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Key drivers for phytoplankton composition and biomass in an Ethiopian highland lake

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ABSTRACT

We studied the temporal phytoplankton community pattern of the deep crater Lake Hayq in the highlands of Ethiopia from October 2007 to October 2008. Earlier sporadic surveys indicated that the phytoplankton community was predominantly characterized by heavy diatoms, which characteristically suffer from rapid sedimentation. The trophic status of Lake Hayq was reported to have changed from oligotrophic to eutrophic in 1992. The present study addresses the potential reasons for the diatom dominance as well as causes of the trophic change. Net and integrated water samples were used for determination of physico-chemical parameters and phytoplankton biovolumes. Our results revealed that diatoms and chlorophytes dominated during most of the study period in Lake Hayq and seem to be favored by the mixing regime of the water body, which can be described as partial atelomixis with daily mixing of the epilimnion maintaining the algae within the euphotic depth *via* regular re-suspension. However, the epilimnion may be decoupled from the hypolimnion by a seasonal chemocline. Nutrients were not limiting in the lake with an overall mean concentration of soluble reactive phosphorus of 22 $\mu g\, L^{-1}$ and total phosphorus of 58 $\mu g\, L^{-1}$ and of dissolved inorganic nitrogen of 305 $\mu g\, L^{-1}$, with ammonium being the primary form. In the 1940s only diatoms were reported, but since the 1990s other phytoplankton groups and taxa have become relevant. Canonical correspondence analysis showed that chlorophytes were mainly associated with nutrients and rainfall, euglenophytes with elevated alkalinity and the diatoms with silica and zooplankton. Chlorophyll *a* as measure of total phytoplankton biomass was significantly influenced by seasonality and underwater light supply, reflecting the significant role of atelomixis in persistent occurrence of heavy taxa in the epilimnion. The lake is still categorized as a eutrophic system, demonstrating that the trophic change reported in 1992 was not short-lived. In addition to changes in the catchment the eutrophication process was probably primarily triggered by a previous introduction of Tilapia in the lake, causing a cascading effect in the food–web interactions. This implied that the phytoplankton composition and biomass of this tropical deep tropical lake can be controlled through biomanipulation, as has been demonstrated for temperate lakes.

Introduction

Tropical limnology in Africa started in the 1930s with short-term expeditions (Talling and Lemoalle 1998). Compared to temperate systems, however, African inland waters have been studied only scarcely, with a few exceptions (Fetahi et al. 2011a,b; Ganf 1975; Hecky and Fee 1981; Oduor and Schagerl 2007; O'Reilly et al. 2002; Talling 1957, 1965; Vareschi 1982; Willén et al. 2011). This is particularly true of Ethiopian highland lakes even though rift valley lakes have been relatively more frequently studied (Kebede and Belay 1994; Kifle and Belay 1990; Lemma 1994). In this study we investigated the deep Lake Hayq located in the highlands of Ethiopia, which was one of the lakes studied earlier in Africa (Cannicci and Almagia 1947; Vatova 1940; Zanon 1941). The latter described the lake as '*limpida e verdastra*', which means 'clear and greenish water'. Baxter and Golobitsch (1970), after about 30 years, also described it as 'an unusual clear-water lake' with a Secchi depth of 9 m, very low phytoplankton biomass (<1 $mg\, m^{-3}$ Chlorophyll *a* = Chl *a*) and oxic conditions down to 40 m depth. Nevertheless some years later, Kebede et al. (1992) reported a remarkable shift of the lake to an eutrophic status that probably related to increased nutrient concentrations and/or the introduction of Tilapia (*Oreochromis niloticus* Linnaeus 1758) in the late 1970s. The trophic change was associated with water transparency of only around 1.2 m Secchi disk readings, Chl *a* concentrations up to 23 $mg\, m^{-3}$ and the absence of oxygen below 15 m.

Phytoplankton assemblages reflect autecological aspects of preference and tolerance, as phytoplankton species have developed

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morphological and physiological adaptive strategies for surviving in different environments (Reynolds 1997, 2006). Accordingly, use of phytoplankton assemblages for monitoring the ecological status of lakes has been recommended (Reynolds 2006; Souza et al. 2008) and is already incorporated in the European water framework directive (Anneville et al. 2008). The assemblages (and intuitively their succession) can be structured by physical, chemical or biological variables: phytoplankton growth and biomass is regulated *via* availability of resources (Huisman and Weissing 2001; Reynolds 2006; Zhang et al. 2007), through top-down control (Spencer and King 1984) and other biological interactions such as viral infection (Brussaard 2004; Tijdens et al. 2008). Furthermore, the physical conditions structure the general patterns of the phytoplankton community, though these are often neglected as an explanation for the occurrence of certain taxa. One of these physical variables is water temperature associated with the mixing pattern and supply of photons within the water column (Dokulil 1994; Huisman et al. 1999). Non-motile and heavy organisms like diatoms or desmids are highly affected by the mixing, in particular by mixing depth in relation to euphotic depth (Reynolds 1997).

Lake Hayq is a relatively deep lake (Z_{max} = 88 m) with pronounced chemical stratification and the previous surveys revealed diatoms as the main phytoplankton group (Baxter and Golobitsch 1970; Kebede et al. 1992). We therefore assumed that a special mixing pattern might act as an overall key variable that drives the phytoplankton assemblages as heavy plankton forms would not be expected to dominate in stably stratified water bodies. Of the physical factors, atelomixis – stratification and de-stratification taking place within 24 h – has been employed to characterize the phytoplankton assemblages of tropical deep water bodies (Lewis 1973; Reynolds 1997; Barbosa and Padisák 2002), and its ecological significance was discussed by Barbosa and Padisák (2002). Some studies have demonstrated the importance of atelomixis to explain the dominance of heavy phytoplankton assemblage in tropical lakes and reservoirs (Lewis 1978, 1986; Tavera and Martinez-Almeida 2005; Souza et al. 2008), but this mechanism has not investigated for tropical-African highland lakes and this is the first spatial and seasonal study for Lake Hayq. Although the lake is remote, the introduction of planktivorous fish, a nearby town, increased settlement (the number of population in 2005 is about 14,000 which is almost doubled since the 1994 census) and tourism as well as reduction of the inflow to the lake are likely to have led to eutrophication processes in the recent past. The problem of eutrophication is still largely neglected in developing countries and monitoring programs have scarcely been established for such lakes. We therefore investigated the phytoplankton community composition with monthly sampling for 15 months, and characterized the major functional groups *sensu* Reynolds et al. (2002) and Padisák et al. (2009). Additionally, we measured variables including the major nutrients and applied multivariate tools to get insights into major structuring variables of phytoplankton within the given physical condition. We discuss the results in relation to zooplankton abundances published earlier (Fetahi et al. 2011b) and compare them to the historical taxonomic lists published by Baxter and Golobitsch (1970) and by Kebede (1992).

Study area

Lake Hayq (11°15′ N, 39°57′ E) is located some 440 km north of Addis Ababa, the capital of Ethiopia, at an altitude of 2030 m a.s.l. The study area is categorized as sub-humid tropical with an annual rainfall of 1173 mm and a mean air temperature of 18.2 °C (National Meteorological Service Agency). Based on rainfall data since 1963, the major rainy season is from July to September. During the present study, there was no rainfall from December to March, which is considered as dry season (Fig. 1). Until some 20 years before, Lake Hayq was connected to the nearby Lake Hardibo (11°14′ N, 39°46′ E; altitude 2150 m a.s.l.) through the Ankwarka River. However, at present these lakes are terminal and there is no known surface outlet due to the irrigation scheme upstream. While this change has reduced the option for nutrient losses from the lake, loading to the lake is likely to have increased: based on data from the Ethiopia Central Statistical Agency in 2005, the population of Hayq City of about 14,000 has almost doubled since the 1994 census, farming takes place just on the verge of the lake and the farmers use fertilizer to boost production. Furthermore, Lake Hayq is becoming a touristic destination particularly for local tourists.

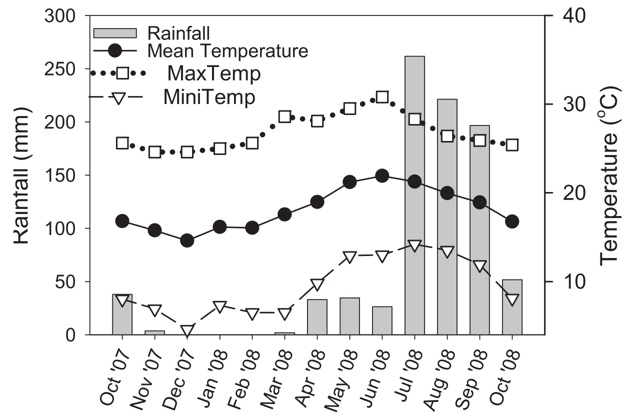

Fig. 1. Air temperature (mean, maximum and minimum) and rainfall near Lake Hayq during the sampling period from October 2007 to October 2008. Data from National Meteorological Services Agency.

Lake Hayq is large (23.2 km^2), deep, steeply shelving lake, with a maximum depth of 88 m recorded in 1938 (Table 1) and a salinity of 0.828 g L^{-1} (Zinabu et al. 2002). Predominant cations and anions are magnesium and carbonate/bicarbonate, respectively (Table 2).

The fish that inhabit Lake Hayq are *Oreochromis niloticus* (Nile Tilapia), *Clarias gariepinus* Burchell 1822 (African catfish), *Cyprinus carpio* (common carp) and *Garra dembecha* Getahun and Stiassny 2007. The last two fish species were introduced in Lake Hardibo most likely in 1980, and eventually reached Lake Hayq due to the connecting river (Tizazu, personal communication). Tilapia is also stocked (Kebede et al. 1992) and hence Catfish are the only indigenous fish species (Baxter and Golobitsch 1970). The dominant zooplankton are *Mesocyclops aequatorialis* Van de Velde 1984, *Thermocyclops ethiopiensis* Kiefer 1934, *Ceriodaphnia reticulata* Jurine, *Daphnia magna* Straus 1820, *Diaphanosoma excisum* Sars and the common rotifers includes *Euchlanis parva* Rousselet 1892, *Keratella tropica* Apstein, *Polyarthra* sp. (Fetahi et al. 2011b). The land uses in the catchments include agriculture (on steep land) and livestock grazing.

Table 1
Morphometry of Lake Hayq (from Baxter and Golobitsch 1970).

Variables	Values
Max. length (north–south)	6.7 km
Max. width	6.0 km
Shoreline	21.7 km
Surface area	23.2 km^2
Max. depth	88.2 m
Mean depth	37.37 m
Volume	0.867 km^3