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The seasonal succession of diatoms in phytoplankton of a soda lake (Lake Hazar, Turkey)

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Abstract: Some physicochemical variables and climatic effects on the succession of a diatom community in the plankton of the pelagic zone of Lake Hazar, an alkaline soda lake, were investigated. Monthly diatom samples were collected from the surface water at western, central, and eastern pelagic areas of the ellipsoid-shaped lake using a plankton net from November 2004 to October 2005. When high temperature and pH levels prevailed in May and September, *Epithemia*, *Rhopalodia*, *Cocconeis*, and *Cyclotella* were dominant. *Cymbella* was dominant in early spring and late autumn, but was not significantly correlated with temperature or pH. The species of *Gomphonema*, *Fragilaria*, *Navicula*, and *Nitzschia* were dominant at low temperature and pH levels in winter. However, the diatom community of the surface phytoplankton in the lake comprised largely cosmopolitan and nonplanktonic species of *Cocconeis*, *Cyclotella*, *Cymbella*, *Epithemia*, *Fragilaria*, *Gomphonema*, and *Rhopalodia* detached from benthic habitats of littoral zone by wind-driven currents.

Key words: Diatom, succession, water quality, soda lake

Introduction

Soda lakes as extreme ecosystems represent the most stable natural alkaline environments. They are characterised by high concentrations of sodium carbonate. The presence of carbonate provides the buffering capacity of the lake waters (Ulukanlı & Dığrak, 2002). Soda lakes show large salinity and pH ranges and the pH may rise to high values, especially in closed lakes. The formation of high alkalinity in soda lake environments requires a combination of geographical, topographical, and climatic conditions (Reimer et al., 2009).

The oligotrophic Lake Hazar is the second largest natural lake in Eastern Anatolia (Şen et al., 2003). The algal flora of Lake Hazar mainly comprises *Bacillariophyta*, *Chlorophyta*, *Cyanophyta*, *Dinophyta*, and *Euglenophyta*. Lake Hazar, with a high pH value and carbonate content, is characterised by the dominance of pennate diatoms in the phytoplankton and phytobenthos (Şen et al., 1995).

Diatoms, besides being important components of primer productivity, are valuable indicators of environmental conditions because they respond directly and sensitively to many physical, chemical, and biological changes in aquatic ecosystems. Diatoms have proven to be extremely powerful tools with which to explore and interpret many ecological conditions (Round et al., 1990; Stoermer & Smol, 1999; Reynolds, 2006).

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This study aims to reveal the environmental factors leading to the diversity and dominance of diatoms in phytoplankton and the influences on the succession of planktonic diatoms in surface water of the pelagic zone of Lake Hazar.

Material and methods

Study site

The oligotrophic Lake Hazar is the second largest natural lake in Eastern Anatolia. Lake Hazar, formed by faulting of the Eastern Anatolia Fault, is a tectonic lake located at 38°31′N, 39°25′E. The lake, with a parallelogram or elliptical shape, has a surface area of 80 km^2 and a basin area of 403 km^2 at an altitude of 1238 m. Since there is no exact bathymetrical measurement of the lake, previous studies have reported various maximum depths ranging between 80 and 300 m (Şen et al., 2003). The lake is monomictic, with the incomplete mixing in spring and the complete mixing between autumn and early winter. It is stratified from June to September, forming a thermocline between 10 and 20 m (unpublished data).

Sampling and analysis

Surface water samples for analysis of physicochemical variables were taken monthly from November of 2004 to October of 2005. The minimum depth of the sampling stations was 10 m, which was the pelagic zone during the study period. Diatom samples were qualitatively collected along about 1 km of trawling with a boat using a plankton net with a pore size of 55 µm (Figure 1). Water samples for diatom counting were placed in 250-mL bottles and fixed with Lugol's solution.

Temperature, pH, and conductivity were measured using a YSI 63 model instrument in situ. Total alkalinity, bicarbonate, and carbonate were determined with amperometric titration (Radtke et al., 1998). Nitrate nitrogen, total nitrogen, soluble reactive phosphorus, total phosphorus, and silica were determined with automatic methods using a Lachat Instrument QuickChem 8000 flow injection analyser. Chlorophyll *a* was determined with a Thermo Helios-α spectrophotometer after acetone extraction (APHA et al., 1995).

Permanent slides were prepared after boiling with acidic solution and mounting with Entellan medium (Wetzel & Likens, 1991; APHA et al., 1995). Diatoms were identified under 1000× magnification on an Olympus CX41 research microscope according to the methods of Patrick and Reimer (1966, 1975), Hustedt (1985), and Krammer and Lange-Bertalot (1986, 1988, 1991a, 1991b).

Data evaluation

Normality of data was checked by the Shapiro–Wilk test. The differences of variables with normal distribution among the sampling depths were tested using the signed rank test (Wilcoxon) for nonnormal distribution. The Wilcoxon test did not detect significant differences between the regions

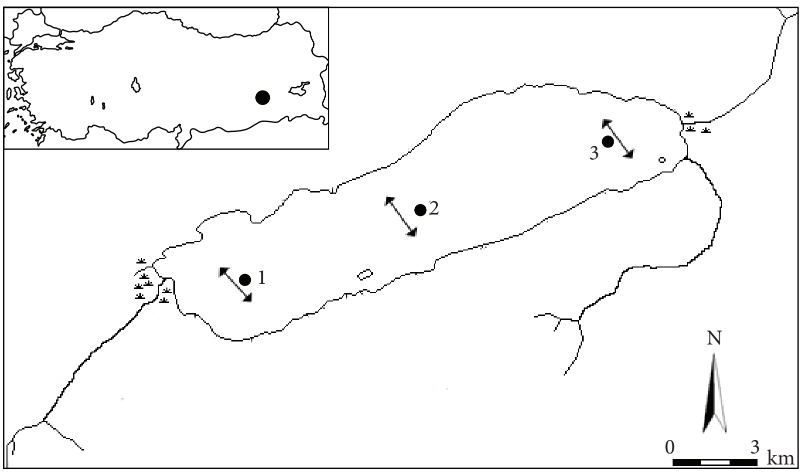

Figure 1. Lake Hazar and sampling sites in the pelagic zone of the lake.

in terms of relative abundances of species and physicochemical variables ($P > 0.05$). Therefore, the data were evaluated calculating the mean values of relative abundances and physicochemical variables.

We resorted to multivariate analysis to determine the relationships between phytoplankton composition and physicochemical environmental variables. In the first step of the analysis, an unconstrained ordination was calculated to select linear or unimodal methods in detrended correspondence analysis (DCA). Species data were transformed logarithmically (log (a × y + b)). In DCA with detrending by segments and Hill's scaling, the length of the longest axis provided an estimate of the beta diversity in the data set. Because DCA showed short gradient lengths (<0.95 standard deviation), a linear model was appropriate for our data (ter Braak, 1995; Lepš & Šmilauer, 2003). Principal component analysis (PCA) was then used for scaling in interspecies relations and dividing species scores by the standard deviation. Logarithmically transformed species data were centred (ter Braak, 1995; ter Braak & Verdonschot, 1995; Lepš & Šmilauer, 2003). Multivariate analysis and triplot loading were performed using CANOCO 4.5.

Results and discussion

The surface water temperature of the pelagic zone of Lake Hazar was measured between 4.7 and 29.4 °C during the study period. The mean pH value was 9.1 ± 0.2, being consistent with high alkalinity and high bicarbonate and carbonate concentrations. High conductivity can be attributed to high dissolved solids content, including mainly bicarbonate, carbonate, and calcium. The mean concentrations of total nitrogen in the surface water of the pelagic zone changed between 0.525 and 0.570 mg N/L while total phosphorus changed between 0.020 and 0.027 mg P/L. Mean chlorophyll *a* concentrations at the sites changed between 1.2 and 1.4 µg/L with a maximum concentration of 2.2 µg/L (Table 1). Although there appeared to be some differences among the sampling sites in terms of physicochemical variables, variance analysis did not detect statistically significant differences ($P > 0.05$). Based on the trophic status classification (OECD, 1982), the surface water of the pelagic zone of Lake Hazar exhibited oligotrophic characteristics in terms of total nitrogen and mean and maximum chlorophyll *a* concentrations, but it was mesotrophic in total phosphorus. Overall, the main physicochemical characteristics suggest that Lake Hazar is an oligotrophic, hard-water, and alkaline soda lake with regard to the surface water of the pelagic zone.

In the study period, there were 50 taxa belonging to genera *Achnanthes*, *Amphora*, *Caloneis*, *Cocconeis*, *Cyclotella*, *Cymatopleura*, *Cymbella*, *Diatoma*, *Epithemia*, *Fragilaria*, *Gomphonema*, *Navicula*, *Nitzschia*, *Pinnularia*, *Rhoicosphenia*, *Rhopalodia*, and *Surirella* (Table 2).

The number of species observed was minimum (17 taxa) in August and maximum (43 taxa) in March. The number of species was low between May and October. It showed an increasing trend between January and April, when low temperature conditions prevailed (Figure 2).

In winter (January, February, and March), *Gomphonema clavatum* was dominant (19%, 16%, and 22%, respectively). *Fragilaria capucina* var. *rumpens*, *Gomphonema olivaceum*, and *Cymbella helvetica* were subdominant species in the same period. The dominant species of spring (March and April) was *Cymbella affinis* (16% and 20%, respectively), followed by *Gomphonema clavatum*, *Gomphonema olivaceum*, *Cymbella cymbiformis*, and *Cymbella leptoceros*. The relative abundance of *Epithemia turgida* (32%) and *Rhopalodia gibba* (12%) increased in the late spring (May) when thermal stratification formed (Figure 3).

The dominance of *Cyclotella meneghiniana* (32%, 24%, and 15%, respectively) and *Cocconeis placentula* (5%, 22%, and 29%, respectively) was observed during summer (June, July, and August) when *Cocconeis placentula* var. *lineata*, *Epithemia turgida*, and *Rhopalodia gibba* were subdominant. Again, *Cymbella affinis* was found to be dominant (21%) in September, and it became the major component of the diatom community in phytoplankton (40%) in October. *Cocconeis placentula* was the dominant taxon in August and subdominant in September. The relative abundances of *Gomphonema clavatum* and *Gomphonema olivaceum* showed an increasing tendency in October. There was a marked increase of *Gomphonema clavatum* in November (Figure 3).

Table 1. The mean concentration and standard deviation (minimum–maximum) of variables of surface water in the pelagic zone of Lake Hazar during the study period.

Variables	Site 1	Site 2	Site 3
Temperature (°C)	14.0 ± 8.9 (4.7–29.4)	13.2 ± 8.5 (5.1–28.6)	13.5 ± 8.8 (5.2–28.8)
pH	9.1 ± 0.2 (8.5–9.2)	9.1 ± 0.2 (8.6–9.4)	9.1 ± 0.2 (8.7–9.3)
Conductivity (µS/cm)	2249 ± 129 (2001–2510)	2235 ± 127 (1920–2469)	2244 ± 142 (1953–2490)
Alkalinity (mg $CaCO_3$/L)	466 ± 56 (369–640)	467 ± 70 (344–656)	455 ± 42 (328–574)
Bicarbonate (mg HCO_3^-/L)	303 ± 33 (212–400)	292 ± 77 (200–435)	298 ± 61 (208–405)
Carbonate (mg CO_3^{-2}/L)	97 ± 9 (83–136)	97 ± 8 (84–120)	99 ± 10 (86–127)
Calcium (mg Ca^{+2}/L)	99.8 ± 5.7 (72.9–105.2)	100.9 ± 3.9 (89.9–107.9)	103.2 ± 6.0 (92.8–121.5)
Magnesium (mg Mg^{+2}/L)	10.1 ± 5.0 (5.2–24.0)	8.5 ± 1.9 (6.4–12.0)	8.9 ± 2.5 (6.4–14.4)
Nitrate (mg NO_3^--N/L)	0.368 ± 0.137 (0.100–0.847)	0.409 ± 0.191 (0.100–1.020)	0.371 ± 0.239 (0.100–1.280)
Total nitrogen (mg N/L)	0.525 ± 0.170 (0.160–1.126)	0.570 ± 0.236 (0.180–1.326)	0.552 ± 0.284 (0.190–1.643)
Soluble reactive phosphorus (µg PO_4^{-3}-P/L)	13.9 ± 7.7 (8.7–50.0)	19.4 ± 6.8 (10.0–67.5)	15.0 ± 6.5 (8.7–40.0)
Total phosphorus (µg P/L)	20.0 ± 12.5 (12.3–62.5)	26.9 ± 9.3 (12.5–92.8)	21.5 ± 10.9 (12.9–65.0)
Silica (mg SiO_2/L)	3.3 ± 0.6 (2.1–5.2)	2.8 ± 0.8 (1.7–4.7)	2.8 ± 0.6 (1.8–4.5)
Chlorophyll *a* (µg/L)	1.2 ± 0.1 (0.7–2.0)	1.2 ± 0.2 (0.4–2.0)	1.4 ± 0.3 (0.6–2.2)

The species of *Cocconeis*, *Cyclotella*, *Cymbella*, *Epithemia*, *Fragilaria*, *Gomphonema*, and *Rhopalodia* almost completely represented the diatom community in phytoplankton from the lake surface during the study period (total relative abundance: 83%–98%). Moreover, these genera showed a clear seasonal succession tendency. There was a periodicity that emerged in the dominance of *Gomphonema* and *Fragilaria* in winter, *Cymbella* in early spring and autumn, *Epithemia* and *Rhopalodia* in late spring, and *Cyclotella* and *Cocconeis* in summer (Figure 4).

PCA revealed 2 main directions of variation, with axis 1 explaining 55.6% of the total variance and axis 2 explaining an additional 14.0% (Figure 5). The interset correlations of species and environmental data showed that the strongest direction of variation (axis 1) was primarily a gradient of species succession together with temperature, carbonate, conductivity, pH, silica, alkalinity, and species number. The second gradient (axis 2) was mainly characterised by the correlations of soluble reactive phosphorus and silica together with some species. *Epithemia* and *Rhopalodia*, dominant in late spring, and *Cocconeis* and *Cyclotella*, dominant in high temperature conditions, were placed on the right side of the graph near May, June, July, August, and September. *Cymbella*, dominant in early spring and late autumn, was not significantly correlated with temperature. The species of *Gomphonema*, *Fragilaria*, *Navicula*, and *Nitzschia*, dominant in the period of low temperature, were placed on the left side of the graph near December and January (Figure 5).

Table 2. The list of diatom species in the phytoplankton of the pelagic zone of Lake Hazar.

Taxa	Taxa
Achnanthes delicatula (Kützing) Grunow	*Fragilaria capucina* var. *vaucheriae* (Kützing) Lange-Bertalot
Amphora ovalis Kützing	*Fragilaria crotonensis* Kitton
Caloneis obtusa (W.Smith) Cleve	*Fragilaria fasciculata* (C.Agardh) Lange-Bertalot
Cocconeis placentula Ehrenberg	*Fragilaria ulna* (Nitzsch) Lange-Bertalot
Cocconeis placentula var. *lineata* (Ehrenberg) Van Heurck	*Fragilaria ulna* var. *acus* (Kützing) Lange-Bertalot
Cyclotella meneghiniana Kützing	*Fragilaria virescens* Ralfs
Cymatopleura solea (Brebisson) W.Smith	*Gomphonema angustatum* (Kützing) Rabenhorst
Cymbella affinis Kützing	*Gomphonema clavatum* Ehrenberg
Cymbella cymbiformis C.Agardh	*Gomphonema constrictum* Ehrenberg
Cymbella ehrenbergii Kützing	*Gomphonema olivaceum* (Hornemann) Brebisson
Cymbella helvetica Kützing	*Gomphonema parvulum* Kützing
Cymbella lata Grunow	*Navicula exigua* (Gregory) Grunow
Cymbella leptoceros (Ehrenberg) Kützing	*Navicula menisculus* var. *upsaliensis* Grunow
Cymbella tumidula Grunow	*Navicula phyllepta* Kützing
Cymbella turgidula Grunow	*Navicula reinhardtii* Grunow
Diatoma vulgaris Bory	*Navicula tripunctata* (O.F.Müller) Bory
Epithemia adnata (Kützing) Brebisson	*Navicula viridula* Kützing
Epithemia argus (Ehrenberg) Kützing	*Nitzschia hantzschiana* Rabenhorst
Epithemia sorex Kützing	*Nitzschia sigmoidae* (Nitzsch) W. Smith
Epithemia sorex var. *gracilis* Hustedt	*Pinnularia viridis* (Nitzsch) Ehrenberg
Epithemia turgida (Ehrenberg) Kützing	*Rhoicosphenia abbreviata* (C.Agardh) Lange-Bertalot
Epithemia turgida var. *granulata* (Ehrenberg) Brun	*Rhopalodia gibba* (Ehrenberg) O.F.Müller
Fragilaria brevistriata Grunow	*Rhopalodia gibba* var. *parallela* (Grunow) H.Peragello & M.Peragallo
Fragilaria brevistriata var. *pusilla* Grunow	*Surirella ovalis* Brebisson
Fragilaria capucina var. *rumpens* (Kützing) Lange-Bertalot	*Surirella turgida* W.Smith

The pH value of Lake Hazar was always highly alkaline (8.7 to 9.2), and thus most species had to be alkaliphilic. The influence of pH was characterised with the same directions of *Epithemia* and *Rhopalodia*, predominantly alkaliphilic, and with the opposite direction of *Gomphonema,* which is more acidophilic (Stoermer & Smol, 1999). The preference for high electrolyte content of *Epithemia* and *Rhopalodia* (Krammer & Lange-Bertalot, 1988) was clearly reflected in the graph with placement in the same position and direction as conductivity. Moreover, *Epithemia* and *Rhopalodia*, which are found in oligotrophic hard waters (Kramer and Lange-Bertalot, 1988), showed relatively significant correlations with carbonate. *Cymbella*, distributed in surface waters with different electrolyte contents (Kramer & Lange-Bertalot, 1986), did not show any significant relations with pH and conductivity (Figure 5).

Despite these approaches aiming to explain the succession patterns of diatoms in plankton, most of the species discussed, except for *C. meneghiniana*, are benthic algae that are primarily epilithic and epiphytic forms. Some of them can tolerate depth variations (eurytopic) and can be planktonic (Servant-Vildary & Roux, 1990), but there are no euplanktonic species. Carrick et al. (1993) showed that wind turbulence increases the spatial differentiation in phytoplankton.

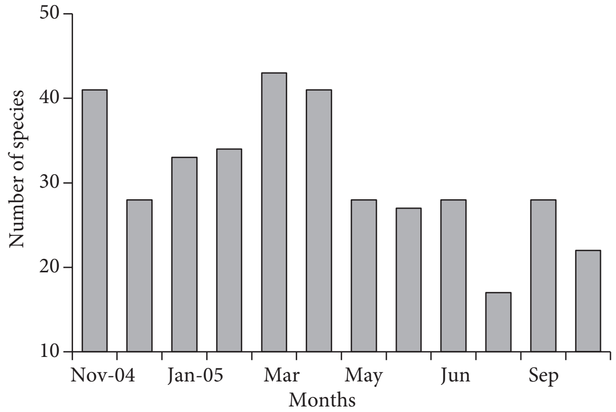

Figure 2. Monthly changes of the species number.

Indeed, many studies have verified that wind-induced currents can cause considerable heterogeneity in the horizontal distribution of phytoplankton cells (Carrick et al., 1993; Verhagen, 1994; Webster & Hutchinson, 1994). In mildly saline (total salts of 500–2000 mg/L) lakes, algal flora is fairly rich and composed of a variety of diatoms (e.g., species of *Amphora*, *Cyclotella*, *Epithemia*, *Fragilaria*, *Navicula*, *Nitzschia*, and *Rhopalodia*), especially if nitrogen and phosphorus are high (Wehr & Sheath, 2003).

The tychoplanktonic species, especially in *Cocconeis*, *Cymbella*, *Fragilaria*, *Gomphonema*, and *Epithemia*, have been found to be important components of the phytoplankton communities of various lakes (Elmacı & Obalı, 1998; Kılınç, 1998; Akbulut & Yıldız, 2002; Karacaoğlu et al., 2004; Atıcı & Obalı, 2006; Çelekli & Köylüoğlu, 2006; Yılmaz, 2007; Atıcı & Obalı, 2010) and streams (Pala & Çağlar, 2008; Barinova et al., 2011; Solak et al., 2011). The genera *Cymbella* and *Gomphonema*, representing highly abundant taxa of diatoms in the phytoplankton of Lake Hazar, have been reported as common species in the benthos and plankton of surface waters in the same region (Çetin & Şen, 1998; Çetin & Yavuz, 2001; Yıldırım et al., 2003; Alp & Sen, 2010). These genera are generally dominant in the littoral phytoplankton and benthic habitats of Lake Hazar (Şen et al., 1995).

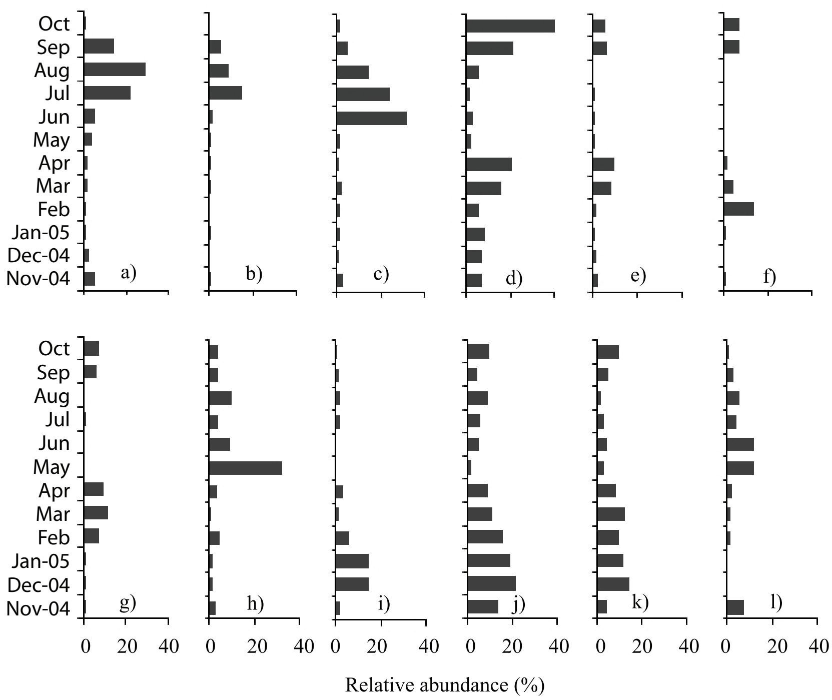

Figure 3. The changes of relative abundances of dominant diatom species: a) *Cocconeis placentula*, b) *Cocconeis placentula* var. *lineata*, c) *Cyclotella meneghiniana*, d) *Cymbella affinis*, e) *Cymbella cymbiformis*, f) *Cymbella helvetica*, g) *Cymbella leptoceros*, h) *Epithemia turgida*, i) *Fragilaria capucina* var. *rumpens*, j) *Gomphonema clavatum*, k) *Gomphonema olivaceum*, l) *Rhopalodia gibba*.

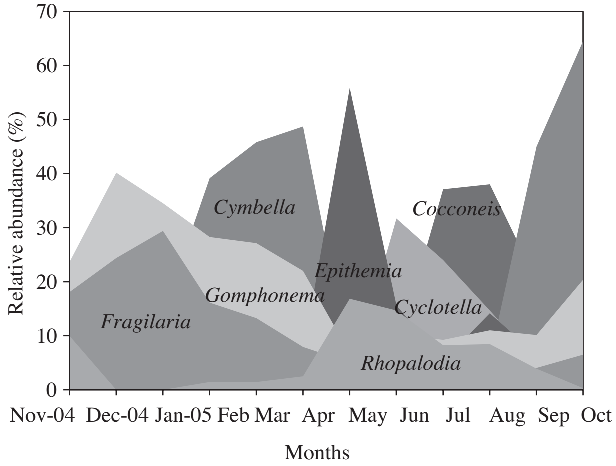

Figure 4. Succession of diatom genera in the plankton of Lake Hazar.

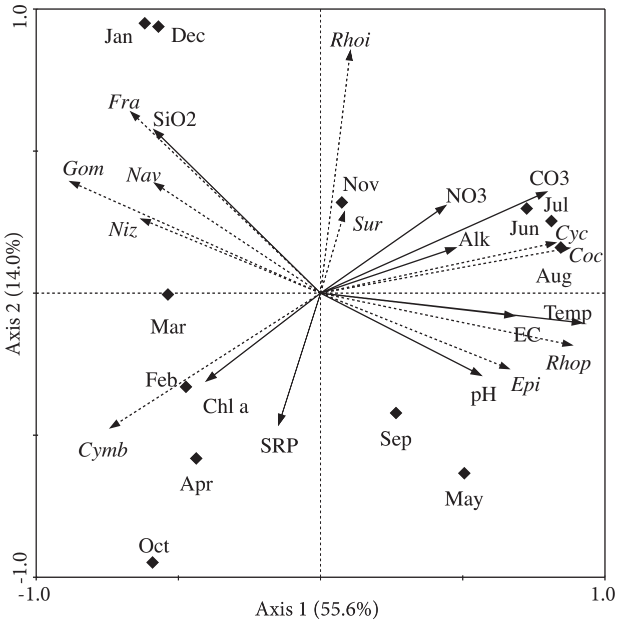

Figure 5. PCA graph of genera and environmental data (Temp, temperature; EC, conductivity; Alk, alkalinity; CO3, carbonate; NO3, nitrate; SRP, soluble reactive phosphorus; SiO2, silica; Chl a; chlorophyll *a*; *Coc*, *Cocconeis*; *Cyc*, *Cyclotella*; *Cymb*, *Cymbella*; *Epi*, *Epithemia*; *Fra*, *Fragilaria*; *Gom*, *Gomphonema*; *Nav*, *Navicula*; *Niz*, *Nitzschia*; *Rhoi*, *Rhoicosphenia*; *Rhop*, *Rhopalodia*; *Sur*, *Surirella*).

It is well known that benthic algae on epipelagic substrates frequently join phytoplankton by detaching as a result of mixing due to wind and wave actions and contribute to phytoplanktonic primer production (Hutchinson, 1967; Round, 1981). Indeed, during the samplings it was observed that the massive mucilage pads and stalks detached from benthic substrata were floating freely on the surface of the lake. The same phenomenon was recorded in the littoral phytoplankton of the lake (unpublished data). The wind and wave effects on the succession pattern of diatoms in the surface water of the pelagic zone were further supported by the observation of the dominance of a true planktonic species, *C. meneghiniana*, during the summer thermal stratification.

The results show that cosmopolitan species with high alkalinity tolerance are generally dominant. The diatom population in the surface plankton of Lake Hazar is mainly composed of benthic species detached from the littoral area. Hence, intensive floating mucilage pads and stalks in the pelagic zone detached from substrates along the shoreline were observed over the course of the study. Temperature, which manages the seasonal changes of benthic algae, the thermal stratification, and the mixing of the water column, seems to be one of the principal controlling mechanisms of the periodicity of diatom species in phytoplankton. Long-term monitoring studies are clearly required to better understand the succession and productivity of phytoplankton in the lake.

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