Effects of fish removal in the Furnas Lake, Azores

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Bio, A., A. Couto, R. Costa, A. Prestes, N. Vieira, A. Valente & J. Azevedo 2008. Effects of fish removal in the Furnas Lake, Azores. *Arquipélago*. Life and Marine Sciences 25: 77-87.

The Furnas Lake is a small volcanic, monomitic and increasingly eutrophised water body. Next to agricultural nutrient inputs, high densities of herbivorous fish are thought to contribute to high levels of turbidity in the lake, through zooplankton consumption and re-suspension of the nutrients accumulated in the sediment. According to the alternative state hypothesis a shift from turbid to clear water conditions is favoured by reduction of nutrient concentrations, increased light availability and reduction of planktivorous and benthos-feeding fish stock. To improve water quality in the Furnas Lake, a substantial part of the bottom-feeding fish population (62% of the estimated common carp population, *Cyprinus carpio,* and 5% of the estimated roach population, *Rutilus rutilus*) was removed. Effects of fish removal on turbidity and associated trophic state were analysed next to post-manipulation chlorophyll *a* concentration, zooplankton and macrophytes densities. Results suggest that fish removal was not enough to change lake conditions towards a lasting clear state dominated by macrophytes. Excessive nutrient load, in water and sediments, nutrient input from the lake basin and fish recruitment causing enhanced zooplankton grazing are appointed causes. Any further biomanipulation efforts should be associated to nutrient reduction; and continued monitoring of water quality, fish stock, macrophytes and zooplankton is needed.

Key words: range size, functional groups, herbivore, predator, resource availability model

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INTRODUCTION

Scheffer et al. (1993) suggested that turbidity in shallow lakes is not a smooth function of their nutrient status. Lakes are thought to have two distinct equilibria between which they can alternate: a clear state dominated by macrophytes and a turbid state dominated by algae. Turbidity hinders vegetation growth through reduced light availability. Vegetation, in turn, lowers turbidity reducing re-suspension of sediments and protecting (hiding) phytoplankton-grazing zooplankton from planktivorous fish. Furthermore, vegetation competes with algae for nutrients. It was found that vegetation can stabilize clear water conditions up to certain nutrient loadings, but increasing nutrient loadings favour algal growth, causing turbidity and a rapid reduction in macrophytes. To invert that situation and regain a vegetation-rich, clear-water state, nutrients have to be drastically reduced, or light availability increased (e.g. lowering the water level). The switch to a clear state can also be triggered by reducing the planktivorous fish stock (Jeppesen et al. 2007b). Omnivorous, benthos-feeding fish like carps degrade water quality in several ways (Crivelli 1983; Breukelaar et al. 1994; Beklioglu et al. 2003). They increase water

turbidity consuming zooplankton and macrophytes and revolving the sediment, re-suspending sediment and accumulated nutrients (increasing turbidity directly with suspended solids and indirectly by feeding on phytoplankton). Studies investigating the interaction between planktivorous fish, zooplankton, phytoplankton and water chemistry in Northern and central Europe, included several experiments of planktivorous fish removal, which frequently resulted in significant decreases in algal biomass and turbidity (Langeland 1990; Meijer et al. 1994; Tátrai et al. 1997). There are, however, few studies on biomanipulation applied to warm lakes (Moss et al. 2004; Romo et al. 2004; Romo et al. 2005; Scasso et al. 2001; Vázquez et al. 2004).

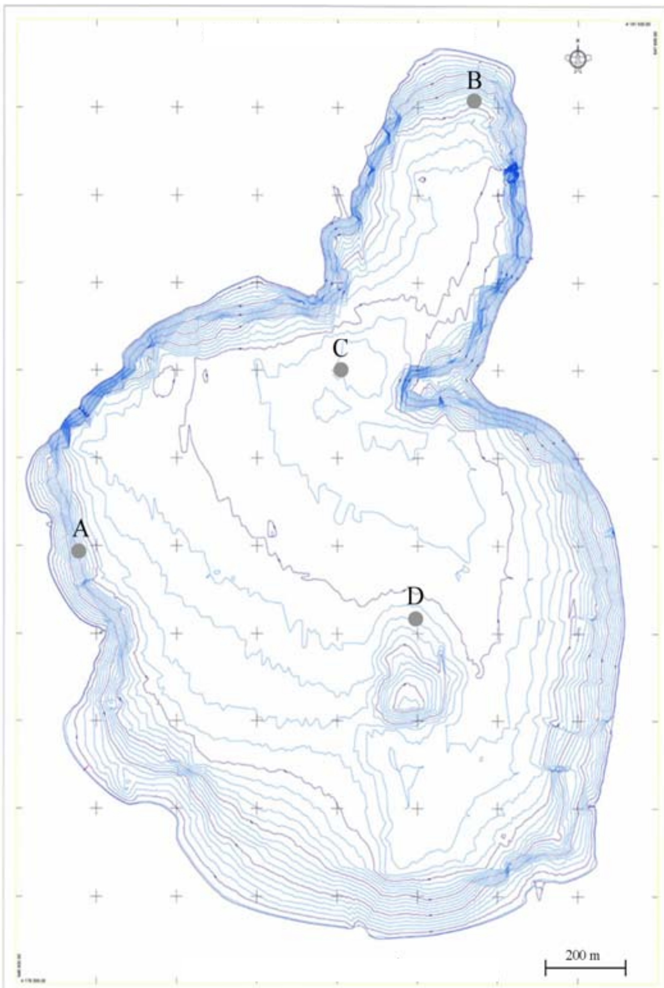

Fig. 1. Batimetry of the Furnas Lake (isobaths at 0.5 m intervals) and location of the sample sites A to D.

Lake Furnas is a small, shallow water body located in an ancient volcanic crater, on the island of São Miguel, Azores. Agriculture and fertilized pasture are common activities in its basin, contributing to the lake's nutrient load and causing an increasing eutrophication. In the recent past the lake has been turbid and algal blooms have been frequent (Santos et al. 2005). The lake has a protected status but local authorities have difficulties controlling fertilization in the lake drainage area, and consequent nutrient input. In the mid-nineties, bottom aeration was adopted in an effort to improve water quality increasing dissolved oxygen concentrations near the bottom and in the water column. Water quality, however, did not improve, as positive effects may have been offset by the negative effects of sediment re-suspension and consequent nutrient release into the water column (Azevedo et al. 2006). In the lake common carps are abundant and predators scarce. Considering the alternative state hypothesis, and given that Lake Furnas has shown relatively low phosphorous concentrations in recent years but high herbivorous and benthos-feeding fish density, biomanipulation was decided on, to provide an impulse for a switch to clear-water conditions. The carp *Cyprinus carpio* (L.) populations were substantially reduced, removing more than 60% of the estimated population, and lake evolution was monitored in terms of water quality parameters, macrophytes and zooplankton.

LAKE FURNAS

Lake Furnas is located at 37º45'30"N-25º20'03"W, at an altitude of 281 m, with maximum length, width and depth of 2025 m, 1600 m and 15 m, respectively, and average depth of 6.9 m (Fig. 1). The island's climate is marine temperate, with an average temperature of 13.6 ºC; a dry season and a colder, wet season; and a yearly average precipitation of 1874 mm.

The lake has a total area of 1.93 km^2 and a basin of 12.45 km^2, occupied by forest (533 ha), pasture (460 ha; mainly cattle) and agriculture (5.7 ha). Basin land use, excessive fertilization and soil slope (averaging 20%) contribute to soil erosion and lake deterioration through sediment and nutrient inputs (Porteiro 2000). DROTRH/INAG (2001) estimated potential diffuse nutrient sources between 1996 and 1998 to reach 6.9 T per ha and yr of nitrogen, and 0.79 kg per ha and yr of phosphate; affluent creeks were estimated to supply 29.8 $T \cdot yr^{-1}$ of N and 1.44 $T \cdot yr^{-1}$ of P to the lake. These values exceed the loads permissible for such a shallow lake 10 and 7.5 times and critical loads for eutrophication 5 and 4 times, for N and P respectively (Santos et al. 2005; Harper 1992).

PRE-BIOMANIPULATION DATA

Records of water quality are available from 1994 onward. Between 1994 and 2004, there are generally two to four observations per year of total phosphorus, total nitrogen, dissolved oxygen and pH (Fig. 2). The same applies for turbidity (secchi depth), but with almost monthly observations after July 2001 (Fig. 3).

In 2004, total phosphorous (TP) in the lake water ranged from 24 to 76 $\mu g \cdot l^{-1}$, with an average of 45 $\mu g \cdot l^{-1}$; an improvement in comparison to the mid-nineties, when surface TP values of more than 300 $\mu g \cdot l^{-1}$ were recorded. Total nitrogen (TN) shows an opposite trend, increasing from about 700 $\mu g \cdot l^{-1}$ in the mid-nineties, towards an average of 1120 $\mu g \cdot l^{-1}$ in 2004. Between 1994 and 2004, Secchi disk depths varied between 30 and 250 cm and the lake's trophic state was meso- to eutrophic, with Secchi depth-based Index (TSI) values between 47 and 77. Algal blooms occurred regularly, especially after heavy rainfalls. Conditions at the

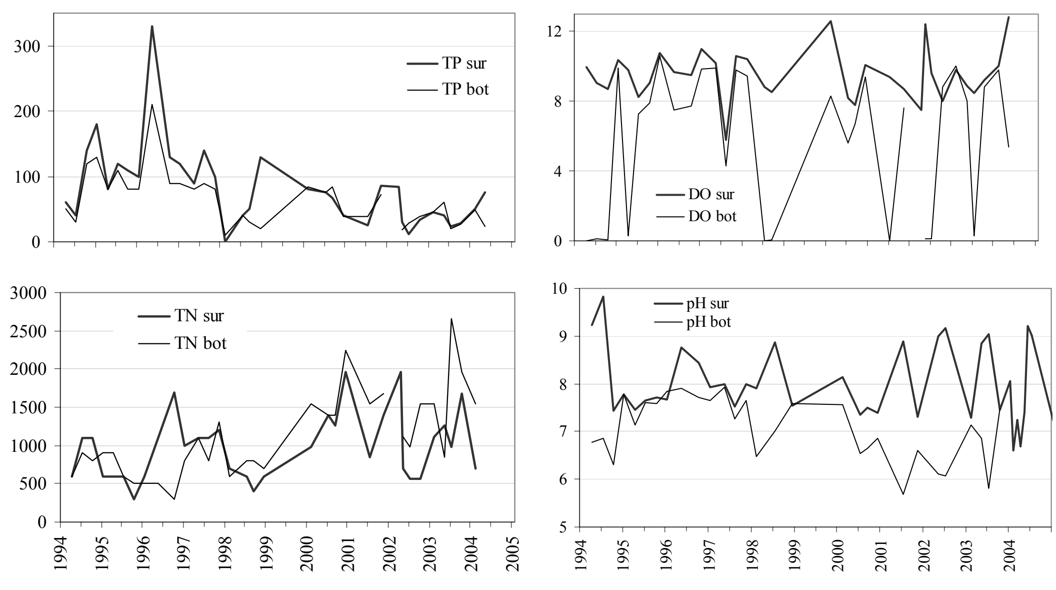

Fig. 2 Pre-biomanipulation data for surface (sur) and bottom (bot) total phosphorous (TP, in $\mu g \cdot l^{-1}$), total nitrogen (TN, in $\mu g \cdot l^{-1}$), dissolved oxygen (DO, in $mg \cdot l^{-1}$) and pH.

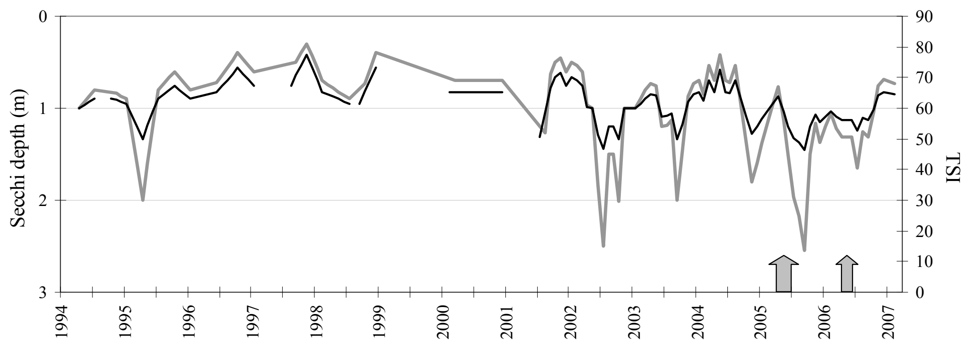

Fig. 3 Secchi depth in left axis and grey line; and Secchi depth-based Carlson's Trophic State Index (TSI) values on right axis and black line; arrows mark fish removal periods.

lake bottom were frequently anoxic in summer.

In 1995, bottom aeration was introduced to increase dissolved oxygen (DO) and decrease eutrophication. An aerator was placed near the bottom (close to the sample point B of the present study) and switched on during a few to 180 hours per month, especially during the summers of 1995 to 1997 and almost during the whole years of 1999 and 2000 (Fig. 4). Aeration as applied in this lake, is not strictly hypolimnetic as the flow caused by ascending air bubbles drags sediments and nutrients to the lake surface, causing vertical mixing and favouring phytoplankton development, even in the summer periods when nutrient depletion (typical of a stratified lake) should cause phytoplankton decline.

Before biomanipulation, total dissolved solids (TDS) and electrical conductivity (EC) were only measured from January to July 2004, ranging from 72 ppm to 82 ppm, with an average of 75.4 ppm, and from 143 µs to 165 µs, with an average of 151.3 µs, respectively.

Fish population is dominated by benthos-feeding, omnivorous common carp and roach. There are also three carnivorous species – pike, zander and perch – considered to be of great interest to sport fishing.

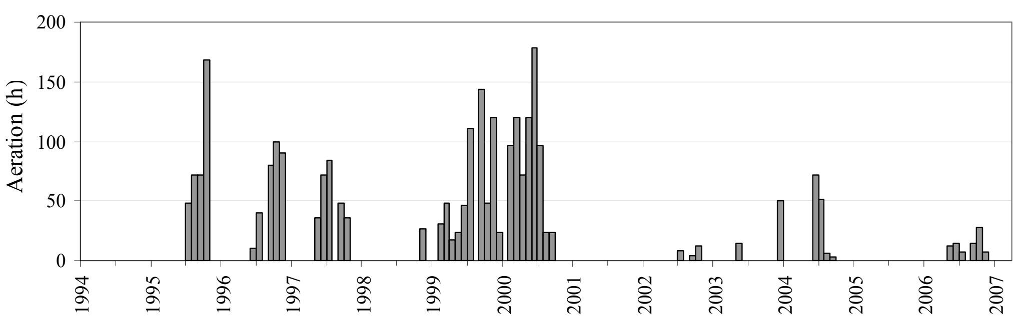

Fig. 4 Monthly hypolimnetic aeration.

MATERIAL AND METHODS

BIOMANIPULATION

Prior to biomanipulation, in 2004, a mark and recapture experiment estimated average common carp (*Cyprinus carpio*) densities of 88 kg·ha^{-1}, with a 95% confidence interval from 50 to 186 kg·ha^{-1} (Azevedo et al. in press). Roach (*Rutilus rutilus*) density was estimated to range from 20 to 80 kg·ha^{-1} (unpublished data).

During April, May and June of 2005, about 10 tons of fish were captured with nets (80 mm mesh size) and removed from the lake. These included

2805 carps, totalling 9204 kg – i.e. about 54% of the estimated population – and 7069 roaches, weighting 470 kg. During May and June of 2006, 452 carps, totalling 1384 kg (about 8% of the original estimated population) were removed. Less fish was captured in the second year, because there was less bigger-sized fish available and because of exceptionally low temperatures for the season, causing carps to avoid lake margins and, hence, capture.

WATER QUALITY ASSESSMENT

After biomanipulation, water samples were taken approximately every two weeks, at 4 fixed representative sample sites (A to D, Fig. 1). At each site, Secchi disk depth was determined and 1 to 4 water samples taken at different depths. Chlorophyll *a* concentrations were determined filtering water through a 47 mm, 0.45 µm pore size nitrocellulose filter and extracting the pigments in an aqueous solution of acetone. Chlorophyll *a* concentrations were subsequently determined spectrophotometrically and resulting absorbance measurements applied to a standard equation. Water temperature, electrical conductivity (EC), total dissolved solids (TDS) and pH were measured with a Hanna Combo pH & EC HI 98129. In the deepest part of the lake a series of 12 temperature and luminosity sensors was placed, performing 6 measurements per hour, at depths of 0.3 m, and 1 to 11 m with 1m intervals.

ZOOPLANKTON AND MACROPHYTES

Next to water samples, plankton was collected at the four sites, at the surface and near the bottom, with bottom water depths averaging 5.6 m at site A, 2.1 m at B, 11.6 m at C and 9.4 m at D. Samples were collected using a Schindler trap, preserved in a 5% formalin solution with 20 $g \cdot l^{-1}$ sucrose and divided into halves with a Folsom plankton sample splitter in the lab. One half of each sample was preserved for future analysis, the other was lumped, mixing samples from sites A to D into one surface and one bottom sample for each sampling period. These were used to identify zooplankton according to taxonomic groups (cladocera, copepods, rotifers or others) and size classes (0.5, 1.0, 1.5 and 2.0 mm). Main macrophyte species were mapped in spring 2005 and 2006, through visual surveys on a 20 m × 20 m grid (the lake was subdivided into approximately 4750 squares). Macrophyte cover was recorded according to 5 classes (no macrophytes, 25%, 50%, 75% and 100% cover) and total lake covering calculated.

DATA ANALYSIS

Carlson's Trophic State Index (TSI) was computed from Secchi disk depth measurements using the equation (Carlson 1977):

TSI = 10x (6 – ln(secchi depth in m) / ln(2)).

Carlson's index uses a natural logarithm transformation of Secchi disk values as a measure of algal biomass on a scale from 0 to 110, where each increase of ten units represents a doubling of algal biomass. To assess possible correlations between variables, cross-correlations were computed for the time series, after confirming data stationarity, and tested for significance. Cross-correlations between aeration and turbidity were calculated separately for the periods with seasonal and monthly samples between 1994 and 2004. Post-biomanipulation data analysis was based on monthly averages. Comparison of pre- and post-biomanipulation data was difficult given the lack of comparable data (e.g. nutrient concentrations were not measured after biomanipulation, chlorophyll *a*, macrophytes and zooplankton where not sampled before biomanipulation); not enough data for time series analysis; yet data with seasonal patterns and autocorrelation that should not be compared by simple statistical tests. Given these limitations it was not possible to distinguish inter-annual variation from temporal trends or biomanipulation effects. All analyses were done in R (R Dev. Core Team 2005).

RESULTS

WATER QUALITY

Considering July 2005 the first month after biomanipulation, there is a marked decrease in turbidity in the first summer after bio-manipulation (Fig. 3), but, within one year, turbidity approached pre-manipulation values.

Analogously, the TSI dropped from about 63 in late spring to 47 in summer 2005, after the first biomanipulation. In December 2005 the TSI rose to 55 and in the winter of 2007 to 65.

Total dissolved solids and EC remain quite similar, though slightly increasing, for the two years (Fig. 5). Considering the few measurements of TDS and EC taken in 2004, there is an increase towards 2005 and 2006, though more historical data would be needed for a sound comparison between before and after biomanipulation values. EC increased from an average of 151.3 µs before to 184.4 µs after biomanipulation, and TDS, from 75.4 ppm to 92.0 ppm, respectively. Chlorophyll *a* concentrations (Fig. 6) and pH also increased from 2005 to 2006 (a variation similar to that observed in previous years, Fig. 2).

Except for pH, all water parameters show marked seasonal variation, with temperature increasing in summer, chlorophyll *a* and turbidity decreasing in summer, and TDS and EC decreasing in spring. Lake Furnas shows characteristics of a typical volcanic lake in temperate regions. Depth-dependent temperature measurements revealed that the Furnas lake is a warm monomitic lake, with stratification between April and September reaching a maximum difference of 4.8 ºC between surface and bottom water at 11 m depth. Chlorophyll *a* concentrations appear to have a single peak in winter, instead of a spring and an autumn peak (this should be confirmed with long-term observations).

Several of the water quality parameters are strongly correlated. Total dissolved solids and electrical conductivity show significant positive correlation (correlation of 0.978). Chlorophyll *a* shows significant negative correlation with temperature (–0.817).

No statistically significant correlation between aeration and turbidity was found. Months with intensive aeration tend to have high turbidity (all months with ≥20 hours of aeration have ≤0.8m secchi disk depths), but many months without aeration have high turbidity too. After biomanipulation only little aeration took place, in comparison to the period before, and again no statistically significant correlation was found between aeration and turbidity. Cross-correlation showed also no significant correlation between surface or bottom dissolved oxygen levels (only available for 1994 – 2004).

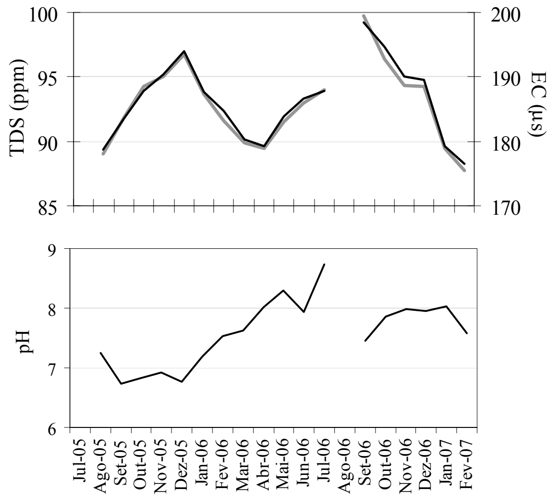

Fig. 5. Above, monthly averages of surface total dissolved solids (TDS), grey line; electrical conductivity (EC), black line; below, pH monthly averages.

There was, however, a significant correlation between precipitation and turbidity or trophic state. Monthly average Secchi depth is negatively and TSI is positively correlated to the precipitation (Fig. 7). They are both significantly correlated to the precipitation observed in the same month (lag 0, correlation = –0.42 and 0.46, for Secchi depth and TSI respectively) and to that observed in the two months before (lag −1 with correlations of –0.64 and 0.64; and lag –2 with correlations of –0.45 and 0.46, respectively).

There is little spatial heterogeneity in water quality within the lake, except for sample point B which showed significantly higher turbidity in the first summer after biomanipulation, frequent peaks in chlorophyll *a* concentration and less alkaline values when compared to the other sites.

ZOOPLANKTON AND MACROPHYTES

Zooplankton (Fig. 6) is dominated by rotifers (especially in winter) and cladocera (especially in spring and summer). Copepods and other zooplankton taxa are less abundant. All groups show a sharp decrease in numbers in the winter of

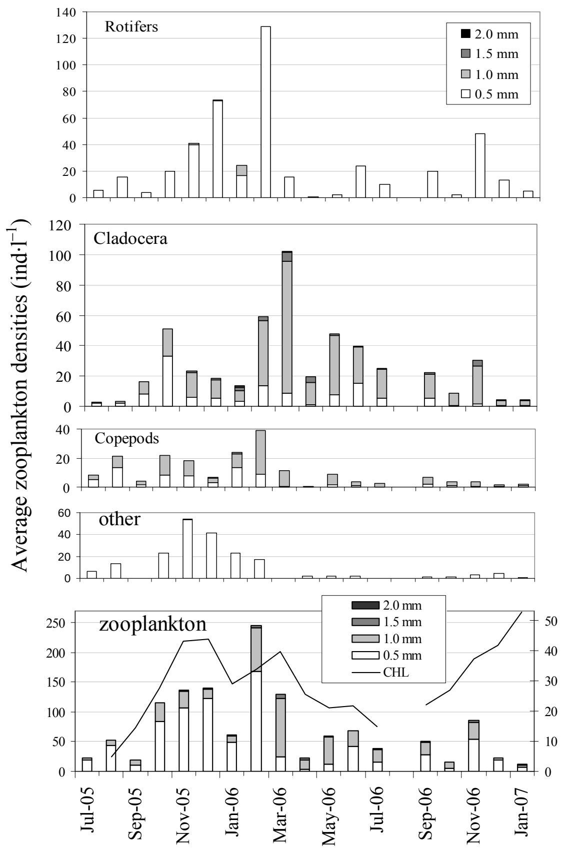

Fig. 6. Monthly average zooplankton densities (ind·l^{-1}) per taxonomic group and size class; total zooplankton density (notice the different y-axis scale) is presented with average monthly Chlorophyll a concentration (line, right axis, in mg·l^{-1}).

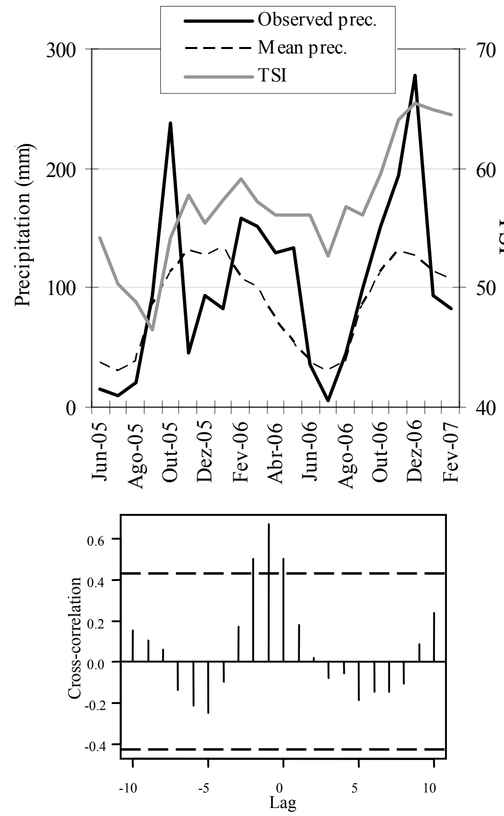

Fig. 7. Above, observed and average monthly precipitation (years 1961–1990), and Secchi depth-based Carlson's Trophic State Index values (TSI); below, cross-correlation between observed monthly precipitation and TSI (CI for $\alpha = 0.05$ are given by dashed lines).

2006. Monthly average zooplankton numbers follow monthly chlorophyll *a* concentrations in the first year, but collapse in the second year, in spite of increasing chlorophyll. In terms of individual size, cladocera and copepods belong predominantly to the 1.0 mm size class, whereas rotifers (and other zooplankton) are smaller, occupying mostly the 0.5 mm class.

Macrophyte growth was restricted to the lake shore, covering about 3.7% of the lake surface in the spring of 2005 and 5.4% in the spring of 2006. The main species found were *Egeria densa* (Planch.), *Ceratophyllum demersum* (L.) and *Potamogeton lucens* (L.). The most abundant species *Egeria densa* and the least abundant *Ceratophyllum demersum* about doubled their estimated biomass from 2005 to 2006, while the biomass of *Potamogeton lucens* remained approximately unchanged.

DISCUSSION

Biomanipulation in the Furnas Lake did not yield the wanted shift towards stable clear-water conditions. Immediately after the first fish removal campaign a marked decrease in turbidity was observed. However, similar summer

decreases were observed in 2002 and 2003, and within one year after fish removal turbidity approached pre-manipulation values. Analogously, the lake's trophic state, which had been mesotrophic to eutrophic in the recent past improved visibly after the first biomanipulation effort, reaching a TSI of less than 50. But this phenomenon lasted only a few months and, by the end of 2005, TSI values had climbed to eutrophic conditions.

Contrary to the expected improvement in water quality, there was an increase in chlorophyll *a* concentrations, indicating increasing phyto-plankton biomass, and a decrease in zooplankton densities in the two years after biomanipulation. Macrophyte biomass, however, increased, probably due to the reduction of damage by adult carps. But the macrophyte cover is still very limited, and the gain in biomass after biomanipulation is likely to be lost given the increasing turbidity. While macrophyte growth is limited by grazing and light availability (turbidity), macrophyte fixation may also be hampered by the steep slopes of the lake border and by lake depth.

However the available data series are short and the observed variations in water quality macrophytes and zooplankton may reflect typical inter-annual variability. To assess possible long-term results continued monitoring of fish stock, macrophytes, zooplankton and water quality (including nutrient concentrations) would be necessary (monitoring stopped after February 2007, due to lack of funding).

Confirming previous observations, the deterioration of the trophic state is associated to precipitation, showing the impact of run-off nutrient input from the lake basin. No statistically significant effect of aeration on turbidity could be found in either pre- nor post-biomanipulation data. Aeration showed also no positive effect on dissolved oxygen concentrations (only available for the pre-biomanipulation period). It is however difficult to assess the true effect of aeration as it was not continuously applied, but intensified in the warmer seasons and suspended during winter. Its application should therefore be reviewed, testing its effects and testing alternative methods, such as truly hypolimnetic aeration.

Given our results, there are several possible reasons for the apparent failure to achieve a lasting clear water state:

1) Fish removal may have been insufficient. Lake restoration through biomanipulation has been successfully applied in temperate regions (Jeppesen et al. 2007a) but a number of conditions must be met. For biomanipulation to be successful, studies in the Netherlands suggest that biomanipulation should involve drastic planktivorous and benthivorous fish stock reduction, removing >75% of the populations (Meijer et al. 1999). A lake is considered to have a good ecological status when fish stocks are about 20 $kg \cdot ha^{-1}$ of benthivores and planktivores each. Van de Bund & Van Donk (2002) show an example where removing 50% of fish lead to rapid recovery of pre-biomanipulation conditions. In the Furnas Lake only about 60% of the common carp and a small proportion of the roach populations was removed. Furthermore, small fish were not captures (80 mm net mesh-size).

2) Lake Furnas is sub-tropical. Only little is known about the trophic dynamics and the role of fishes in warm lakes. Jeppesen et al. (2005b, 2007a) present site studies suggesting that it is more difficult to provoke and not least maintain a trophic cascade effect by biomanipulation in subtropical and tropical lakes than in temperate lakes, for which the concept of biomanipulation as a restoration tool was developed, with very short-termed effects, even after massive planktivorous fish-stock reduction. Biological interactions differ, with often higher dominance and abundance of small fish, more aggregation of fish in vegetation, more fish cohorts per year, higher proportions of omnivorous feeding by fish and less piscivory in subtropical and tropical lakes than in temperate lakes (Jeppesen et al. 2005b). Although lake Furnas behaves more like a temperate than a sub-tropical system in terms of dominance and abundance of small fish, the recruitment of fish may have indeed been a decisive factor in the biomanipulation outcome. Adult fish removal is likely to have favoured the development of juveniles, causing increas-ed zooplankton consumption, decreased phyto-plankton grazing, and consequently increased

turbidity (Scheffer et al. 1993). This could explain the observed reduction in zooplankton in the second year after biomanipulation. Unfortunately, fish densities and size distributions were not monitored after biomanipulation.

3) Nutrient levels may have been excessive. In the years before biomanipulation, the Furnas Lake had total phosphorous concentrations of 30 to 80 $\mu g \cdot l^{-1}$, apparently low enough to expect biomanipulation to succeed (Meijer et al. 1999) – however recent data is missing. But there are studies suggesting that the influence of nutrient loading on phytoplankton biomass is greater in southern shallow lakes, indicating that nutrient control may have to be a greater priority in these systems than in more northern lakes (Romo et al. 2004, 2005; Moss et al. 2004). There are examples of rapid switches to a turbid state after P loadings increased to only 100 – 150 $\mu g \cdot l^{-1}$, and of only short term increases in water transparency in some warm shallow lakes after bio-manipulation in combination with nutrient reduction (Scasso et al. 2001; Beklioglu et al. 2003). Langeland (1990) argues that if the external phosphorus load is mainly caused by supply from non-point sources, which are difficult to reduce, and the internal load is high, the only realistic procedure is to manipulate the fish stocks. The Furnas basin is classified as protected water shed, and local authorities are trying to enforce the strict rules that apply. But it has proven very difficult to control nutrient input into the lake. Furthermore, the sediments constitute a nutrient pool, which may take decades to diminish even if input could be drastically diminished. A study of data from 2001 to 2003 (Rodrigues et al. 2004), confirms nutrient accumulation in the sediments, revealing 873 mg of total phosphorous per kilogram of surface sediment, next to 20 g of aluminium and 18 g of iron. It is estimated that about 90% of the phosphorous mineralized by algae is stored in the sediment in metal complexes, serving as a phosphorous pool that can be re-dissolved and made available to the phytoplankton, when environmental conditions change. Sediments are very mineralized (only 20% of organic matter in dry weight) and display slightly acid, anaerobic conditions (redox potential of -160 mV). Under these conditions, biomanipulation may be indispensable, though it remains a challenge to managers to control the density of fish stocks in biomanipulated systems over time. Another nutrient that may be of importance is nitrogen. González Sagrario et al. (2005) suggest that, given moderate phosphorous concentrations, nitrogen concentrations between 1000 and 2000 $\mu g \cdot l^{-1}$, as those observed in the Furnas Lake, suppress macrophyte growth. Yet the lower total nitrogen concentrations observed in the 90's, compared to the following decade, were apparently (data are scarce for the 90's) not associated to a better trophic state.

4) Exceptionally rainy 2006 spring and winter seasons may have further compromised biomanipulation success, reducing water quality through sediment and nutrient input from the nutrient rich basin. Turbidity (and the TSI) in the Furnas lake is known to oscillate, with peaks generally following strong rainfalls (Santos et al. 2005); a relationship confirmed by our data. In January 2007, after extreme rainfalls in December (December precipitation doubled the normal monthly average), the lake suffered the worst algal bloom (mainly *Microcystis aeruginosa*) recorded so far.

Recent studies suggest that a drastic reduction of the external nutrient loading seems to be the best way forward for restoring lakes (Jeppesen et al. 2005b), though appropriate nutrient thresholds are not yet established for sub-tropical regions. Studies in European and North American Lakes (Anderson et al. 2005) showed that many approached a new equilibrium of phosphorus (P) and nitrogen (N) concentrations within 10 to 15 years and 0 to 5 years, respectively, after a major reduction in loading. Phytoplankton biomass decreased and a shift towards meso-oligotrophic species dominance occurred. Worldwide studies showed that fish respond surprisingly fast to the loading reduction in lakes, with an increase in the percentage of piscivores and decrease of total fish biomass (Anderson et al. 2005; Jeppesen et al. 2005a). Local authorities now plan to improve fertilization control in the basin of the Furnas

Lake and to create retention basins in affluent creeks, to retain solids and nutrients and reduce sediment accumulation and eutrophication in the lake. Given the nutrient sediment pool and the impact of non-algal light attenuation caused by sediment re-suspension (Ibelings et al. 2007), further biomanipulation may be necessary. But according to the present study and lake sub-tropical characteristics, biomanipulation should be combined with a significant reduction in nutrient inputs and possibly applied repeatedly. More data are needed for a better understanding of the processes in the Furnas lake and more studies are necessary for a better understanding of warm lake systems in general; an understanding that will become even more important as future climate warming is expected to aggravate lake eutrophication as a result of increasing water residence times and decrease of vertical mixing, as well as enhanced growth of phytoplankton (Santos et al. 2004; Schindler 2006; Matzinger et al. 2007; Jeppesen et al. 2007b).

ACKNOWLEDGEMENTS

This study was funded by the Direcção Regional do Ordenamento do Território e dos Recursos Hídricos (DROTRH), the Azorean governmental agency for the management of water resources and land use.

REFERENCES

Anderson, N.J., E. Jeppesen & M. Søndergaard 2005. Ecological effects of reduced nutrient loading (oligotrophication) on lakes: an introduction. *Freshwater Biology* 50: 1589–1593.

Azevedo, J.M.N., R.M. Costa, A.I. Couto, V. Gonçalves, A. Prestes, A. Valente & N. Vieira 2006. *Biomanipulação e arejamento hipolimnético: efeitos na transparência da água na Lagoa das Furnas.* Internal Report of BIOMANIP, Reabilitação das Lagoa das Furnas - Estudo do impacto da biomanipulação através da redução da densidade dos ciprinídeos. Universidade dos Açores, Ponta Delgada. 8pp. [Biomanipulation and hypolimnetic aeration: effects on water transparency in the Furnas lake; in Portuguese]

Azevedo, J.M.N., M.M.C.S. Leitão, R. Moreira & R. Patrício in press. Ensaio de Quantificação da Fauna Piscícola de Lagoas em São Miguel (Açores). *Silva Lusitana*. [Trial Quantification of the Fish Fauna in São Miguel Lakes; in Portuguese]

Beklioglu, M., O. Ince & I. Tuzun 2003. Restoration of the eutrophic lake Eymir, Turkey, by biomanipulation after a major external nutrient control I. *Hydrobiologia* 489: 93–105.

Breukelaar, W.A., H.R.R.E. Lammens, J.G.P.K. Breteler & I. Tatrai 1994. Effects of benthivorous bream (*Abramis brama*) and carp (*Cyprinus carpio*) on sediment resuspension and concentrations of nutrients and chlorophyll-a. *Freshwater Biology* 32: 113–121.

Carlson, R.E. 1977. A trophic state index for lakes. *Limnology and Oceanography* 22: 361–369.

Crivelli, A.J., 1983. The destruction of aquatic vegetation by carp. *Hydrobiologia* 106: 37–41.

DROTRH/INAG 2001. *Plano Regional da Água da Região Autónoma dos Açores – Versão para Consulta Pública*. DROTRH-INAG, Ponta Delgada, Azores. 414 pp. [Regional Water Plan of the of the Azores Authonomous Region– Version for public consultance; in Portuguese].

González Sagrario, M.A., E. Jeppesen, J. Gomà, M. Søndergaard, J.P. Jensen, T. Lauridsen & F. Landkildehus 2005. Does high nitrogen loading prevent clear-water conditions in shallow lakes at moderately high phosphorus concentrations? *Freshwater Biology* 50: 27–41.

Harper, D. 1992. *Eutrophication of Freshwaters*. Chapman & Hall, London. 327 pp.

Ibelings, B.W., R. Portielje, E.H.R.R. Lammens, R. Noordhuis, M.S. van den Berg, W. Joosse & M.L. Meijer 2007. Resilience of Alternative Stable States during the Recovery of Shallow Lakes from Eutrophication: Lake Veluwe as a Case Study. *Ecosystems* 10: 4–16.

Jeppesen, E., M. Søndergaard, J.P. Jensen, K.E. Havens, O. Anneville, L. Carvalho, M.F. Coveney et al. 2005a. Lake responses to reduced nutrient loading – an analysis of contemporary long-term data from 35 case studies. *Freshwater Biology* 50: 1747–1771.

Jeppesen E., M. Søndergaard, N. Mazzeo, M. Meerhoff, C. Branco, V. Huszar & F. Scasso 2005b. Lake restoration and biomanipulation in temperate lakes: relevance for subtropical and tropical lakes. Pp. 331–349 in: Reddy, V. (Ed.). *Restoration and management of tropical eutrophic lakes*. Oxford & IBH Publishing Co., New Delhi. 534 pp.

Jeppesen E., M. Meerhoff, B.A. Jacobsen, R.S. Hansen,

M. Søndergaard, J.P. Jensen, T.L. Lauridsen, N. Mazzeo & C.W.C. Branco 2007a. Restoration of shallow lakes by nutrient control and biomanipulation – the successful strategy varies with lake size and climate. *Hydrobiologia* 581: 269–285.

Jeppesen, E., M. Søndergaard, M. Meerhoff, T.L. Lauridsen & J.P. Jensen 2007b. Shallow lake restoration by nutrient loading reduction – some recent findings and challenges ahead. *Hydrobiologia* 584: 239–252.

Langeland, A. 1990. Biomanipulation development in Norway. *Hydrobiologia* 200/201: 535-540.

Matzinger, A., M. Schmid, E. Veljanoska-Sarafiloska, S. Patceva, D. Guseska, B. Wagner, B. Müller et al. 2007. Eutrophication of ancient Lake Ohrid: Global warming amplifies detrimental effects of increased nutrient inputs. *Limnology and Oceanography* 52: 338–353.

Meijer, M-L., E. Jeppesen, E. van Donk, B. Moss, M. Scheffer, E. Lammens, E. van Nes et al. 1994. Long-term responses to fish-stock reduction in small shallow lakes: interpretation of five-year results of four biomanipulation cases in The Netherlands and Denmark. *Hydrobiologia* 275/276: 457–466.

Meijer M.-L., I. De Boois, M. Scheffer, R. Portielje & H. Hosper 1999. Biomanipulation in shallow lakes in The Netherlands: an evaluation of 18 case studies. *Hydrobiologia* 408/409: 13–30.

Moss, B., D. Stephen, D.M. Balayla, E. Bécares, S.E. Collings, C. Fernández-Aaláez, M. Fernández-Aláez et al. 2004. Continental-scale patterns of nutrient and fish effects on shallow lakes: synthesis of a pan-European mesocosm experiment. *Freshwater Biology* 49: 1633–1649.

Porteiro, J.M. 2000. *Lagoas dos Açores: elementos de suporte ao planeamento integrado*. Ph.D. Thesis, Azores University, Portugal. 344 pp. [Lakes of the Azores: elements to support an integrated planning; in Portuguese]

R Development Core Team 2005. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria.

Rodrigues, A.C., D. Pacheco, Y. Romanets, S. Bruns, R. Nogueira, R. Coutinho & A.G. Brito 2004. Modelação da qualidade da água da Lagoa das Furnas e da Lagoa Verde das Sete Cidades. Actas da 8ª Conferência Nacional de Ambiente, Universidade Nova, Lisbon. [Modelling water quality in Furnas Lake and Green Lake of Sete Cidades. Conference Proceedings; in Portuguese]

Romo S., M.R. Miracle, M.-J. Villena, J. Rueda, C. Ferriol & E. Vicente 2004. Mesocosm experiments on shallow lake food webs in a Mediterranean climate. *Freshwater Biology* 49: 1593–1607.

Romo, S., M.-J. Villena, M. Sahuquillo, J.M. Soria, M Giménez, T. Alfonso, E. Vicente et al. 2005. Response of a shallow Mediterranean lake to nutrient diversion: does it follow similar patterns as in northern shallow lakes? *Freshwater Biology* 50: 1706–1717.

Santos, F.D., M.A. Valente, P.M. A. Miranda, A. Aguiar, E.B. Azevedo, A.R. Tomé & F. Coelho 2004. Climate change scenarios in the Azores and Madeira islands. *World Resource Review* 16: 473–491.

Santos, M.C.R., D.M. Pacheco, F.J.P. Santana & A.M.F. Rodrigues 2005. *A Eutrofização das Lagoas das Sete-Cidades e Furnas (S. Miguel – Açores). Análise evolutiva entre 1988 e 2002.* Tecnologia da Água, Edição I, Maio. 54–65 pp. [Eutrhophication of the Sete-Cidades and Furnas lakes (São Miguel – Azores). Evolutionary analysis between 1988 and 2002; in Portuguese]

Scasso, F., N. Mazzeo, J. Gorga, C. Kruk, G. Lacerot, J. Clemente, D. Fabián et al. 2001. Limnological changes in a sub-tropical shallow hypertrophic lake during its restoration: two years of a whole-lake experiment. *Aquatic Conservation: Marine And Freshwater Ecosystems* 11: 31–44.

Scheffer, M., S.H. Hosper, M.-L. Maijer, B. Moss & E. Jeppesen 1993. Alternative equilibria in Shallow lakes. *Trends in Ecology and Evolution* 8: 275–279.

Schindler, D.W. 2006. Recent advances in the understanding and management of eutrophication. *Limnology and Oceanography* 51: 356–363.

Tátrai, I., J. Oláh, V. Józsa, B. J. Kawiecka, K. Mátyás & G. Paulovits 1997. Biomass dependent interactions in pond experiments: responses of lower trophic levels to fish manipulations. *Hydrobiologia* 345: 117–129.

Van de Bund, W.J. & E. Van Donk 2002. Short-term and long-term effects of zooplanktivorous fish removal in a shallow lake: a synthesis of 15 years of data from Lake Zwemlust. *Freshwater Biology* 47: 2380–2387.

Vázquez, G., M.E. Favila, R. Madrigal, C. Montes del Olmo, A. Baltanás & M.A. Bravo 2004. Limnology of crater lakes in Los Tuxtlas, Mexico. *Hydrobiologia* 523: 59–70.

Accepted 18 October 2008.