiological saturation (Long *et al*, 1994; Falkowski and Raven, 1997).

The decrease in photosynthetic rates results from photo-oxidative disruption of pigment systems (Amha Belay and Fogg, 1978; Falkowski and Raven, 1997), inactivation of photosynthetic enzymes (Steemann-Nielsen, 1962; Steemann-Nielsen and Jørgensen, 1962) and increased photorespiration (Harris and Lott, 1973; Osmond, 1981).

Calculating the difference between the photosynthetic rate at the surface and A_{max} and expressing it as a percentage of the latter can estimate the extent of photoinhibition. In the present study, the reduction in photosynthetic rates due to photoinhibition varied from 16.8 to 66.8 % and was most marked during periods when irradiance was greatest. The extent of photoinhibition as a function of irradiance was, however, variable. For example, an irradiance of (PAR) 798 $\mu E\ m^{-2}\ s^{-1}$ in November, 2004 produced a 66.8% reduction from the light-saturated rate (A_{max}), while an irradiance of 115 $\mu E\ m^{-2}\ s^{-1}$ in July, 2005 caused a 16.8% reduction from A_{max}. The highest irradiance of 946 $\mu E\ m^{-2}\ s^{-1}$ in August, 2005 caused a 28% reduction from A_{max}. Investigations conducted in other water bodies of the tropical regions (Girma Tilahun, 1988; Demeke Kifle and Amha Belay, 1990) as well as the temperate (Jones, 1978; Demeke Kifle, 1992) have also come up with similar results.

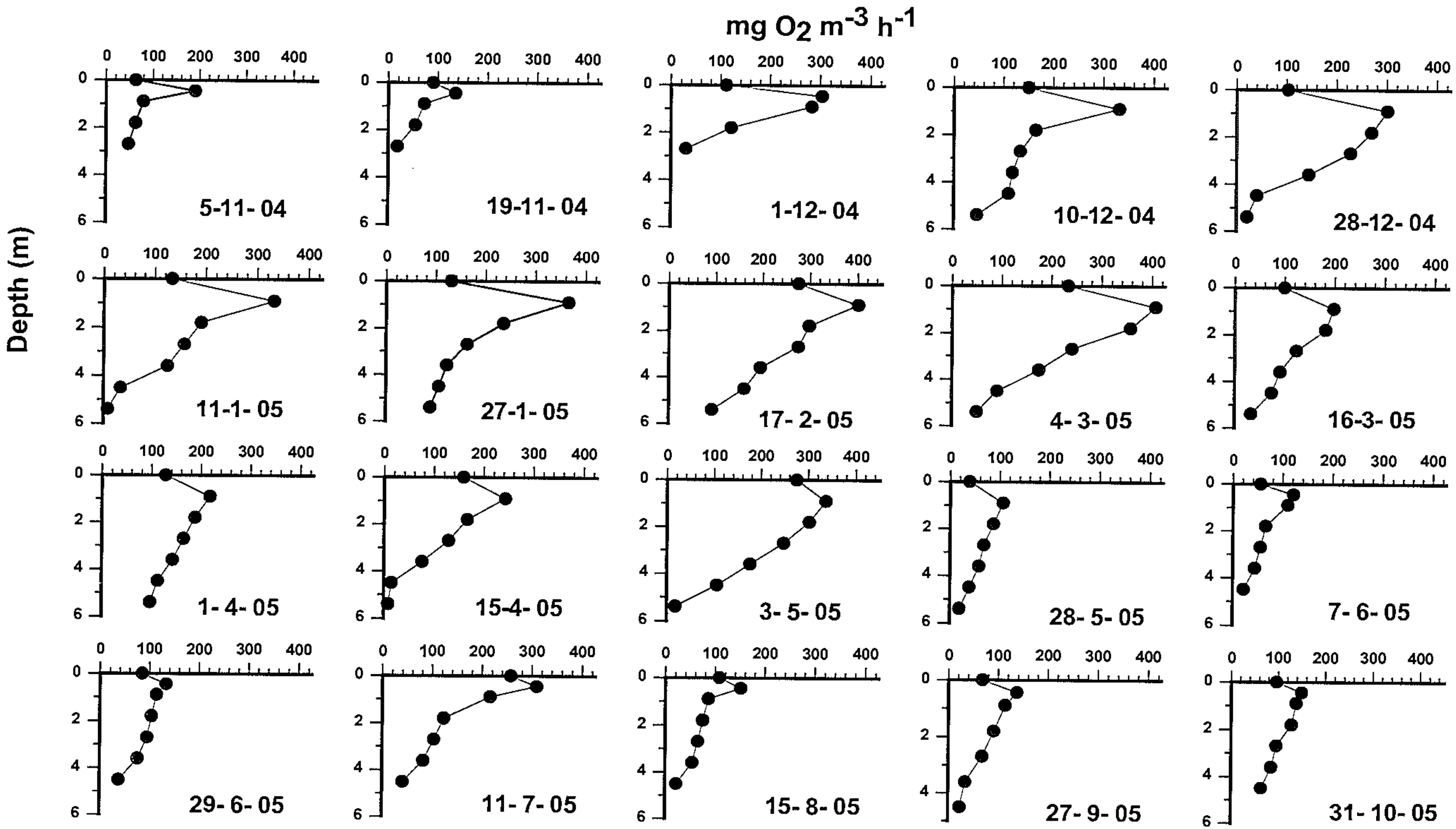

Fig. 6. Depth-profiles of gross photosynthesis per unit water volume (mg O_2 m^{-3} h^{-1}) at a central station in Lake Bishoftu Guda.

Thus, the intensity of irradiance is not the only factor that determines the magnitude of photoinhibition in phytoplanktonic photosynthesis. The extent of photoinhibition may vary with previous light history of algal cells (Kok, 1956) and differences in photoacclimation strategies of phytoplankton, which are species-specific (Jorgensen, 1964; Behrenfeld *et al.*, 1998).

The depth distribution patterns of net photosynthetic rates are similar to those of gross photosynthesis, with peak net productivity occurring at a depth of 0.9m (Appendix 7). The net photosynthetic rates varied within the range of 3 mg O_2 m^{-3} h^{-1} in May to 145 mg O_2 m^{-3} h^{-1} in March (≈0.94 to 45.24 mg C m^{-3} h^{-1}, assuming the most commonly observed photosynthetic ratio of 1.2.). The net photosynthetic rates at light-saturation showed a general increase from December, 2004 to March, 2005 and reached a high value in March, which was the period of high algal biomass. The minimum net photosynthetic rate at light saturation occurred in October, 2005, concomitant with the time of low phytoplankton biomass.

The net photosynthetic rates were high during periods of increasing rainfall, which may reflect the importance of allochthonus nutrient input during precipitation events (months) since some increases in nutrients were followed by increases in net photosynthetic rates.

Respiration rates varied from 22.8 mg O_2 (≈7.11 mg C) m^{-3} h^{-1} to 183.14 mg O_2 (≈57.14 mg C) m^{-3} h^{-1} with the minimum in April and the maximum in February.

4.2.3.2. Photosynthetic parameters

The seasonal variations in light-saturated rate of photosynthesis (A_{max}), specific rates of gross photosynthesis at light-saturation [P_{max}, mg O_2 (mg Chl *a*)$^{-1}$ h^{-1}], and hourly rates of integral photosynthesis ($\sum A$, g O_2 m^{-2} h^{-1}) in relation to phytoplankton biomass (B) and Photosynthetically Active Radiation (Ph. AR) are shown in Fig. 7.

Temporal changes in light-saturated rates of photosynthesis (A_{max}) were observed with a seasonal minimum value of 106 mg O_2 (~33.1 mg C) m^{-3} h^{-1} in May, 2005 and with a maximum value of 407 mg O_2 (~127 mg C) m^{-3} h^{-1} in March, 2005, which coincides with the seasonal maximum Chl *a* concentration (see Appendix-8). The minimum rate of gross photosynthesis at light-saturation corresponded to a low value of chlorophyll *a* concentration.

Most of the high values of A_{max} were observed beginning in January-March, 2005, with additional peaks in May and July, 2005, which generally corresponded to similarly high levels of phytoplankton biomass. The maximum A_{max} values recorded for Lake Bishoftu-Guda are within the ranges reported (in mg O_2 m^{-3} h^{-1}) for Lake Awassa (Demeke Kifle and Amha Belay, 1990), Sonachi, Kenya (Melack, 1976) and several perennial irrigation reservoirs in Sri Lanka (Silva *et al.*, 2002). (see Appendix 18). However, they are considerably lower than those recorded for a near-shore station of Lake Chamo (Eyasu Shumbulo, 2004), Lake Ziway (Girma Tilahun, 1988) and Lake George, Uganda (Ganf, 1975). Exceptionally high values of light-saturated rates of photosynthesis are also known from several crater lakes in the tropics including Lakes Hora-Hoda (Talling *et al.,* 1973) and Hora-Kilole (Talling *et al.*, 1973) in Ethiopia and Lake Simbi (Melack, 1979c) in Kenya (see Appendix 18).

As has been reported by Talling and Lemoalle, (1998) the wide range of the saturation parameter per unit water volume, A_{max}, is known to be a function of primarily variable biomass concentration, B and photosynthetic capacity, the light-saturated specific rate per unit biomass, P_{max}, mg O_2 (mg chl *a*)$^{-1}$ h^{-1}. A strong and positive correlation (r=0.76) was found between A_{max} and phytoplankton biomass for Lake Bishoftu-Guda. A linear regression of A_{max} on biomass also seemed to show that about 60% of the variation in A_{max} is due the variation in the photosynthetic biomass (see Appendix 9).

Although similarly high correlations are also known from some other freshwaters including Welsh lakes (Pentecost and Happey-Wood, 1978) and Sri Lankan irrigation reservoirs (Silva *et al.*, 2002), much weaker correlations of 0.3 and 0.36 between A_{max} and phytoplankton biomass were also reported by Eyasu Shumbulo, (2004) for Lake Chemo and Girma Tilahun (1988) for Lake Ziway respectively.

The highest phytoplankton biomass (20 mg Chl *a* m^{-3}) of Lake Bishoftu-Guda was associated with the highest A_{max} value of 407 mg O_2 m^{-3} h^{-1} while the lowest phytoplankton biomass (4 mg Chl *a* m^{-3}) was associated with the lowest A_{max} value of 106 mg O_2 m^{-3} h^{-1}.

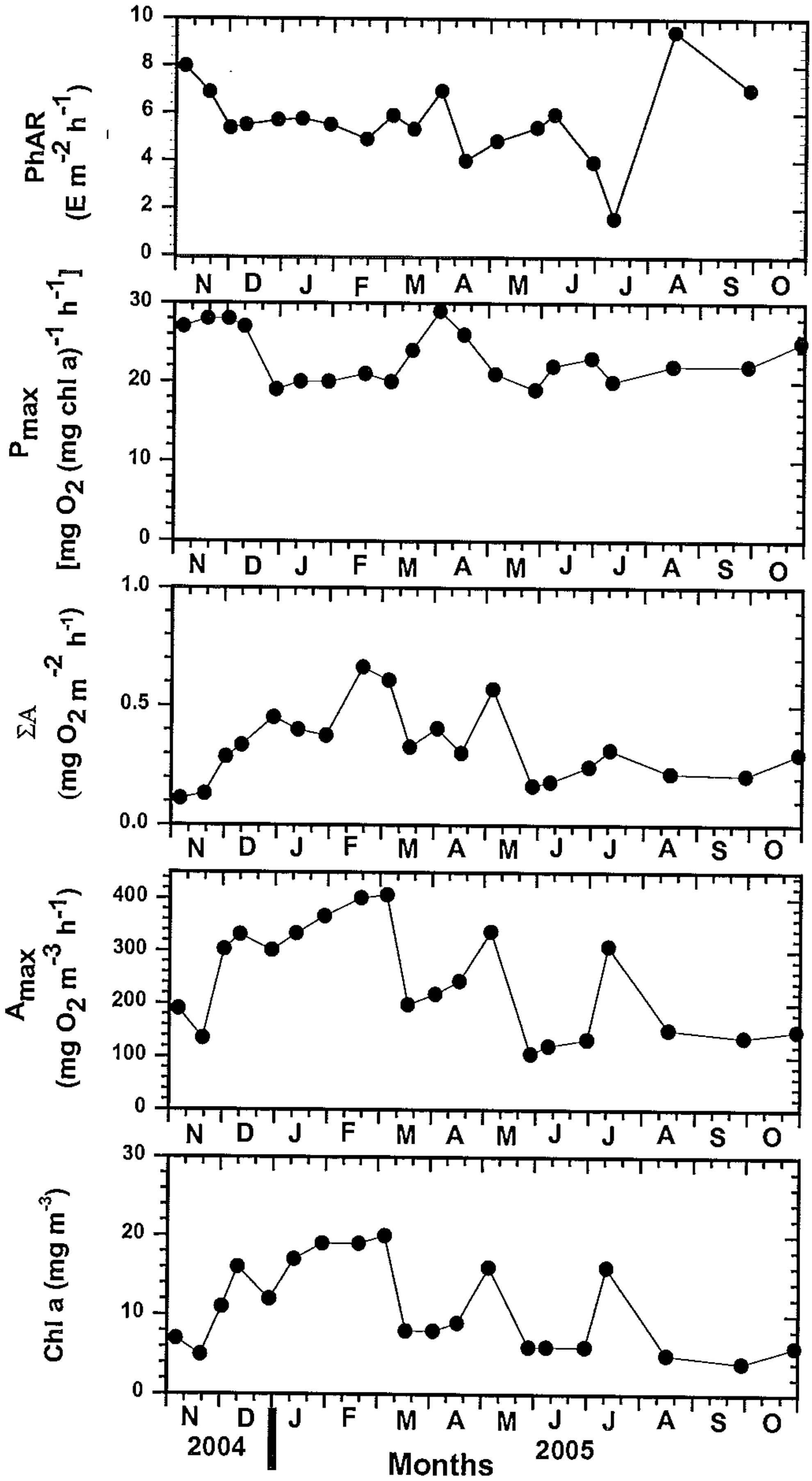

Fig. 7. Temporal variations in phytoplankton photosynthetic parametes in relation to biomass and integral irradiance of the incubation period in Lake Bishoftu Guda.

However, lack of correspondence between biomass and A_{max} was reported for several East African lakes including Lake Awassa (Demeke Kifle and Amha Belay, 1990), Lake Chamo (Eyasu Shumbulo, 2004) and Lake Hora-Hoda (Talling *et al.*, 1973), all in Ethiopia. According to Talling (1965) and Hammer (1981), high A_{max} values associated with low algal biomass are the result of high specific activity (specific rates of gross photosynthesis), which may be related to nutrient regimes (Falkowski and Stone, 1975), the usually favourably high tropical temperatures (Lemoalle, 1981) and cell size and algal type (Malone, 1971).

A positive, but weak correlation ($r = 0.35$) was found between A_{max} and the Photosynthetically Active Radiation (Ph. AR) falling on a horizontal surface in the lake's area and about 12 % of the variation in A_{max} seemed to be a function of the variation in Ph. AR (see Appendix 9).

A useful index to compare the photosynthetic rates of phytoplankton communities is to consider the magnitude of the light-saturated rate of photosynthesis per unit of chlorophyll *a*, the photosynthetic capacity [$P_{max,}$ mg O_2 (mg chl $a)^{-1}$ h^{-1}]. The patterns in the depth distribution of specific rates of phytoplankton photosynthesis are similar to those of gross photosynthetic rates, with a maximum value (photosynthetic capacity) at a depth of 0.9 m (see Appendix 7). The values of biomass- specific rates were low at the surface due to photoinhibition. In the present study, the photosynthetic capacity of phytoplankton in Lake Bishoftu-Guda (specific rate at light-saturation) was found to vary from 19 to 29 mg O_2 (mg chl $a)^{-1}$ $h^{-1.}$

The biomass-specific rates at light-saturation of Lake Bishoftu-Guda are comparable to those reported for Lake Hora-Kilole (Talling *et al.,* 1973), Lake Chamo (Eyasu Shumbulo, 2004) and an offshore station in Lake Victoria, Uganda (Talling, 1965). They are, however, considerably higher than those observed for Lake Ziway (Amha Belay and Wood, 1984; Girma Tilahun, 1988), Lake Awassa (Demeke Kifle and Amha Belay, 1990), Lake Abijata (Amha Belay and Wood, 1984) and Lake Hora-Hoda (Talling *et al.*; 1973), all in Ethiopia and Lakes Simbi and Sonachi, Kenya (Melack, 1981) (see Appendix 18).

Photosynthetic capacity of Lake Bishoftu-Guda phytoplankton was negatively correlated (r=-0.23) with phytoplankton biomass (see Appendix 9). Similarly, Eyasu Shumbulo (2004) for Lake Chamo, Ganf (1972) for Lake George, Uganda and Robarts (1979) for Lake MacIlwaine, Rhodesia reported an inverse correlation between specific rates of gross photosynthesis at light-saturation and phytoplankton biomass.

Temperature (Eppley, 1972), light (Beardall and Morris, 1976; Falkowski, 1981), nutrient regimes (Falkowski and Stone, 1975) and cell size (Malone, 1971) have been considered as potentially controlling factors of photosynthetic capacity. Because temperature and light are uniformly high in the tropics, cell size, nutrients and CO_2 supply may be considered to be of greater importance in determining the magnitude of photosynthetic capacity of phytoplankton. The minimum and maximum values of P_{max} corresponded to low and high concentration of nutrients respectively in Lake Bishoftu-Guda.

4.2.3.3. Production rates per unit area

The hourly integral rate values were obtained by the Grid Enumeration Analysis (Olson, 1960) and are listed in Appendix 8 and their temporal variations shown in Fig. 7.

Integration of the area enclosed by the curve produced in a plot of gross photosynthetic production per m^{-3} h^{-1} against depth gave the hourly integral gross photosynthesis, which ranged from 0.112 to 0.66 g O_2 (~0.03 to 0.21 g C) m^{-2} h^{-1}. The highest hourly integral phytoplankton productivity was recorded during February, 2005, at the time of high algal biomass and photosynthetic activity. During periods of low algal biomass, the production rates per unit area were also very low.

A positive but weak correlation (r=0.36) was found between phytoplankton biomass and hourly integral photosynthesis. About only 13 % of the variation in hourly integral photosynthesis also seems to be accounted for by the variation in the photosynthetic biomass (see Appendix 9).

The areal production rates of Lake Bishoftu-Guda are lower than those reported for most of the East African Lakes, such as Lakes Chamo (Eyasu Shumbulo, 2004) and Ziway (Girma Tilahun, 1988) both in Ethiopia and Lake Elmenteita, Kenya (Melack, 1979b). Much higher integral rates (in g O_2 m^{-2} h^{-1}) have also been reported for lakes with larger photosynthetic biomass including Lake Simbi (120-970 mg Chl *a* m^{-3}), Lake Hora-Hoda (917-2170 mg Chl *a* m^{-3}) and Lake Bogoria, Kenya (150-800 mg Chl *a* m^{-3}) by Melack (1979c), Talling *et al.* (1973) and Melack (1976) respectively (see Appendix 19).

Temporal variations in the photosynthetic production of phytoplankton in Lake Bishoftu-Guda were observed in the present study. It is generally believed that tropical waters exhibit limited temporal variability in their primary production owing to the great reduction in variation imposed by marked seasonality in temperature and irradiance (Lewis, 2000). Because the extent of the seasonality in phytoplankton production per unit area in a lake can not be easily perceived from absolute values of areal production rates, Melack (1979a) used coefficient of variation (CV, standard deviation/mean) as an index for recognizing temporal variability in the rates of phytoplankton production per unit area. Lake Bishoftu-Guda, with a CV of 45.5% for areal production rates and 51% for phytoplankton biomass, falls under Pattern A of Melack (1979a), with most tropical lakes including Lakes Chamo (Eyasu Shumbulo, 2004), the Kenyan freshwater Lakes Naivasha Crater Lake and Oloidien (Melack, 1879b), Chad (Lemoalle, 1975) and Victoria (Talling, 1965) in which production rates varied in relation to dry-wet seasons or vertical mixing/stratification or increased river discharge or a combination of two or more of these and the associated changes in turbidity and levels of nutrients (Melack, 1979a).

Daily production rates per unit area ($\sum\sum A$, g O^2 m^{-2} d^{-1}), were estimated from hourly integrated rates. The conversion of hourly rates to daily rates per unit area was made by a factor (0.9) used by Talling (1965) for other east African lakes. The hourly integral rates were multiplied by a factor of 0.9 and then the products were multiplied by the number of hours of sunlight, which was assumed to be 10 hours. The calculated daily integral production values for Lake Bishoftu-Guda ranged from 1.01 to 5.98 g O_2 (~0.32 to 1.87 g C) m^{-2} d^{-1} (see Appendix 8). These values are much lower than those reported for Lake Chamo (Eyasu shumbulo, 2004), Lake Ziway (Girma Tilahun, 1988) Lake Awassa (Demeke Kifle and Amha Belay, 1990) all in Ethiopia , Lake Baringo, Kenya (Patterson and Wilson, 1995) and Lake Muzahi, Uganda (Mukankomeje *et al.*, 1993) (see Appendix 19).

5. General Discussion

Despite the presence of sufficient light energy for photosynthesis as can be judged from the low extinction coefficients of down-welling irradiance, Lake Bishoftu-Guda has low algal biomass and primary production. The low biomass and production of phytoplankton in Lake Bishoftu-Guda are associated with unusually low concentrations of nitrate and phosphate, which must have resulted from their low external and internal inputs (loads) into the trophogenic zone. The enrichment of the photosynthetic zone of the lake with nutrients from the nutrient-rich deeper waters is excluded by the great depth of the lake and its protection from wind, which is afforded by its crater walls and the surrounding vegetation acting as a wind-break, changes in nutrient levels as a result of rainfall seem to be moderated by the persistent and more or less complete plant cover of the surrounding area, which is believed to act as a nutrient filter.

The phytoplankton community in this lake was constituted, for most of the study period, largely by dinoflagellates, whose dominance was favoured by the hydrographic conditions of the lake (physical stratification/mixing), which are regarded as factors of over-riding importance in determining the seasonal dominance of algal groups in Lake Bishoftu-Guda.

The hydrological conditions (water input-output through runoff from precipitation and evaporation) are contributory factors for the marked temporal fluctuations in the abundance, biomass and photosynthetic activity of phytoplankton observed in Lake Bishoftu-Guda.

Talling (1986) has also emphasized the importance of hydrological and hydrogrpahic factors to the temporal variations in the species composition, biomass and primary production of phytoplankton in African lakes. Phytoplankton biomass and production in Ethiopian Rift Valley lakes are probably light-limited as a consequence of the relatively high chlorophyll, low light penetration due to suspended inorganic particles and weak stratification (Taylor *et al.,* 2000). Phytoplankton of Lake Bishoftu-Guda may, however, be nutrient-limited. Concentrations of silica in Lake Bishoftu-Guda were frequently high compared to those of nitrate and phosphate. In light of the relative concentration of nitrate and phosphate, nitrogen may be the first to play the role of a limiting nutrient in the epilimnetic waters of Lake Bishoftu-Guda during periods of thermal stratification. Data that suggest the likelihood of both nitrogen (Talling and Talling, 1965; Lewis, 1996; Elizabeth Kebede and Willen, 1998; Talling and Lemoalle, 1998; Eyasu Shumbulo, 2004) and phosphorus-limitation (Kalff, 1983) of phytoplankton in East African lakes have been generated.

6. RECOMMENDATIONS

Lake Bishoftu-Guda, unlike most other Ethiopian lakes, seems to have been less impacted by anthropogenic activities until quite recently. The tendency to use the lake for recreation, watering of animals and of washing clothes has grown rapidly during the last few years. If the afore-said human activities go unchecked for a long time, the loss of the integrity of the aquatic ecosystem is imminent. Concerned authorities are, therefore, urged to keep an eye on this beautiful lake.

The data on the hydrographic conditions and its importance to phytoplankton dynamics is not conclusive. Future studies should, therefore, include measurements of temperature, dissolved oxygen, and concentration of inorganic nutrients along a vertical profile that extends to the deepest parts of the water column.

Future investigations on the water chemistry of Lake Bishoftu-Guda should include a look into the importance of the exchange of nutrients between the sediment and the overlying water so as to complement the existing chemical data and provide a better picture of the significance of inorganic nutrients in controlling the dynamics, biomass and production of phytoplankton in the lake.

Future studies on the species composition of phytoplankton and its seasonal dynamics should involve collection of samples with bottle samplers as the present investigation may have overlooked the smaller planktonic algae.

Since the standing crop, species composition and production of phytoplankton are the result of physicochemical and biological factors, future investigations should give due consideration to biological controls of phytoplankton.

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APPENDICES

8. APPENDICES

Appendix 1. Meteorological Data of Lake Bishoftu-Guda: Mean monthly maximum and minimum air temperature, Total Monthly Rainfall and Wind Speed of the sampling day and weekly average of the days preceding sampling day.

Month	Mean monthly Maximum air Temperature (⁰C)	Mean monthly Maximum air Temperature (⁰C)	Total Monthly Rainfall (mm)	Sampling date	Wind Speed of the Sampling Day	Weekly Average Wind Speed preceding the sampling day
Nov.,2004	25.5	7.3	10.3	5/11/2004	2.15	1.46
Dec.,2004	25.4	8.2	_	19/11/2004	1.23	2.07
Jan., 2005	26.2	8.1	21.8	1/12/2004	1.50	2.42
Feb., 2005	29	8	225.2	10/12/2004	1.71	1.80
Mar., 2005	28.6	12.1	122.1	28/12/2004	1.86	1.65
April, 2005	28.7	12.3	77.3	11/1/2005	1.40	1.55
May, 2005	27.1	13.1	86.5	27/1/2005	1.21	1.64
Jun., 2005	27.2	12.2	96.7	17/2/2005	2.74	2.13
July, 2005	24	13	168	4/3/2005	1.75	1.76
Aug.,2005	24.8	13.6	186.7	16/3/2005	2.12	2.10
Sept.,2005	25.6	12.6	153.3	1/4/2005	2.33	2.27
Oct., 2005	_	_	_	15/4/2005	2.03	2.11
				3/5/2005	1.27	2.63
				28/5/2005	2.03	1.60
				7/6/2005	1.71	1.52
				29/6/2005	1.31	1.26
				11/7/2005	0.86	1.29
				15/8/2005	0.95	1.19
				27/9/2005	1.12	1.09
				31/10/2005	_	_

Appendix 2. Depth profiles of oxygen and temperature in the upper part of the water column (0-3.50 m) at the central station in Lake Bishoftu-Guda.

Date	Depth (cm)	O_2 (mg l^{-1})	Temp. (^0C)	Percentage Saturation
5/11/2004	0.00	7.66	23.4	90.5
	0.25	7.62	23.3	88.6
	0.50	7.63	23.3	89.8
	0.75	7.62	23.3	88.6
	1.00	7.55	23.3	89.4
	1.50	7.53	23.3	87.4
	2.00	7.45	23.2	84.1
	2.50	7.64	23.2	89.4
	3.00	7.72	23.2	94.3
	3.50	7.68	23.1	92
19/11/2004	0.00	_	23.1	_
	0.25	_	23	_
	0.50	_	23	_
	0.75	_	23	_
	1.00	_	22.9	_
	1.50	_	22.9	_
	2.00	_	22.9	_
	2.50	_	22.9	_
	3.00	_	22.8	_
	3.50	_	22.8	_
1/12/2004	0.00	7.12	23.4	84.80
	0.25	7.1	23.3	83.80
	0.50	7.44	23.3	86.70
	0.75	7.35	23.3	85.00
	1.00	7.49	23.3	87.20
	1.50	7.56	23.3	89.30
	2.00	7.63	23.2	90.50
	2.50	7.77	23.2	93.90
	3.00	7.89	23.2	95.40
	3.50	7.68	23.2	92.10
10/12/2004	0.00	7.94	22.7	95.8
	0.25	7.92	22.7	94.9
	0.50	7.84	22.7	92.8
	0.75	7.87	22.7	93.3

	1.00	7.95	22.7	96.1
	1.50	7.79	22.7	91.9
	2.00	7.82	22.7	92.6
	2.50	7.75	22.6	90.3
	3.00	7.43	22.6	86.8
	3.50	7.38	22.5	87.9
28/12/2004	0.00	12.68	22.3	158.00
	0.25	12.65	22.7	156.40
	0.50	12.67	22.7	158.00
	0.75	12.69	22.7	159.50
	1.00	12.69	22.8	160.00
	1.50	12.71	22.8	160.60
	2.00	12.73	22.8	161.60
	2.50	12.7	22.8	160.30
	3.00	12.74	22.8	161.30
	3.50	12.68	22.8	158.50
11/1/2005	0.00	2.75	22.4	31.5
	0.25	2.77	22.5	31.6
	0.50	3.23	22.5	38.9
	0.75	3.04	22.5	34.8
	1.00	3.81	22.4	43.6
	1.50	2.95	22.4	33.6
	2.00	2.55	22.3	29.6
	2.50	2.65	22.3	30.2
	3.00	2.74	22.2	31.2
	3.50	2.57	22.2	30.3
27/1/2005	0.00	15.80	23.90	183.5
	0.25	15.69	24.10	180.06
	0.50	16.01	24.40	185.7
	0.75	16.00	24.00	185.6
	1.00	16.50	23.90	191
	1.50	16.15	23.70	186.1
	2.00	16.20	23.70	187.6
	2.50	15.50	23.60	178.2
	3.00	15.57	23.60	178.9
	3.50	15.30	23.50	172.3
17/2/2005	0.00	12.64	23.3	158.5
	0.25	12.67	23.4	158.7
	0.50	12.7	23.4	158.2
	0.75	12.72	23.4	158.2
	1.00	12.4	23.5	152.1
	1.50	12.42	23.5	152.4

	2.00	12.77	23.5	158.9
	2.50	12.82	23.4	159.7
	3.00	12.61	23.4	158.3
	3.50	12.9	23.4	160.3
4/3/2005	0.00	13.75	26.3	172.7
	0.25	14.2	26.3	173.3
	0.50	14	26	172.8
	0.75	14.6	25.7	174.1
	1.00	14.8	25.7	174.5
	1.50	14.9	25.5	174.8
	2.00	15.1	25.4	175.8
	2.50	15.18	25.3	176.2
	3.00	15.22	25.2	176.5
	3.50	15.05	25.1	175.3
16/3/2005	0.00	_	26.6	_
	0.25	_	26.5	_
	0.50	_	26.3	_
	0.75	_	25.9	_
	1.00	_	25.9	_
	1.50	_	25.9	_
	2.00	_	25.9	_
	2.50	_	25.9	_
	3.00	_	25.9	_
	3.50	_	25.9	_
1/4/2005	0.00	6.42	25.1	75.1
	0.25	6.57	25	77.6
	0.50	6.46	24.9	75.7
	0.75	6.48	24.9	75.8
	1.00	6.46	24.8	75.6
	1.50	6.41	24.8	74.9
	2.00	6.42	24.7	75
	2.50	6.37	24.7	74.1
	3.00	6.5	24.7	75.8
	3.50	6.4	24.7	74.3
15/4/2005	0.00	8.56	24.8	98.6
	0.25	8.68	24.8	98.9
	0.50	8.14	24.8	96.57
	0.75	8.18	24.8	96.3
	1.00	8.27	24.8	96.8
	1.50	8.34	24.7	97.1
	2.00	8.33	24.6	97.1
	2.50	8.26	24.6	96.7

	3.00	8.37	24.5	97.2
	3.50	8.34	24.5	97.2
3/5/2005	0.00	9.62	25.8	113.9
	0.25	9.74	25.8	114.3
	0.50	9.74	25.7	114.4
	0.75	9.83	25.6	115.2
	1.00	9.92	25.6	115.9
	1.50	9.92	25.6	115.7
	2.00	9.76	25.6	114.6
	2.50	9.62	25.4	114.1
	3.00	9.6	25.4	114.3
	3.50	9.5	25.4	113.6
28/5/2005	0.00	7.38	24.9	88.2
	0.25	7.35	24.8	87.7
	0.50	7.39	24.8	88.2
	0.75	7.42	24.8	88.6
	1.00	7.46	24.7	88.9
	1.50	7.56	24.7	89.8
	2.00	7.62	24.7	90.5
	2.50	7.45	24.7	88.7
	3.00	7.43	24.7	88.7
	3.50	7.39	24.7	88.4
7/6/2005	0.00	_	26.3	_
	0.25	_	26.2	_
	0.50	_	26.1	_
	0.75	_	25.6	_
	1.00	_	25.4	_
	1.50	_	25.2	_
	2.00	_	25	_
	2.50	_	24.9	_
	3.00	_	24.9	_
	3.50	_	24.9	_
29/6/2004	0.00	8.42	23.7	101.3
	0.25	8.35	24.2	95.9
	0.50	7.79	24.7	95.2
	0.75	7.85	24.8	96.7
	1.00	7.84	24.9	96.3
	1.50	7.97	24.9	97
	2.00	7.99	24.9	98
	2.50	7.8	24.9	94.2
	3.00	7.83	24.9	95.8
	3.50	7.82	24.9	94.7

11/7/2005	0.00	12.12	24.3	159.7
	0.25	13.26	24.5	164.3
	0.50	13.85	24.6	172.2
	0.75	-	24.8	-
	1.00	-	24.8	-
	1.50	-	24.9	-
	2.00	-	24.9	-
	2.50	-	24.9	-
	3.00	-	24.9	-
	3.50	-	24.9	-
15/8/2005	0.00	7.58	24.3	96.8
	0.25	7.59	24	92.4
	0.50	7.64	23.8	94.5
	0.75	7.74	23.7	93.8
	1.00	7.73	23.6	94.1
	1.50	8.3	23.6	98.9
	2.00	8.7	23.6	102.1
	2.50	8.67	23.5	108.8
	3.00	9.08	23.4	114.6
	3.50	9.21	23.3	115.7
27/9/2005	0.00	5.77	26.4	72.3
	0.25	6.42	26.2	79.4
	0.50	6.79	26.1	82
	0.75	6.75	26	83.00
	1.00	6.83	25.9	85.5
	1.50	6.8	25.80	83.3
	2.00	7.14	25.70	90.3
	2.50	7.73	25.70	93.8
	3.00	7.74	25.70	93.7
	3.50	7.89	25.70	94.4
31/10/2005	0.00	9.34	24.1	72.3
	0.25	9.43	24.1	79.4
	0.50	9.95	24.1	82
	0.75	9.90	24.1	83.00
	1.00	10	24.1	85.5
	1.50	7.6	24.00	83.3
	2.00	7.76	24.00	90.3
	2.50	7.52	24.00	93.8
	3.00	7.5	23.90	93.7
	3.50	7.53	23.90	94.4

Appendix 3. Conductivity (K_{25}), temperature and salinity values measured at different depths of the water columns in Lake Bishoftu-Guda.

Date	Depth (m)	K_{25} ($\mu s\ cm^{-1}$)	Temp. (^0C)	Salinity (ppt)
5/11/2004	0	800	21.8	0.4
	1	800	21.8	0.4
	2	805	21.8	0.4
	3	806	21.8	0.4
	4	806	21.8	0.4
	5	806	21.7	0.4
	6	806	21.7	0.4
	7	806	21.7	0.4
	8	806	21.7	0.4
	9	806	21.7	0.4
	10	806	21.7	0.4
	11	807	21.5	0.4
	12	807	21.4	0.4
	13	808	21.4	0.4
19/11/2004	0	806	21.3	0.4
	1	806	21.4	0.4
	2	806	21.4	0.4
	3	805	21.3	0.4
	4	804	21.3	0.4
	5	806	21.2	0.4
	6	805	21.2	0.4
	7	806	21.2	0.4
	8	806	21.2	0.4
	9	806	21.2	0.4
	10	806	21.2	0.4
	11	807	21.2	0.4
	12	808	21.1	0.4

	13	808	21.1	0.4
1/12/2004	0	793	21	0.4
	1	793	21.1	0.4
	2	760	21.3	0.4
	3	750	21.3	0.4
	4	673	21.5	0.4
	5	665	21.6	0.4
	6	661	21.5	0.4
	7	660	21.5	0.4
	8	659	21.5	0.4
	9	654	21.4	0.4
	10	651	21.4	0.4
	11	677	21.7	0.3
	12	667	21.7	0.3
	13	662	21.6	0.3

Appendix 4 **Ambient concentration of inorganic nutrients and phytoplankton biomass measured in composite samples collected from the Central and Near-shore stations of Lake Bishoftu-Guda.**

Sampling Date	NO_3.N (μg/L)		PO_4-P (µg/L)		SiO_2 (mg/L)		Chl *a* (mg m^{-3})	
	C	S	C	S	C	S	C	S
11/5/2004	6	6	2	3	24	21	7	5
19/11/2004	6	18	2	1	33	32	5	6
1/12/2004	31	29	4	3	34	29	11	9
10/12/2004	6	6	5	5	46	43	16	13
28/12/2004	24	21	3	3	14	16	12	14
11/1/2004	24	5	3	2	48	44	17	12
27/1/2005	26	15	1	1	42	36	19	22
17/2/2005	24	28	3	3	20	24	19	24
4/3/2005	27	31	1	1	32	40	20	16
16/3/2005	10	27	4	3	23	26	8	8
1/4/2005	10	30	2	2	32	34	8	8
15/4/2005	1	2	1	1	25	25	9	9
3/5/2005	12	8	3	3	50	50	16	12
28/5/2005	17	3	3	2	20	15	6	5
7/6/2005	17	12	2	2	18	13	6	5
29/6/2005	17	10	0	0	35	35	6	5
11/7/2005	10	8	0	1	58	54	16	13
15/8/2005	12	13	11	13	11	13	5	10
27/09/2005	10	6	11	3	16	18	4	4
31/10/2005	10	3	3	3	11	11	6	4

Appendix 5. **Depth profiles of inorganic nutrients and phytoplankton biomass at the Central and Near- shore stations of Lake Bishoftu-Guda.**

Sampling Date	Depth (m)	NO_3-N (μg/L)		PO_4-P (μg/L)		SiO_2 (mg/L)		Chl *a* (mg m^{-3})	
		C	S	C	S	C	S	C	S
5/11/2004	0.00	0.01	25.60	2.00	3.00	23.87	21.65	4.45	5.14
	1.00	0.01	0.01	2.00	3.00	22.53	21.20	4.17	3.34
	2.00	6.00	0.01	2.00	3.00	23.42	22.09	5.42	5.70
	3.00	0.01	0.01	2.00	3.00	24.31	18.98	7.92	4.73
19/11/2004	0.00	0.01	40.00	1.36	2.00	38.07	35.85	10.15	4.87
	1.00	23.20	30.40	1.81	1.00	33.19	26.97	10.15	5.70
	2.00	0.01	0.01	2.27	0.00	26.09	33.63	6.67	7.09
	3.00	0.01	0.01	2.72	0.00	22.98	32.75	6.39	8.06
1/12/2004	0.00	32.80	32.80	3.40	1.36	22.53	24.75	3.89	8.06
	1.00	29.60	24.80	3.40	3.40	33.19	31.41	7.78	9.45
	2.00	29.60	33.60	3.63	2.04	24.75	26.09	8.76	8.48
	3.00	30.40	25.60	2.04	3.22	28.31	35.41	8.90	8.06
10/12/2004	0.00	6.00	24.00	6.81	6.59	42.96	41.63	13.48	14.73
	1.00	0.01	0.01	5.22	4.77	51.84	46.51	15.43	10.43
	2.00	10.00	0.01	4.09	4.31	47.40	43.85	17.24	12.23
	3.00	0.01	0.01	5.00	5.00	43.40	40.29	17.93	14.46
28/12/2004	0.00	0.01	24.00	4.09	2.95	16.76	15.87	16.82	11.12
	1.00	25.60	0.01	3.18	3.18	14.10	14.99	11.40	14.60
	2.00	0.01	36.80	3.18	3.18	15.43	18.09	14.46	13.21
	3.00	0.00	24.00	2.95	3.63	14.54	13.21	12.09	15.29
11/1/2005	0.00	0.01	10.00	3.00	2.95	49.17	48.29	15.99	11.12
	1.00	10.00	0.01	3.00	3.86	47.40	48.73	17.38	10.01
	2.00	25.60	0.01	2.00	0.45	50.06	39.85	15.85	12.79
	3.00	25.60	10.00	0.00	1.13	42.07	38.52	15.01	13.90
27/1/2005	0.00	25.60	12.00	0.91	0.91	41.63	37.19	13.34	26.55
	1.00	27.20	22.40	0.00	1.14	38.52	31.86	15.71	17.24
	2.00	23.20	12.00	1.14	0.69	31.41	33.19	15.57	23.91

	3.00	10.00	_	0.69	1.82	46.51	42.51	21.27	18.77
17/2/2005	0.00	22.40	25.60	1.60	2.73	20.76	18.09	10.56	25.58
	1.00	31.20	25.60	2.50	3.87	17.65	26.97	19.60	20.02
	2.00	32.80	28.00	3.87	2.96	18.54	23.87	19.32	23.77
	3.00	34.40	33.60	1.82	4.10	20.31	27.42	21.27	27.24
4/3/2005	0.00	31.20	35.20	0.45	1.59	28.31	45.62	18.49	15.85
	1.00	22.40	30.40	1.36	1.36	34.08	29.64	21.82	12.79
	2.00	22.40	27.20	1.81	1.36	31.41	36.74	27.24	20.99
	3.00	27.20	32.80	1.59	1.00	30.53	46.95	23.77	15.85
16/3/2005	0.00	25.60	25.60	3.63	2.72	18.09	18.54	10.43	6.26
	1.00	27.20	27.20	2.72	2.50	24.75	26.97	12.23	8.34
	2.00	24.80	_	4.09	2.95	26.97	31.41	7.78	7.23
	3.00	27.20	28.00	6.36	2.95	18.09	26.09	7.65	8.90
1/4/2005	0.00	27.20	_	2.50	1.59	42.96	42.51	7.65	7.92
	1.00	22.40	28.80	1.59	1.59	33.19	38.07	9.04	7.09
	2.00	30.40	31.20	1.36	1.81	42.51	29.19	8.90	7.92
	3.00	28.00	29.60	2.04	2.04	27.86	24.75	7.37	7.78
15/4/2005	0.00	0.01	0.01	2.50	1.81	22.09	26.09	5.98	7.51
	1.00	6.00	6.00	0.90	0.68	27.42	23.87	8.34	10.56
	2.00	0.01	0.01	0.45	0.45	32.75	25.64	7.65	9.45
	3.00	0.01	0.01	0.90	1.59	25.64	22.98	8.06	8.06
3/5/2005	0.00	0.01	0.01	2.27	3.00	50.51	50.06	15.01	11.12
	1.00	10.00	22.40	2.27	3.00	50.95	50.95	15.01	10.01
	2.00	0.01	0.01	2.50	3.00	51.39	47.84	15.85	12.79
	3.00	27.20	10.00	3.18	3.00	50.95	49.62	14.46	13.90
28/5/2005	0.00	0.01	0.01	0.45	1.13	18.54	16.32	4.87	6.26
	1.00	6.00	6.00	0.68	1.81	20.76	15.43	5.00	6.53
	2.00	10.00	6.00	1.59	2.04	18.98	15.87	4.31	4.17
	3.00	0.01	0.01	1.59	2.27	14.99	13.65	4.59	4.03
7/6/2005	0.00	10.00	10.00	0.82	1.60	13.44	14.69	5.00	4.31
	1.00	12.00	6.00	2.85	1.75	18.86	13.44	6.81	4.45
	2.00	10.00	16.80	2.22	1.28	16.78	13.02	8.20	5.98

	3.00	12.00	16.80	1.60	3.94	13.86	10.52	6.81	5.84
29/6/2005	0.00	12.00	10.00	0.25	0.00	40.11	33.44	4.03	4.45
	1.00	6.00	16.80	0.75	1.00	35.22	32.11	7.23	5.42
	2.00	6.00	12.00	2.00	0.00	33.88	37.44	8.20	5.84
	3.00	16.80	0.01	0.00	0.00	39.66	36.55	6.39	5.84
11/7/2005	0.00	10.00	0.01	0.00	0.25	55.66	52.99	13.48	14.73
	1.00	10.00	10.00	0.00	0.75	53.44	52.55	15.43	10.43
	2.00	10.00	10.00	0.00	1.00	49.88	53.44	17.24	12.23
	3.00	0.01	12.00	0.00	1.00	48.99	55.22	17.93	14.46
15/8/2005	0.00	12.00	16.80	14.59	14.59	12.00	17.34	6.12	10.29
	1.00	10.00	16.80	14.59	9.50	12.00	12.38	4.87	7.78
	2.00	10.00	10.00	7.80	11.19	18.40	11.00	5.00	6.81
	3.00	10.00	10.00	14.59	17.99	10.00	12.74	11.68	14.96
27/9/2005	0.00	16.80	6.00	12.89	4.40	11.68	20.53	3.61	3.89
	1.00	10.00	0.01	9.50	2.70	15.22	18.76	4.03	3.20
	2.00	16.80	6.00	12.89	1.01	12.03	14.51	4.59	4.03
	3.00	10.00	12.00	12.89	4.40	24.07	19.82	4.31	4.73
31/10/2005	0.00	0.01	0.01	2.70	3.00	9.55	10.61	4.73	3.75
	1.00	0.01	6.00	4.40	4.40	10.61	10.97	4.59	5.14
	2.00	10.00	0.01	1.01	2.70	9.91	10.26	5.98	5.00
	3.00	10.00	6.00	4.40	1.01	11.68	10.26	6.26	3.20

Appendix 6. Measurements of chemical and biological parameters for Lake Bishoftu-Guda as reported by different authors.

Parameter	Date of sampling	value	References
Conductivity (K_{25}) (μS cm^{-1})	Apr., 1963	900	Prosser *et al.* (1968)
pH	Apr., 1992	9.5	Zinabu Gebre-Mariam (1994)
Alkalinity (meq l^{-1})	Apr., 1963	10.2	Prosser *et al.* (1968)
Salinity (g l^{-1})	Apr., 1963	0.3	Prosser *et al.* (1968)
Solubl Reactive P(μg l^{-1})	Apr., 1963	<5	Prosser *et al.* (1968)
	Apr., 1992	81	Zinabu Gebre-Mariam (1994)
NO_3+ NO_2-N (μg l^{-1})	Apr., 1963	20	Prosser *et al.* (1968)
	Apr., 1992	40	Zinabu Gebre-Mariam (1994)
Silica (mg l^{-1})	Apr., 1963	38	Prosser *et al.* (1968)
	Apr., 1992	25	Zinabu Gebre-Mariam (1994)
Chlorophyll *a* (μg l^{-1})	Feb., 1990	37	Zinabu Gebre-Mariam and Taylor (1997)
	Jul., 1991	29	Zinabu Gebre-Mariam and Taylor (1997)
	Apr., 1992	33	Zinabu Gebre-Mariam and Taylor (1997)

Appendix 7 Depth distribution of gross photosynthesis, A (mg O_2 m^{-3} h^{-1}), net photosynthesis, Net P (mg O_2 m^{-3} h^{-1}) and specific rate of photosynthesis, P_{max} [mg O_2 (mg Chl *a*)$^{-1}$ h^{-1}] of Lake Bishoftu-Guda.

Sampling Date	Depth (m)	P	Net P	P
5/11/2004	0.00	63	16	9
	0.25	190	143	27
	0.50	79	32	11
	1.00	63	16	9
	2.00	48	0	7
19/11/2004	0.00	90	54	18
	0.25	135	99	28
	0.50	72	36	15
	1.00	54	18	11
	2.00	18	-18	4
1/12/2004	0.00	111	40	10
	0.25	303	232	28
	0.50	283	212	26
	1.00	121	51	11
	2.00	30	-168	3
10/12/2004	0.00	150	47	12
	0.90	331	228	27
	1.80	165	63	13
	2.70	134	31	11
	3.60	118	16	10
	4.50	110	8	9
	5.40	47	-55	4
28/12/2004	0.00	103	73	7
	0.90	301	250	19
	1.80	270	239	17
	2.70	228	197	15
	3.60	145	114	9
	4.50	41	10	3
	5.40	21	-10	1

Appendix 8 Biomass and photosynthetic parameters of phytoplankton in Lake Bishoftu-Guda.

Sampling Date	B	A_{max}	% reduction from A_{max}	P_{max}	$\sum A$	$\sum\sum A$
5/11/2004	7	190	66.84	27	0.112	1.008
19/11/2004	5	135	33.33	28	0.132	1.188
1/12/2004	11	303	63.37	28	0.288	2.592
10/12/2004	16	331	54.68	27	0.336	3.024
28/12/2004	12	301	65.78	19	0.452	4.068
11/1/2005	17	333	60.06	20	0.4	3.6
27/1/2005	19	366	64.48	20	0.376	3.384
17/2/2005	19	401	31.42	21	0.664	5.976
4/3/2005	20	407	42.75	20	0.608	5.472
16/3/2005	8	198	50.00	24	0.328	2.952
1/4/2005	8	218	41.28	29	0.406	3.654
15/4/2005	9	243	34.57	26	0.304	2.736
3/5/2005	16	337	18.40	21	0.572	5.148
28/5/2005	6	106	63.21	19	0.166	1.494
7/6/2005	6	121	54.55	22	0.183	1.647
29/6/2005	6	133	36.09	23	0.246	2.214
11/7/2005	16	309	16.83	20	0.316	2.844
15/8/2005	5	151	28.48	22	0.218	1.962
27/9/2005	4	137	50.36	22	0.21	1.89
31/10/2005	6	149	35.57	25	0.3	2.7

B - in mg Chl *a* m^{-3}

A_{max}- in mg O_2 m^{-3} h^{-1}

P_{max} - in mg O_2 (mg Chl *a*)$^{-1}$ h^{-1}

$\sum A$ - in g O_2 m^{-2} h^{-1}

$\sum\sum A$- in g O_2 m^{-2} d^{-1}

Appendix 9. Statistical relations between different parameters measured in Lake Babogay in this study.

X (dependent Variable)	Y (predictor)	r	r^2	P	Regression equation
Z_{sd}	Biomass	-0.41	0.17	0.076	Biomass = -49.3 - 14.95 Z_{SD}
pH	Alkalinity	0.69	0.48	0.001	TA = -110.5 + 13.5 pH
$NO_3.N(\mu g/L)$	Biomass	0.5	0.25	0.025	Biomass = 5.92 + 0.325 NO_3-(μg/L)
PO_4-P(µg/L)	Biomass	0.35	0.12	0.133	Biomass = 12.9 - 0.647 PO_4-P(μg/L)
SiO_2(mg/L)	Biomass	0.6	0.36	0.005	Biomass = 3.65 + 0.242 SiO_2(mg/L)
Biomass	A_{max}	0.76	0.58	0.000	A_{max}= 52.5 + 17.7 Biomass
PAR	A_{max}	0.35	0.12	0.577	A_{max} = 279 - 6.5 Ph.AR
P_{max}	A_{max}	0.26	0.069	0.263	A_{max} = 428 - 7.99 P_{max}
Biomass	$\sum A$	0.36	0.13	0.000	$\sum A$ = 0.0925 + 0.0221 Biomass
PAR	$\sum A$	0.3	0.085	0.390	$\sum A$ = 0.413 - 0.0152 Ph.AR
A_{max}	$\sum A$	0.83	0.68	0.000	$\sum A$ = 0.0255 + 0.00125 Amax

T-test values for Biomass, NO_3-N, PO_4-P and SiO_2 between the two stations.

Paired T	T-Value	P-Value	T-test from Table (p=0.05,df=19)
Biomass	0.97	0.347	2.019
NO_3-N	0.45	0.658	
PO4-P	0.97	0.345	
SiO_2	0.79	0.440	

r- Correlation

r^2- Regression

Appendix 10. Surface water temperature in Lake Bishoftu-Guda and other East African Lakes as reported by various authors.

Lake	Sampling Date	Temperature (^{0}C)	Data Source
Awassa	1983-85	20.5-28.4	Demeke Kifle (1985)
Ziway	1987-88	18.5- 27.5	Girma Tilahun (1988)
Abijata	1980-1981	18-27	Kassahun Wodajo, (1982)
Langano	1980-1981	18-27	Kassahun Wodajo (1982)
Hora-Hoda	Oct., 1966	19.7-27	Wood *et al.* (1976)
Bishoftu-Guda	Oct., 1966	19.2- 24.5	Wood *et al.* (1976)
	2004/05	**22.3-26.8**	**This Study**
Chamo	Mar. 2004	23-30	Eyasu Shumbulo (2004)
George	1974	26-36	Ganf and Horne (1975)
Turkana	1974	27.5-32.5	Ganf and Horne (1975)

.Appendix 11. Secchi depth (Z_{SD}) in Lake Bishoftu-Guda and other East African Lakes as reported by various authors

Lake	Date	Z_{Sd} (cm)	Data Source
Koka	Feb., 1985	13-23	Melaku Mesfin *et al.* (1988)
Chamo	2004	21-39	Eyasu Shumbulo (2004)
Langano	March, 1991	25-35	Elizabeth Kebede, *et al.(1994)*
Koka	March, 1991	28	Elizabeth Kebede, *et al.*(1994)
Ziway	March, 1991	35	Elizabeth Kebede, *et al.*(1994)
Abaya	March, 1991	43	Elizabeth Kebede, *et al.*(1994)
George	1972	40	Ganf and Viner (1973)
Awassa	Mar., 1985	77-80	Demeke Kifle and Amha Belay (1990)
Naivasha	1973/1974	100-150	Melack(1979b)
Hayq	March, 1989	124	Elizabeth Kebede *et al.* (1992)
Ardibo	March, 1989	188	Elizabeth Kebede *et al.* (1992)
Bishoftu-Guda	**2004/05**	**148-446 (C)**	**This study**
		139-466 (S)	

Appendix 12. Euphotic Depth (Z_{eu}) in Lake Bishoftu-Guda and other East African Lakes as reported by various authors

Lake	Sampling Date	Z_{eu}(m)	Data Source
Hora-Hoda	Jan./Jul.'66	0.15-0.27	Talling *et al.*(1973)
Hora-Kilole	Jan./Jul.'66	0.24-0.38	Talling *et al.*(1973)
Nakuru	1972	0.22-0.41	Vareschi (1982)
George	167-68	0.7	Ganf (1975)
Ziway	1987/88	0.4-1.06	Girma Tilahun (1988)
Chamo	Mar., 2004	0.67-1.25	Eyasu Shumbulo (2004)
Awassa	Mar., 1985	1.59-2.7	Demeke Kifle and Amha Belay (990)
Shalla	Apr., 1981	4.93	Amha Belay and Wood (1984)
Hayk	March, 1989	4.85	Elizabeth Kebede *et al.*, (1992)
Ardibo	March , 1989	8.35	Elizabeth Kebede *et al.*, (1992)
Bishoftu-Guda	**2004/05**	**5-14 (C)**	**This study**
		4-15 (S)	

Appendix 13. Salinity of Lake Bishoftu-Guda and other East African Lakes as reported by various authors

Lake	Sampling Date	Salinity (g l^{-1})	Data Source
Koka	Mar., 1964	0.32	Wood and Talling (1988)
Ziway	Mar., 1964	0.35	Wood and Talling (1988)
George	21 Jun.'61	0.19	Talling and Talling (1965)
Naivasha	5 Jun.'61	0.39	Talling and Talling (1965)
Hora-Kilole	Apr., 1992	0.2	Zinabu Gebre-Mariam (1994)
Bishoftu-Guda	Apr., 1963	0.3	Prosser *et al.* (1968)
	2004/05	**0.4**	**This Study**
Bishoftu	Apr., 1963	1.92	Prosser *et al.* (1968)
Hora-Hoda	Apr., 1963	5.1	Prosser *et al.* (1968)
Shalla	Mar., 1964	21.5	Wood and Talling (1988)
Abijata	Mar, 1991	26.4	Elizabeth Kebede *et al.* (1994)
Chitu	Mar, 1991	49.9	Elizabeth Kebede *et al.* (1994)
Bogoria	3 Feb., '80	50	Kalff, (1983)
Nakuru	24 Feb., '61	114	Talling and Talling, 1965

Appendix 14. Measurements of alkalinity on Lake Bishoftu-Guda and other East African Lakes as reported by various authors

Lake	Sampling Date	HCO_3+CO_3 (meq l^{-1})	Data Source
Hora-Kilole	Apr., 1992	2.4	Zinabu Gebre-Mariam (1994)
Koka	Mar., 1964	3.22	Wood and Talling (1988)
Ziway	1987/88	3.5-4.4	Girma Tilahun (1988)
Naivasha	5 Jun.'61	3.31	Talling and Talling (1965)
Bishoftu-Guda	Apr., 1963	10.2	Prosser *et al.* (1968)
	Apr., 1992	9.5	Zinabu Gebre-Mariam (1994)
	2004-2005	**6.4-12.1**	**This study**
Awassa	1983-85	7.7-9.1	Demeke Kifle (1985)
Chamo	Mar. 2004	9.2	Eyasu Shumbulo (2004)
Hora	Apr., 1963	26.8	Prosser *et al.* (1968)
	Apr., 1992	16.8	Zinabu Gebre-Mariam (1994)
Bishoftu	Apr., 1963	20	Prosser *et al.* (1968)
Metehara	May, 1991	44	Elizabeth Kebede *et al.* (1994)
Hora-Hoda	Apr., 1963	51.4	Prosser *et al.* (1968)
	Apr., 1992	54	Zinabu Gebre-Mariam (1994)
Shalla	Mar, 1991	218	Elizabeth Kebede *et al.* (1994)
Abijata	Mar, 1991	325	Elizabeth Kebede *et al.* (1994)
Chitu	Mar, 1991	573	Elizabeth Kebede *et al.* (1994)
Nakuru	24 Feb., '61	1440	Talling and Talling, 1965

Appendix 15. Measurements of Phosphate for Lake Bishoftu-Guda and other East African Lakes

Lake	Sampling Date	PO_4-P (µg l^{-1})	Data Source
Bishoftu-Guda	2004/05	1 to 15 (C) 1 to 18(S)	This study
	Apr., 1963	< 5	Prosser *et al.* (1968)
	Apr., 1992	81	Zinabu Gebre-Mariam (1994)
Hora	Apr., 1963	< 5	Prosser *et al.* (1968)
	Apr., 1992	117	Zinabu Gebre-Mariam (1994)
Bishoftu	Apr., 1963	< 5	Prosser *et al.* (1968)
	Apr., 1992	28	Zinabu Gebre-Mariam (1994)
Awassa	1983-85	5-42	Demeke Kifle (1985)
Chamo	Mar. 2004	44	Eyasu Shubulo (2004)
Ziway	2004	40-170	Getachew Beneberu (2004)
Abijata	Mar, 1991	98	Elizabeth Kebede *et al.* (1994)
Metehara	May, 1991	1302	Elizabeth Kebede *et al.* (1994)
Hora-Hoda	Apr., 1992	3200	Zinabu Gebre-Mariam (1994)
Hora-Kilole	Apr., 1963	6500	Prosser, *et al.* (1968)
	Apr., 1992	27	Zinabu Gebre-Mariam (1994)
Chitu	Mar, 1991	1985	Elizabeth Kebede *et al.* (1994)
Bogoria	3 Feb., '80	149-202	Varesch (1982)
Nakuru	24 Feb., '61	114	Talling and Talling, 1965
Simbi	Nov. 1976	760	Melack (1979c)

Appendix 17. Measurements of phytoplankton biomass in Lake Bishoftu-Guda and other East African Lakes as reported by various authors.

Lake	Sampling Date	B (mg Chl *a* m^{-3})	Data Source
Shalla	Oct., 1966	5	Wood *et al.* (1978)
	Apr., 1981	6	Amha Belay and Wood (1984)
Langano	Oct., 1966	7	Wood *et al.* (1978)
	Mar, 1980	7	Amha Belay and Wood (1984)
	1980-1981	3-12	Kasahun Wedajo (1982)
Tana	2003/04	0.2-12.6	Ayalew Wondie *et al.* (unpublished)
	1960-61	1.2-5.5	Talling (1965)
Tanganyika	Oct.-Nov.,'75	0.7-4.6	Hecky *et al.*(1978)
	Feb.-Nov.'75	0.2-20.4	Hecky and Kling (1981)
	2003	2.5-5.0	Chale (2004)
Bishoftu-Guda	**2004/05**	**4-20(C)**	**This Study**
		3.96 -24.2(S)	
	1990	37	Zinabu Gebre-Mariam and Taylor (1997)
	1991	29	Zinabu Gebre-Mariam and Taylor (1997)
	1992	33	Zinabu Gebre-Mariam and Taylor (1997)
Koka	Feb., 1985	22	Melaku Mesfin *et al.* (1988)
	Mar-May,'91	16	Elizabeth and Willen (1998)
Metehara	May, 1991	27	Elizabeth Kebede *et al.*(1994)
Awassa	2004	10.43-25.21	Tadesse Fetahi (2004)
Hora	Feb/Nov.'90	29	Zinabu Gebre-Mariam and Taylor (1997)
Kilole	Apr., 1992	30-35	Zinabu Gebre-Mariam (1994)
Hora-Hoda	Feb., 1964	2170	Talling *et al.* (1973)
	1995	195-880	Demeke Kifle *et al.* (unpublished)
Chitu	Aug., 1966	2600	Wood and Talling (1988)
Nakuru	1972	1160	Vareschi (1982)
	May, '73-74	140-960	Melack(1976)
Simbi	Nov. 1976	200	Melack(1979c)

Appendix 18. Light-saturated rates (A_{max}, mg O_2 m^{-3} h^{-1}) and Photosynthetic capacity [P_{max}, mg O_2 (mg Chl *a*)$^{-1}$ h^{-1}] of phytoplankton in Lake Bishoftu-Guda and other East African Lakes as reported by various authors.

Lake	A_{max}	P_{max}	Data Source
Naivasha	150-240	-	Melack (1979b)
Awassa	217-425	4-19	Demeke Kifle and Amha Belay(1990)
Sonachi	130-850	8-14	Mealck (1976)
Bishoftu-Guda	**106-407**	**19-29**	**This study**
Abijata	960	14.8	Amha Belay and Wood (1984)
Oloidein	260-710	-	Melack (1979b)
Chamo	716-1789	10-34	Eyasu Shumbulo (2004)
Ziway	1640-4670	9.6-22.5	Amha Belay and Wood (1984), Girma Tilahun (1988)
Elementeita	270-5540	-	Melack (1976), Melack (1979b)
Victoria,	400-910	14-35	Talling (1965), Melack (1979b)
George	1900-6000	-	Ganf (1975)
Bogoria	640-6000	-	Melack (1976), Melack (1979b)
Simbi	950-12900	15-17	Melack (1979c)
Nakuru	1100-2300	-	Melack and Kilham (1974), Melack (1976, 1979b)
Hora-Kilole	4000-10000	16.3-33.7	Talling *et al.* (1973)
Hora-Hoda	10000-30000	11-18	Talling *et al.* (1973)

Appendix 19. Hourly ($\sum A$, g O_2 m^{-2} h^{-1}) and daily ($\sum\sum A$, g O_2 m^{-2} d^{-1}) production rates per unit area in Lake Bishoftu-Guda and other East African Lakes as reported by various authors.

Lake	Sampling Date	$\sum A$ (g O_2 $m^{-2}h^{-1}$)	$\sum\sum A$ (g O_2 $m^{-2}d^{-1}$)	Data Source
Bishoftu-Guda		0.47-1.8	1.01 to 5.98	This study
Ziway	1987/88	0.3 - 1.6	3.1 - 17.6	Girma Tilahun 1988
Awassa	Mar., 1985		3.3 to 7.8	Demeke Kifle and Amha Belay (990)
Chamo	Mar., 2004		3.8-10.86	Eyasu Shumbulo (2004)
Naivasha	1973/1974		3.7-6.2	Melack (1979b)
Hora-Kilole	Feb.-Mar.'64		1.49-2.4	Talling *et al.*(1973)
Hora-Hoda	1995	1.43 - 2.56	11.25-44.83	Demeke Kifle *et al.* (unpublished)
George	167-68		14.4	Ganf (1975)
	1974		15.56	Ganf and Horne (1975)
Baringo	10 Mar., 1989		3.8	Patterson and Wilson (1995)
Simbi	Nov. 1976	0.62 - 5.22	19.2	Melack (1979c)
Bogoria		0.28 - 3.00	280-3000	Melack (1976)
Nakuru	1972		15.2-21.2	Vareschi (1982)
Oloidien	Jan.1971		11.7	Melack(1979b)
Muzahi			6 to 9.5	Mukankomeje *et al.* (1993)