Four consecutive dry years in Lake Balaton (Hungary): consequences for phytoplankton biomass and composition

Judit Padisák, Gábor Molnár, Éva Soróczki-Pintér, Éva Hajnal, D. Glen George

Introduction

Lake Balaton is the largest shallow lake in Central Europe (length 77.9 km; average width 7.2 km; surface area 593 km^2; mean depth 3.14 m; theoretical retention time 3–8 years; catchment area 5182 km^2). The Zala River, which enters the lake in the southwest, drains an area of 2622 km^2. In the last 150 years, the lake has been subjected to four major anthropogenic influences:

1. The opening of an artificial outlet to the lake (the Sió-channel) in 1867, which lowered the water level by approximately 3 m, restricted the water level fluctuation and separated the swampy areas in the southwest part of the lake that previously served as a self-purification biofilter for the open water.

2. The replacement of approximately 60–70% of the natural shorelines with concrete banks faced with red sandstone bricks in the middle of the 20th century to minimize damage caused by waves.

3. The enrichment of the lake with phosphorous (P). As a result, the originally mesotrophic lake underwent a rapid eutrophication in the 1960s–1970s (HERODEK 1984). Between 1975 and 1981 the total P load was estimated as 2.47 g m^{-2} $year^{-1}$ in the western part of the lake, and 0.31 g m^{-2} $year^{-1}$ in the eastern part (SOMLYÓDY & JOLÁNKAI 1986). As a consequence of the morphometric and loading conditions, a sharp trophic gradient subsequently developed in the lake.

4. The introduction of measures to reduce the phosphorous load in the mid-1980s that proved particularly effective (ISTVÁNOVICS & SOMLYÓDY 2001).

If present trends continue, limnologists believe that changes in the weather will have major effects on the dynamics of lakes throughout Europe. The present climate-change models (Swedish Meteorological and Hydrological Institute) predict more severe summer droughts with less precipitation over much of Europe. Such changes could lead to a seasonal extension of the heterocytic blue-green algae-dominated associations in Lake Balaton and increase the risk of serious algal blooms (PADISÁK 1998).

In 2000–2003, four consecutive dry years led to a negative water balance for Lake Balaton that resulted in a significant lowering of the water level. This paper aims to describe changes in biomass and composition of phytoplankton and to relate the observed changes to the predictions generated by an internal P-load model. Since Lake Balaton is a frequented tourist region of Europe, socio-economic consequences of ecosystemic changes during the drought period are also discussed.

Key words: drought, phytoplankton, biomass, composition, Lake Balaton, climate change

Materials and methods

Some of the phytoplankton data used in this paper were taken from the archives of the Middle Transdanubian Water Authority (1983–1988). For the period 1989–2003, our own data were used and have a sampling frequency in summer varying from three days to biweekly. Phytoplankton (a minimum of 400 settling units per sample) was counted with an inverted microscope; biomass (wet weight) was estimated volumetrically. To obtain summer maxima of phytoplankton biomass, individual species counts at the time of the recorded maximum were averaged with the respective species counts for the sampling dates immediately prior to, and immediately after, the occurrence of maximum. The maximum corresponds to the average of three consecutive data points. In this way, an index was obtained of the phytoplankton closest to the anticipated late summer equilibrium phase (SOMMER et al. 1993). For cluster analysis, Bray-Curtis index and WPGMA fusion algorithm was applied using SynTax III. program package (PODANI 1988).

Results and discussion

Meteorological and hydrological scenario, changes in the water level

The water income of the lake (VARGA in SOMLYÓDI 2003) is primarily determined by precip-

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itation, and losses are chiefly determined by evaporation. All other hydrological components are of minor significance. The only artificial outlet of the lake, the Sió-channel, has been closed since the beginning of the drought period. During the four consecutive dry years (2000–2003) the cumulative precipitation deficit (both direct precipitation onto the lake and to the majority of its watershed) exceeded 500 mm. The water level of the lake decreased by 1 m compared to its maximal capacity, which was 60 cm below the long-term mean (http://www.kvvm.hu/szakmai/balaton/lang_hu/vizszintb.htm). This water level decrease of the shallow lake (average depth 3.1 m) resulted in the shrinking of the water table beyond the shoreline constructions, especially along the slightly sloping southern shore of the lake. Since these summers were not only dry but hot, the water temperature in July-August rarely dropped below 25 °C and sometimes exceeded 28 °C.

Summer phytoplankton biomass and assemblages

The long-term trend of phytoplankton biomass (Fig. 1) in the two basins with different trophic levels indicated the eu-hypereutrophic condition (to the mid-1990s) of the lake and the subsequent oligotrophication (from the mid-1990s to present). The records for the dry period (2000–2003) are consistent with this trend, and there is no indication that changes in phytoplankton biomass were significantly affected by the exceptional hydrological regime. This holds for the species *Cylindrospermopsis raciborskii* (Fig. 1), which has been a major component of the summer phytoplankton biomass. During its worldwide invasion (PADISÁK 1997) the species occurred first in the lake in 1978 and caused severe algal blooms in specific years. A comparison of meteorological data (PADISÁK 1998) and dynamic ecological modeling (PADISÁK & KONCSOS 2002) showed that this species of tropical origin can bloom only if

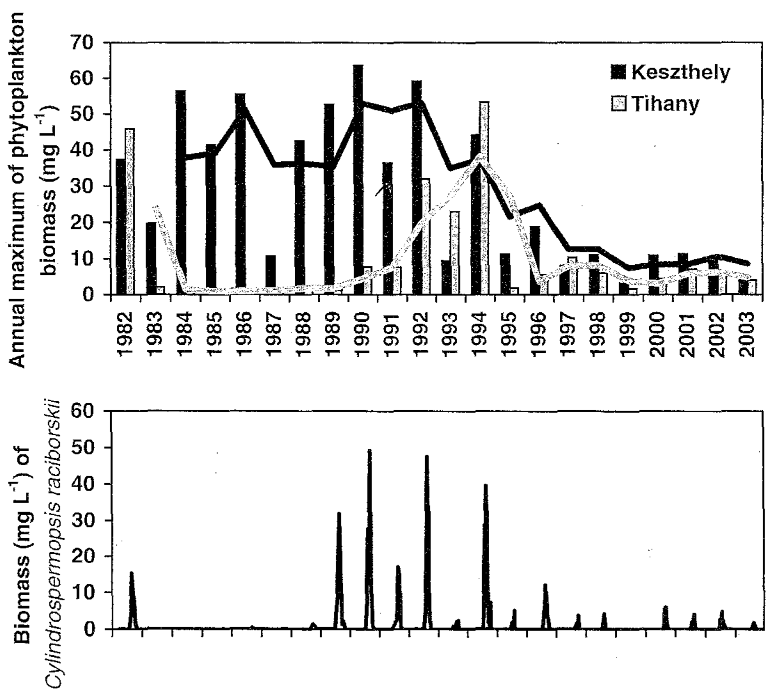

Fig. 1. Upper panel, Summer maximum of phytoplankton biomass in the western (black bars) and eastern (grey bars) basins of Lake Balaton in 1982–2003. Continuous lines represent the 3-y moving average. Lower panel, Biomass of *Cylindrospermopsis raciborskii* in the western basin of Lake Balaton in 1982–2003.

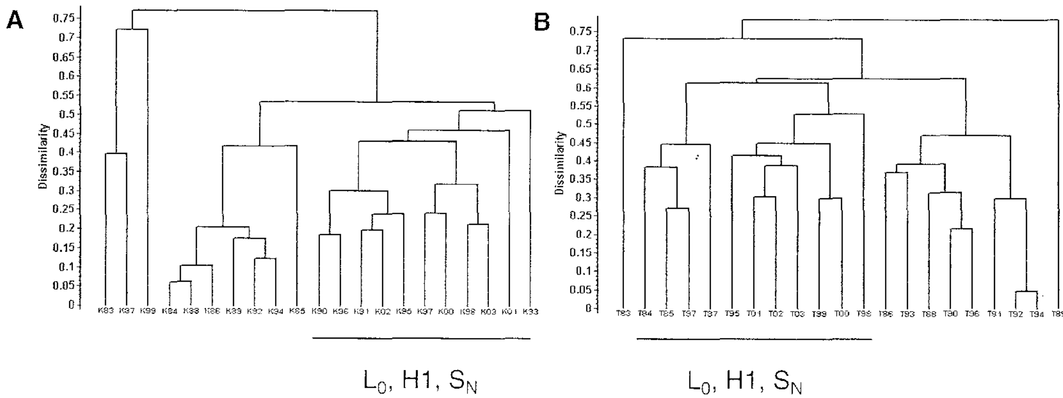

Fig. 2. Cluster dendrograms of summer phytoplankton biomass maxima in the western (A) and in the eastern (B) basin of the lake. Dissimilarity (1-similarity) is indicated on the vertical axes. Horizontal bars mark groups with dominance of **L_0** – **H1** – **S_N** assemblages.

summer temperatures significantly exceed the average. When discussing possible effects of global warming on phytoplankton of Lake Balaton, PADISÁK (1998) concluded that *C. raciborskii* blooms are to be expected in warm years so long as the P-pool of the sediments remains active. Since the temperature requirement of the species was fulfilled in summers of 2000–2003, the sedimentary P-pool must have been insufficient to support increased growth. Indeed, pilot studies on summer of 2003 (JAKAB et al. 2005) have shown that the acid-extractable P-pool of the sediments halved as compared to the records 10–15 years before.

A detailed analysis (PADISÁK & REYNOLDS 1998) on the summer phytoplankton of Lake Balaton identified six major assemblages (REYNOLDS et al. 2002): (1) **S_N**; (2) **H1+S_N**; (3) **H1+H1+S_N**; (4) **L_0**; (5) **H1**; and (6) **L_0**+S1. The **L_0** corresponds to the pre-eutrophication period of the lake and was observed in years 1984, 1985, 1985, 1987, 1993 and 1997 in the that time less eutrophic eastern basin of the lake and only in 1993 in the western basin. An update (Fig. 2) of the cluster analysis in PADISÁK & REYNOLDS (1998) showed that the community structure during the drought was very similar to that reported during the pre-eutrophication period (**L_0** dominance with elements of **H1** and **S_N**) or at least grouped to years with moderate summer algal peaks. This indicates that recovery process of the lake includes re-establishment of the phytoplankton characteristic for the original stage of the lake.

Response of other biota to summer droughts

Phytobenthos: The most visible ecosystem response of the lake to the lowering of the water table was the unusual appearance of extended benthic algal mats, especially *Cladophora*, in areas < 40 cm deep. *Cladophora* is an original element of the flora and was found primarily on the stones of the shore-protection constructions and in the reed belts. Benthic *Cladophora* mats were associated with submerged vegetation (especially *Najas marina*) and extended from 60 to 120 m from the shores (especially on the slightly steep southern shore). Total area of *Cladophora*-covered benthic compartment can be estimated as 7–10 km^2, 1–1.5% of the lake area according to VÖRÖS et al. (2004). These authors have also shown that dry weight of the *Cladophora* along the southern shores was approximately 230 tons, almost reaching the lake's total phytoplankton biomass (270 tons dry weight). Even though the physiological activity measures (e.g. annual net primary production, net growth rate) of *Cladophora* might be significantly lower than that of phytoplankton if summed to year, part of the low summer phytoplankton crop can reasonably be attributed to competition for sedimentary P-pool of the lake. Moreover, the benthic algal crop might have contributed significantly to the reduction in the internal P-pool of the lake that, at least in certain areas, still has the potential to initiate planktonic algal blooms (ISTVÁNOVICS et al. 2004).

Reed-belt and submerged macrophytes: One of the most widely discussed ecological phenomena of Lake Balaton in the past decades was the fragmentation and decline of the reed-belt (PADISÁK & SZABÓ 1997, KOVÁCS et al. 1999). The most widely accepted reason has been the insufficient connectivity (due to the construction of shoreline structures) with the terrestrial vegetation that prevents clone regeneration. By the end of the 2000–2003 drought period, evidence of reed-belt regeneration became more obvious, especially on the more affected southern shores (HERODEK & TÓTH 2004). During the peak of eutrophication, submerged macrophytes were insignificant in the lake. Later, parallel with decrease of phytoplankton, submerged macrophyte beds started to extend into the shallower and/or wind-sheltered areas of the lake (SIPOS et al. 2000). Because *Cladophora* uses macrophytes as a colonizing substrate (VÖRÖS et al. 2004), the extension of the macrophyte beds might have increased significantly.

Macrozoobenthos: The abundance of chyronomids in the profundal of the lake changed roughly parallel to the phytoplankton biomass in the eutrophication and oligotrophication periods and signals the re-establishment of a community structure characteristic of the pre-eutrophication period (SPECZIÁR et al. 2002). The most affected community was inevitably the *Dreissena*-dominated one characteristic for the stone substrate part of the "shoreline-protection" constructions. Although no data are available on the loss of abundance on these stones, it must have been considerable since most stayed dry during the summer of 2003. Direct evidence for the *Dreissena* decrease was provided by zooplankton ecologists who demonstrated a substantial decrease of planktonic veligera larvae (G.-TÓTH et al. 2004). *Dreissena* is not native in the lake: it (together with *Corophium*, another dominant species on the shoreline red sandstones) was shipped to the lake on the route Black Sea-Danube-Sió channel in the early 1930s. Experiments with re-introduction of crayfish (*Astacus leptodactylus*) into the lake resulted in survival of specimens in predator-free (eel used to be the most important predator) cages, with wild young stages reported from the vicinity of the cages (G.-TÓTH et al. 2004)

Fish: Since developmental/generation time of most fish species exceeds the length of the dry period, tracing immediate effects is difficult. However, the yields of native fish have been shown to be influenced by the climatic changes associated with El Niño (BÍRÓ et al. 2003), and therefore delayed changes are expected. Recovery of reed belts and proliferation of submerged macrophytes improve the previously limited breeding conditions of the fish populations and may serve as refuge for the larvae. Decrease of sandstone-associated epizoon (*Dreissena, Corophium*) restricted the nutritional basis of *Anquilla*, a non-native fish of the lake, which was a significant competitor of the native predatory fish.

In summary, the biotic changes associated with the 4-year drought period can be categorized as follows:

1. Planktonic and benthic communities of the open water largely remained unaffected and continued trends that correspond to the overall recovery process from severe eutrophication.

2. Shoreline vegetation is showing signs of recovery, and only alien species suffered serious losses.

Consequently, the hydrological regime set by the irregularities of weather caused no major deterioration in the status of the lake when compared to those recorded during its 'pristine' stage.

Socio-economic implications, tourism

Lake Balaton is one of the most popular tourist destinations in Europe. Tourism contributes 10% to the GDP of Hungary, of which the share for the Balaton region is about 30%. By the end of the drought period in 2003, the number of tourists visiting Balaton had substantially decreased. The economic consequences of this decrease were particularly acute because the tourist loss coincided with a more general economic recession in the rest of Europe. In representative interviews (15–19 August 2003; error: 3–5%, Medián Public Research Center, http://www.median.hu; data are cited here with permission) 50% of the of the respondents placed low water level among the 3 major reasons of tourism decline and 45% attributed the drop to bad water quality. Because tourism is concentrated on a narrow shoreline region, the above public opinion is not surprising. Indeed the tourists had to face at least one of the following phenomena:

1. On the southern shore the water depth was so low that at many bathers had to walk some distance to have sufficient water depth for swimming.
2. At the more seriously affected areas, bathers had to wade through unpleasant concentrations of *Najas* and *Cladophora* to reach open waters.
3. Some areas of the lake bed were exposed and served as a resting place of the waterfowl where the guano further repelled swimmers.
4. Angling from the shores was largely impossible, and, as a consequence, even open-water angling was seriously limited.
5. The landing points of the ferry had to be modified to ensure safe transport.
6. Some large sailing boats were unable to leave harbour because the navigation channels were too shallow.

Permanent inhabitants complained about loss of income, and the local fishing company suffered serious losses because eel traps have remained empty since the closure of the artificial outlet of the lake (April 2000). Additionally, properties (e.g. houses) started to devalue, although this has yet to be quantified. Under such conditions many public organizations have called for government intervention, such as bringing water to the lake from alien watersheds, a topic that was heavily discussed in the media in 2003.

Conclusions

According to results of statistical and modeling studies of the climate and water budget of Lake Balaton (Nováky in Somlyódi 2003, Koncsos et al. in Somlyódi 2003), the drought experienced between 2000 and 2003 was not particularly extreme and so cannot, with confidence, be attributed to definite change in the climate. Moreover, these studies confirm that the water budget of the lake is still characteristically positive, although climate change may increase the frequency of low water periods.

The 4-year dry period in the lake did not result in deterioration of ecological status of the lake; further, many indicator groups included in the Water Framework Directives provided positive responses to the low-water stage. This result corresponds to the original ecological status of the lake. Because Lake Balaton does not have a natural outlet, its surface has changed considerably in the past. The equilibrial water surface (when evapo-transpiration is the only loss) is estimated as 1300 km^2, more than twice that of present. Natural shoreline vegetation not only tolerates but requires an oscillating water level (for example because it enables clone-selection).

In contrast to biotic assemblages, the demand of tourism is for a stable water level, and periodic droughts might lead to socio-economic conflicts. However, it is important to note that the negative phenomena observed by tourists were only seemingly due to low water level. The real reasons were the strictly regulated water level in the last half a century and the shortness of the natural shoreline area.

This case study has some consequences for modeling water quality of shallow lakes. Even the best calibrated and validated model (see for example Padisák & Koncsos 2002) may fail to predict future scenarios because of the importance of different assemblages (in this case phytoplankton/phytobenthos), which may change abruptly in accordance with predictions of the "alternative stable equilibria" concept (Scheffer et al. 1993). Although complete macrophyte dominance is quite unlikely in such a large and dynamic lake as Lake Balaton, its proliferation in the shoreline region is possible, together with its socio-economic consequences. Such phenomena may also arise, to some extent, in shoreline regions of deep lakes (Ostendorp et al. 2003). The aim of this paper is not to provide recipes to solve the apparent contradiction between demands of natural assemblages and tourist uses of a lake. However, locally restricted management measures (such as dredging of ports, establishment of the traditional bath culture with walking piers and wooden houses on piers, constructed angling areas) combined with environmentally sound tourism and environmental education might help.

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Authors' addresses:
J. Padisák, É. Soróczki-Pintér, É. Hajnal, University of Veszprém, Department of Limnology, H-8200 Veszprém, Egyetem u. 10, Hungary.
G. Molnár, Balaton Development Research Council, H-8400 Siófok, Batthyany u. 1, Hungary.
D.G. George, Centre for Ecology and Hydrology, Bailrigg, Library Avenue, University of Lancaster, Lancaster, UK.