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EUROPEAN LARGE LAKES II

Climate-related challenges in long-term management of Säkylän Pyhäjärvi (SW Finland)

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Abstract Säkylän Pyhäjärvi (SW Finland) is an example of a large and shallow lake suffering from eutrophication. During the last 20 years, the quality and general usability of water in Pyhäjärvi have shown considerable variation driven by both a variety of human activities and climate-related factors such as wet and dry years. The lake has been thoroughly studied for decades and has been the object of comprehensive restoration activities both in the catchment and in the lake since the 1990s. Large variety of water protection measures like wetlands, sedimentation ponds and filtering systems have been implemented in the catchment area to reduce external nutrient load. Another important tool for Pyhäjärvi restoration is biomanipulation, done by local commercial fishermen in winter. Twenty-five percent of the annual phosphorus input is removed with fish catch. Currently, restoration work is facing new challenges: short or even nearly missing ice cover period and increased winter time nutrient load from the catchment. In the 2000s, there were 3 years with exceptionally short ice period, allowing only brief winter seining periods. Consequently, the biomanipulation catch was very low in 2007 and 2008 leading to observable food web effects. Phosphorus load was especially high in winters 2006/2007 and 2008/2009. On the basis of the data of 1987–2008, we have tested the hypothesis if climate-related winter time variables like phosphorus load, air temperature and precipitation would affect the water quality of the lake in following summer, here measured as chlorophyll *a* concentration in the lake water. A linear model has been used and a validation procedure has been performed to select the best variables. Our results indicate some of the linkages between climate-related catchment processes and the ecological status of the lake.

Keywords Eutrophication · Lake management · Climatic effects · Length of ice cover · Biomanipulation · External nutrient load

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Introduction

Säkylän Pyhäjärvi, located in the centre of an intensive agricultural area in southwest Finland, is an example of a large and shallow lake suffering from eutrophication. Currently, it has been classified to good ecological status based on criteria of the European Water Framework Directive (www.ymparisto.fi), but the status is seriously threatened by too high external nutrient loading.

Pyhäjärvi has been the target of an intensive restoration programme since 1995 when the Pyhäjärvi Protection Fund (PPF) was created by local municipalities, private industries and local associations to act in collaboration with regional environmental and agricultural authorities (Mattila et al., 2001; Ventelä & Lathrop, 2005; Ventelä et al., 2007). Since 1995, nearly all farmers in the catchment have committed to the European Union's (EU) agri-environmental programme to implement basic water protection measures. In addition, more intensive catchment management practices such as buffer zones, sedimentation ponds and wetlands have been introduced. New innovative treatment methods such as filtering ditches and sand-filters were also constructed and tested for their ability to remove P from runoff waters (Kirkkala, 2001). PPF also has been active in promoting waste water treatment in the rural catchment.

Pyhäjärvi has been the object of intensive biomanipulation for decades. It has been done in winter time by commercial fishermen, whose annual harvest rate approaches the total production of vendace (*Coregonus albula*), which is the main planktivore in Pyhäjärvi (Sarvala et al., 1998a). The restoration project has also subsidised the harvest of commercially unwanted fish since 1995. In 2002–2006, the EU provided funds for this fishing, which was especially intensive in 2002–2004 and apparently resulted in water quality improvement (Ventelä et al., 2007).

The lake is located in the boreal temperate zone (cool climate type). The winter time mean air temperature in the area is −2.1°C and the lake is normally ice covered for 141 days in average. Also the catchment is normally covered by snow in winter. Currently, the recent climate variation seems to pose new challenges to the restoration work. First, the external nutrient load from the catchment to the lake was very high especially in the exceptionally warm winters 2006/2007 and 2008/2009. Secondly, weak ice cover in these winters seriously hindered seine fishing and left planktivorous fish stocks unusually strong in Pyhäjärvi. Here, we have modelled the effects of abiotic and biotic changes on chlorophyll *a* concentration in the lake water in 1987–2008. Our approach differs from traditional nutrient–phytoplankton–zooplankton–fish models, in that we do not pre-define the relationships of the biological processes, but let the data and the model selection procedure 'tell us' how the chlorophyll *a* concentration in lake is determined by various environmental factors. Our hypothesis is that climate-related winter time (October–March) variables like phosphorus load, air temperature and precipitation affect water quality of the lake in following summer, here measured as chlorophyll *a* concentration. Linear model is used to test the hypothesis.

Methods

The basic information on Pyhäjärvi is given in Table 1. The water chemistry and hydrology of Pyhäjärvi have been monitored since the 1960s as part of a national program. Since 1971 monitoring has been more intensive, including the use of automatic meters to continuously measure river flows (Ekholm et al., 1997). The nutrient concentrations in the water of Pyhäjärvi and the main rivers Yläneenjoki and Pyhäjoki have been monitored since 1980, first as part of statutory monitoring (Sarvala & Jumppanen, 1988), then by regional authorities approximately at 2 or 3-week intervals during the open water season. The water chemistry and hydrology data were from Finnish Environment Institute's Oiva data service (www.ymparisto.fi/oiva) where the data were searched in June 2009.

Table 1 Basic information on Pyhäjärvi and catchment

Lake area (km^2)	155
Mean depth (m)	5.5
Maximum depth (m)	26
Catchment area (km^2)	
Total	431
River Yläneenjoki	234
River Pyhäjoki	78

P loads from the major rivers were calculated, based on P concentrations (samples taken at 2 or 3 weeks intervals) and stream flow data (continuous measurement) both annually (year x) and for autumn and winter period by using values of October, November and December from year $x - 1$ and values of January, February and March from year x.

The ice data for years 1958–2009 were from local observers and Finnish Environment Institute's Oiva data service (www.ymparisto.fi/oiva) where the data were searched in June 2009. Data on precipitation and air temperature are from Finnish Meteorological Institute, the data of two closest weather stations Kokemäki and Jokioinen was used. Mean of these Winter North Atlantic Oscillation (NAO) indices was taken from the internet page http://www.cru.uea.ac.uk/~timo/projpages/nao_update.htm.

Water samples for nutrient and chlorophyll *a* analyses were taken from surface to bottom from one sampling point situated in the deepest area of the lake; here we use average open-water season (May–October) values for the 0–5 m layer representing >80% of the total lake volume. The methods of analyses followed Finnish standard laboratory procedures (Ekholm et al., 1997) and the methods are accepted by FINAS (Finnish Accreditation Service).

For phytoplankton analyses, composite samples were collected from 0 to 5 m depth 6 to 24 times during May–October each year in 1980–2008. Two sites were sampled in the first decade, and samples from 10 sampling locations were bulked since the early 1990s. Additional phytoplankton data collected as part of a national monitoring program were available from several years in the period 1963–1979. Phytoplankton was counted using the Utermöhl technique (von Utermöhl, 1931), and the biomass was estimated separately for each cell using standard methodology (Rocha & Duncan, 1985).

Zooplankton was sampled weekly or at 2 or 3 weeks intervals during the open-water season (May–October) since 1987. Samples were taken from 0–5 m with a 0.5- or 1-m high tube sampler (volume 3.4 or 6.8 l) at 10 locations, selected with a stratified random design (Cochran, 1977). Samples were concentrated with a 50-μm mesh sieve and combined in the laboratory to form one composite sample each date. In the laboratory, subsamples were enumerated until 50–200 individuals of each dominant crustacean species were counted and measured. Zooplankton counts and measurements were converted to zooplankton biomass using carbon-length regressions (Sarvala et al., 1998b).

The weight of the 0+ vendace in autumn (S0+) was used as an index for planktivory (pi) (for the figure transformed as: pi = 100 − S0+). Vendace is the dominant planktivore in this lake, and in most years its first-year growth is almost solely determined by intraspecific competition, as indicated by the tight inverse relationship with the abundance of the year-class (Helminen et al., 1993, 1997). In some years, however, exceptional abundance of other planktivores, such as smelt, clearly retards vendace growth, which is thus a good proxy for overall planktivore predation pressure on zooplankton, reflecting the balance between zooplankton production and food consumption by the fish community. The smaller the young-of-the-year vendace remain, the more intra- and interspecific food competition they have experienced, and the more intensive has been the overall fish feeding pressure on zooplankton. Consistent with this reasoning, the effect of vendace and smelt biomass on herbivorous cladoceran zooplankton biomass and size distribution has been statistically significant (Sarvala et al., 1998b; Sarvala, 2006). The 0+ vendace weight data were derived from the 1–3 first sampling dates of the winter seine monitoring. Sampling was done in the fishing harbour after the fishermen returned from the lake with their daily catch in special containers. At the first stage, samples of some kilograms consisting of a variable number of fish were taken from every container, sorted by species and weighed. A minimum of thirty 0+ vendace individuals were measured each time. The biomanipulation catch data presented in this article are from the records of the local fishing association Pyhäjärvi Fishing Area and the daily catch reports of local commercial fisherman. This study excludes the recreational fishery, as there are no annual data available for that.

Linear modelling was used for investigating (1) the relationship between the climatic variables and the variables related to runoff, nutrient load, ice cover length and ice out day and (2) variables affecting the chlorophyll *a* concentration in the lake in years 1987–2009. The goal of the used methodology is to select a minimal number of variables to increase the interpretability of the model. A resampling validation procedure Leave-one-out (LOO) (Efron & Tibshirani, 1993; Lendasse et al., 2008) is used to approximate the generalisation performances of each linear model (Miche et al., 2008). This validation procedure provides the performances of the model on new data that have not been used to build the linear models. Other resampling validation techniques could be used instead to estimate the unbiased performance of a model: bootstrap, jackknife and k-fold cross-validation (Efron & Tibshirani, 1993). Also, a penalty term could be used instead of a resampling method; in this case, the performances are measured on the same data that have been used to build the models: see Akaike's information criterion (AIK) or Bayesian information criterion (BIC). In general, all these resampling and penalty methods are asymptotic methods; they provide an unbiased estimate of the generalisation performances of the models if the number of observations (samples) tends to infinity (asymptotic convergence). For that reason, the LOOt have been selected since experimental evidences have shown that it is converging more rapidly to the correct value of the generalisation performances (Efron & Tibshirani, 1993; Lendasse et al., 2008). Nevertheless, we have compared the results obtained by the LOO with the ones obtained with bootstrap and tenfold cross-validation. The estimated performances and the selected variables are similar. Furthermore, an AIK criterion has been also tested on the selected variables and it is providing similar estimations of the performances of the linear models than the LOO method.

The models that have the best generalisation performance (smallest modelling error) are selected. The models that are selected are sparse (several variables are not selected) and furthermore the generalisation performances are better and the interpretability is improved. In general, the measure of correlation between each explanatory variable alone and the target doesn't allow the selection of the best set of variables. The advantage of that methodology is that we are able to test all the possible combination of explanatory variables. The drawback of the methodology is that we cannot measure the importance of each explanatory variable alone. In order to 'face' this drawback, a ranking of the selected variables is performed using the least angle regression algorithm (Efron et al., 2004). This method provides a reliable ranking of the explanatory variables if the underlying model is linear. This method provides a reliable ranking of the explanatory variables if the underlying model is linear. In order to validate this assumption of linearity, P-values are calculated. Small P-values indicated that the linearity assumption is valid.

The performances of the model can be expressed using the coefficient:

$$R^2_{\mathrm{LOO}} = 1 - 1/N \ \mathrm{sum}\left((y_i - y_i^{\mathrm{LOO}})^2\right)/(\mathrm{var}(y))$$

where y_i^{LOO} is the approximation of y_i if the corresponding explanatory observations x_i are not used to train the linear model. The R_{LOO} notation is used to show that the performances are estimated using a Leave-one-out procedure and not on the data that have been used to build the linear models.

The significance of the relationships between winter NAO and winter time phosphorus load, and winter NAO and ice out date were analysed with linear regression.

Results

Our hypothesis was that climate-related winter time (October–March) variables like phosphorus load, air temperature and precipitation affect water quality of the lake in following summer. We used linear model to investigate the effect of abiotic and biotic variables on lake water quality, here described by chlorophyll *a* (annual mean of the open water period). We had 16 possible explanatory variables consisting of annual means for 22 years. All the possible models ($2^{16} - 1$ models) were tested. The selected model includes the variables presented in Table 2.

We also used linear model to investigate the effect of climatic variables (winter NAO, winter air temperature and winter precipitation) on river runoff, wintertime (October–March) and annual phosphorus loads, length of the ice cover and ice out date. The climatic variables explained 47% of winter time P load variation and 48% of ice out date variation (Table 2). A significant linear relationship between winter NAO and winter P load was found for the time period of 1980–2009 ($R^2 = 0.21$, $y = 0.9249x + 6.8176$, regression coefficient = 0.92, t value = 2.65, P value = 0.013; Fig. 1). Also the date of ice-out was significantly negatively correlated with NAO, so that at high NAO which represents a warmer and wetter winter, ice-out happened earlier ($R^2 = 0.24$, $y = -2.8317x + 119.48$, regression coefficient = −2.83, t value = −3.01, P value = 0.005; Fig. 2).

Table 2 Linear modelling was conducted to investigate the relationships of biotic and abiotic variables. The variables are listed in this table, consisting of annual values for 22 years were used in the analysis. All the possible models were tested. For chlorophyll, the best possible model was selected and it includes the variables marked with *asterisk*. A ranking of the selected variables is performed using the least angle regression algorithm (Efron et al., 2004)

Variables explained	Variables explaining	Ranking	$R^2_{\mathrm{LOO}} = 1 - 1/N \; \mathrm{sum}\left((y_i - y_i^{\mathrm{LOO}})^2\right)/(\mathrm{var}(y))$
River runoff	Winter NAO		0.20
	Air temperature, months X-III	1	
	Precipitation, months X-III		
P load, months X-III	Winter NAO	3	0.47
	Temperature, months X-III	1	
	Precipitation, months X-III	2	
Annual P load	Winter NAO		0.05
	Temperature, months X-III	1	
	Precipitation, months X-III		
Length of the ice cover	Winter NAO	3	0.32
	Temperature, months X-III	2	
	Precipitation, months X-III	1	
Ice out date	Winter NAO	2	0.48
	Temperature, months X-III		
	Precipitation, months X-III	1	
Chlorophyll *a*	Winter NAO		0.70
	Air temperature, months X-III		
	Air temperature, months V-IX		
	*Precipitation, months X-III	8	
	*Annual precipitation	3	
	Winter water temperature		
	*Ice out date	5	
	*P load, months X-III	7	
	*Annual P load	6	
	Total N in the lake		
	*Total P in the lake	2	
	*Phytoplankton biomass	1	
	Zooplankton biomass		
	*Cladoceran biomass	4	
	Daphnia biomass		
	Planktivory index		

Runoff patterns in the catchment have changed in recent four decades. Since 1989 flow during the period January–March of both major rivers has been clearly higher than before (Fig. 3). Mean flow of river Yläneenjoki for period January–March 1989–2008 was three times higher compared to winter period 1971–1988 (Table 3), and the mean flow of river Pyhäjoki was two times higher. The river Pyhäjoki contains a larger fraction of groundwater and therefore the change was smaller. In spring (April) and summer (May–September) seasons, the mean flow has somewhat diminished. The mean flow during the period October–December has not significantly changed.

External phosphorus load was especially high in winters 2006/2007 (October–December 2006 and January–March 2007) and 2008/2009 (October–December 2008 and January–March 2009), when it was two times higher than the mean winter time load for period 1981–2009 (Fig. 4).

The mean duration of the ice cover in Pyhäjärvi in 1958–2009 was 141 days. In the 2000s, there were

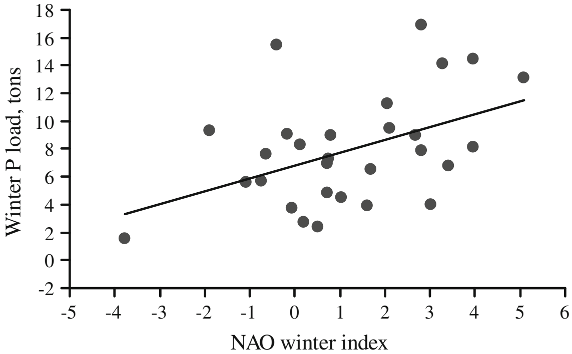


Fig. 1 NAO index (December–March) versus P load in winter period (October–March) in Lake Pyhäjärvi in 1980–2009

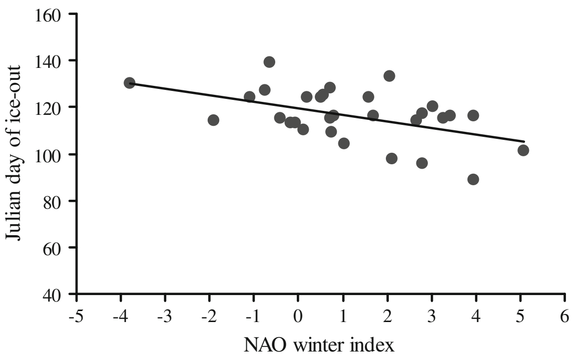


Fig. 2 NAO index (December–March) versus ice-out date in Lake Pyhäjärvi in 1980–2009

3 years with exceptionally short ice period: 88 days in 2005, 77 days in 2007 and 50 days in 2008 (Fig. 5). Short ice cover durations only allowed short winter seining periods. Consequently, also the biomanipulation catch was exceptionally low in 2006–2009 (Fig. 5). As the fishing pressure on vendace was low in these years, large numbers of vendace remained in the lake, resulting in high planktivory (Fig. 6). Consequently, the biomasses of *Daphnia* and *Bosmina* were very low especially in late summer 2008 (Fig. 6).

In 2008, Secchi depth was reduced and the nutrient, chlorophyll *a* and phytoplankton biomass values were higher than for the average in years 1980–2009 (Figs. 7, 8). The mean cyanobacterial biomass for the period 1963–2009 was 0.29 g m^{-3}, while in 2008 biomass was 1.79 g m^{-3}. Phytoplankton community changed in 2008, as the cyanobacterial species *Planktothrix agardhii* became abundant in July, forming large biomass in the deeper water column for the first time since 1982. In 2009, there were no visible algae blooms in surface water.

Discussion

It is already widely known that climate change will affect the ecological interactions in the lake ecosystems (Schindler, 1997; Walther et al., 2002; Beaugrand & Reid, 2003; Malve et al., 2006; Feuchtmayr et al., 2009). In this article, we have tested the hypothesis that climate-related winter time variables would have already affected the water quality of the lake in following summer, here measured as chlorophyll *a* concentration in the lake water in 1987–2008. Our results indicate some linkages between climate-related catchment processes and

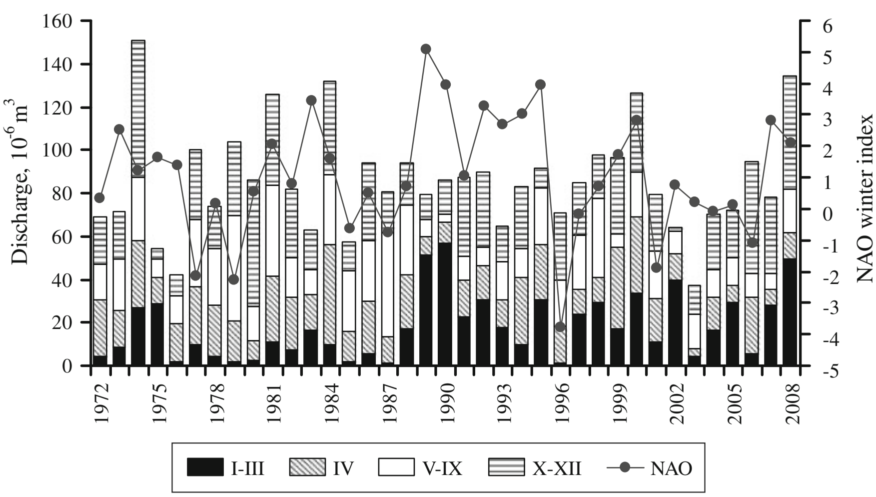


Fig. 3 Water load from Pyhäjoki and Yläneenjoki and NAO index (December–March) in Lake Pyhäjärvi in 1972–2008

Table 3 The seasonal mean flow of rivers Yläneenjoki and Pyhäjoki in years 1971–1988 and 1989–2008

Season	River Yläneenjoki ($m^3 s^{-1}$)		River Pyhäjoki ($m^3 s^{-1}$)	
	1971–1988	1989–2008	1971–1988	1989–2008
January–March	0.8	2.5	0.4	0.8
April	6.5	5.0	2.0	1.5
May–September	1.4	0.8	0.5	0.4
October–December	2.7	2.6	0.9	0.8

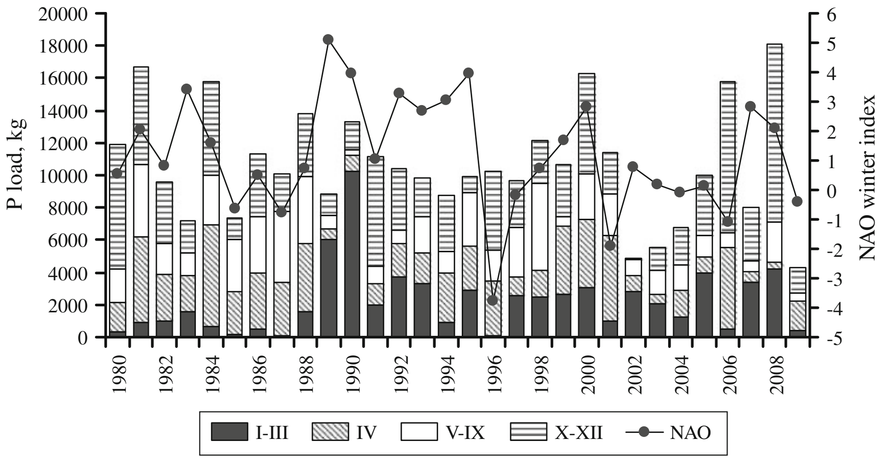


Fig. 4 External phosphorus load from the Rivers Pyhäjoki and Yläneenjoki and NAO index (December–March) in 1980–2009

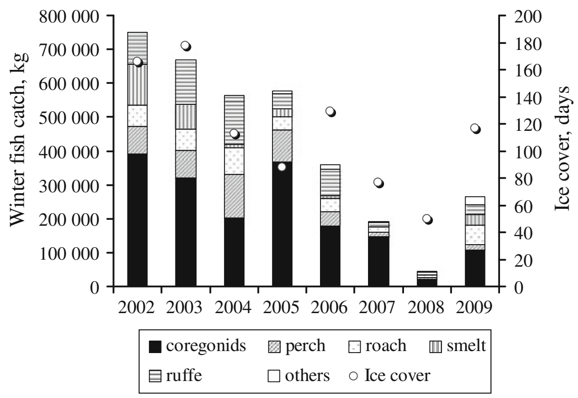


Fig. 5 The fish catch of the commercial fishermen and duration of ice cover in Lake Pyhäjärvi in 2002–2009

a shallow boreal lake ecosystem. Winter precipitation and winter time P load were among the variables selected for the best model, but they were not highly ranked by the model.

Thus, climate-related winter time processes have already partly affected the next year's water quality of Pyhäjärvi during our study period, the latest 22 years. As the winter time load correlated with winter NAO index, we can connect the changes also to the current climatic variation over wider geographical areas and even climate change. Warm winters and their consequences are in accordance with future climate change scenarios (IPCC, 2007).

High nutrient load are caused by high winter time rainfall and snowmelt periods caused by winter temperatures above zero. In Pyhäjärvi area, ground is normally frozen and covered by snow in winter time as the mean temperatures are normally below zero in this area. In 1990s and 2000s, colder and warmer periods (freezing and melting periods) have varied during the winter months in several years. For example in 1989, 1990 and 1992, snow melted early in January and February causing high runoff and P load because of warm periods during the wintertime. According to Finnish Meteorological Institute (2009), year 2008 was the warmest in Southwest Finland since 1961. Also the mean, maximum and minimum temperatures of winter months have been warmer than in 1970s and 1980s.

The timing and length of ice cover has varied considerably. Usually the ice cover is formed at the end of November or in December but, for example, in winter 1988/1989 the ice cover was formed in the

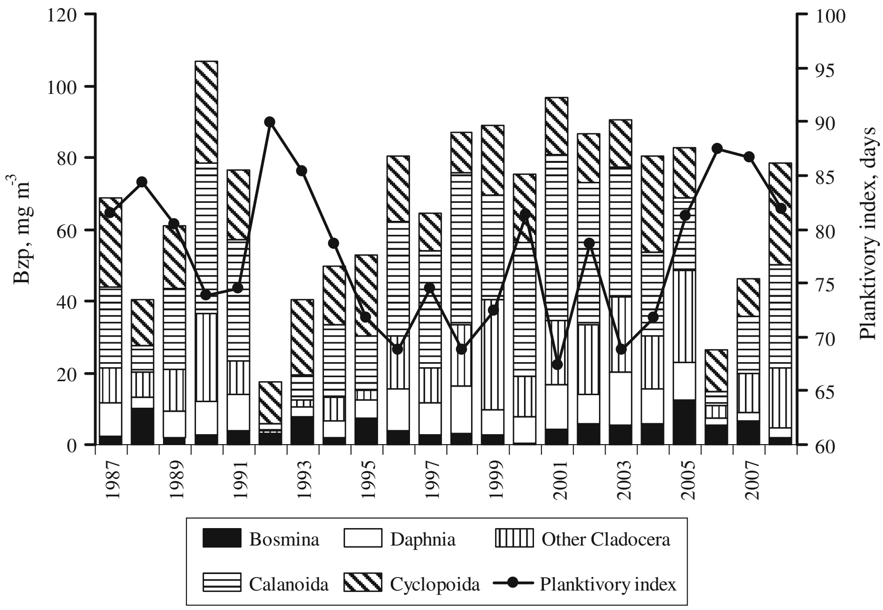


Fig. 6 Late summer zooplankton biomass (Bzp) and planktivory index in Lake Pyhäjärvi in 1987–2008

beginning of November. Ice cover also disappeared early, already in March but because of early formation and thickness the duration of ice cover was rather long. The ice cover allowing winter seining has crucial importance to Pyhäjärvi ecosystem, as the balance between the efficient commercial fishery and the size of the vendace stock is one of the key factors affecting the water quality.

Vendace is the main planktivore in Pyhäjärvi and its feeding has cascading effects in the food web (Helminen & Sarvala, 1997). Earlier analyses (Sarvala et al., 1998b) have shown that the between-year variation in late summer chlorophyll level in Pyhäjärvi is to roughly similar extent explained by total phosphorus concentration in water and late summer herbivorous cladoceran biomass. The latter is further dependent on planktivorous fish abundance. Several factors are thus always simultaneously involved, and therefore single-factor comparisons can be misleading. The total phosphorus concentrations were increasing between 1984 and 2001 (with some year-to-year variation), while there was a notable decrease in 2001–2004, followed by some increase until 2008. Herbivorous cladoceran biomass was particularly low in 1992–1994, 2000 and in 2006–2008 (all years with high planktivory index). The low chlorophyll to phosphorus ratio showed reduced zooplankton grazing effect on phytoplankton (Sarvala et al., 2000) through the 1990s when the phosphorus level was increasing, the grazing effect increased in 2002–2004, and reduced again in later years (Ventelä et al., 2007). The change in 2002–2004 can be attributed to the intensified biomanipulation effort, while the change in the later years is clearly due to the food chain effects of reduced winter catches of vendace caused by the poor ice conditions (i.e. climatic factors). Such climate-induced changes that are mediated via the vendace population (either through recruitment failures or exceptional successes or through fishery failures) tend to be rare events, and they are not very well amenable for ordinary statistical analyses. The relevant factors involved could, however, all be identified in our model analyses, which selected variables from the group of climatic factors (NAO, ice-out date, temperature), from the eutrophication related factors (nutrient loads and concentrations) and from the food web interaction (biomanipulation) factors (cladoceran biomass). More specific model analyses further confirmed that many relevant measured variables were directly related to climatic factors.

Conclusions

This article concludes that long-term management of Pyhäjärvi is currently facing new climate-related

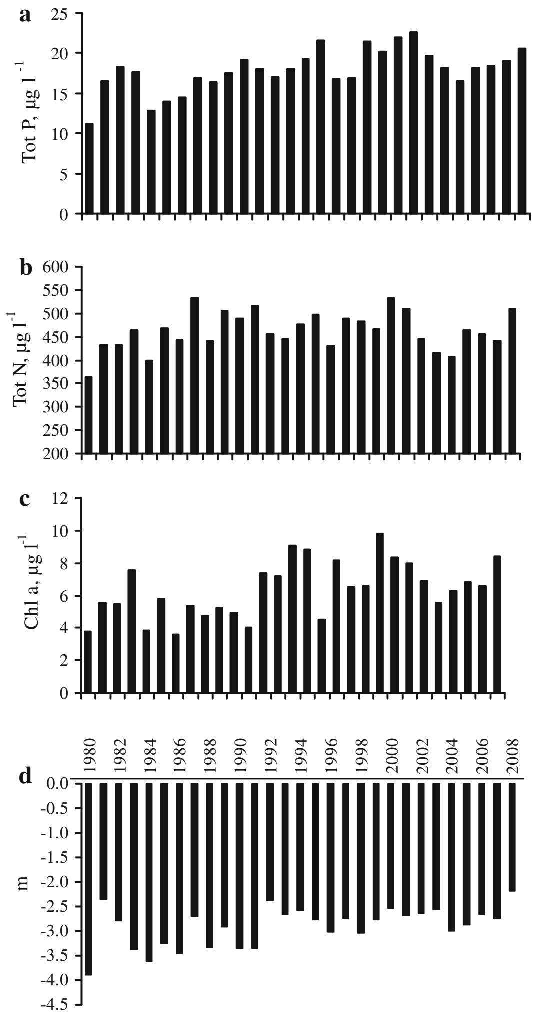
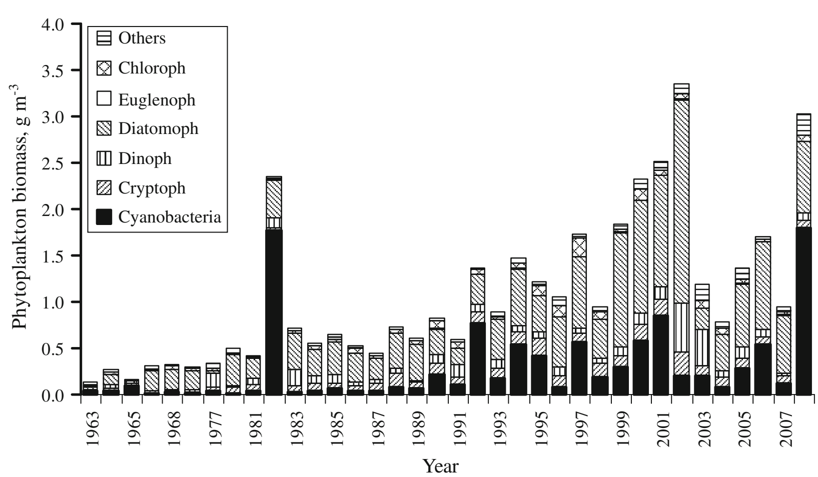


Fig. 7 **a** Total phosphorus, **b** total nitrogen, **c** chlorophyll *a* and **d** Secchi depth in Lake Pyhäjärvi in 1980–2008

challenges. The food web structure has been disarrayed by warm and short winters with short ice cover and low biomanipulation effort. Also, the winter time phosphorus load has been high in recent years. If this trend will continue in future, as suggested by climate models (IPCC, 2007), the long-term ecosystem consequences will appear at some point. Challenges seem to be huge especially concerning the agricultural nutrient load. Most of the water protection measures (wetlands, buffer zones, filter systems) work insufficiently in winter flood situations. Thus, new solutions should be now developed for both flood management and nutrient removal in winter time. Also, environmentally friendly cultivation practices should be developed and implemented. For example, all-year vegetation cover on the fields would reduce wintertime phosphorus load during mild and rainy winters.

Winter time fishery has been so productive and cost-efficient that local fishermen have not been willing to invest in fishing vessels and infrastructure demanded by summer fishery. However, it now seems that the winter seine fishery may be endangered. Under the warming climate scenarios, there is an urgent need for the commercial fishermen to find new efficient fishing methods (trawling, seine fishing) in order to be able to maintain food web structure favourable for water quality. Further, the current fish community may be endangered as the changing climate may have unfavourable effect on coregonid recruitment. The weather conditions of early spring in this latitude are labile and the possibility for failure of recruitment is getting higher.

Fig. 8 Phytoplankton biomass in Lake Pyhäjärvi in 1963–2008



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