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Were there any changes in zooplankton communities due to the limitation of restoration treatments?

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Abstract: Zooplankton is a good indicator of water quality state. Analysing the species composition and abundance, it is possible to assess the condition of the water body and predict the direction of changes. The aim of the study was to analyse the zooplankton in a shallow urban lake, in which restoration was limited to one method, i.e. wind-aeration. The results were compared with the earlier data obtained during sustainable restoration (three methods: wind-aeration, phosphorus inactivation, biomanipulation) and before the restoration period. The zooplankton was sampled monthly in 2015 and 2016 in the deepest place of the lake from the surface to the bottom. The trophic state was determined based on rotifer trophic state index for lakes (TSI_{ROT}). Although the species composition of zooplankton communities varied very little among the restoration periods (*Keratella cochlearis* f. *tecta* mainly dominated), significant changes in the abundance of zooplankton were found in the analysed lake. The maximum of total abundance was noted in 2015, almost 5500 ind. L^{-1}, and in the next year its decrease was almost 3-fold, to ca. 1800 ind. L^{-1}. Based on TSI_{ROT}, the water was still eutrophic. Leaving only one method of restoration (namely, oxygenation of the bottom waters) proved insufficient to support the development of crucial organisms as cladocerans. The changes in the abundance could have resulted more from seasonal changes than from the effects of aeration. A reduction in species number and maintaining a high proportion of rotifers typical for a high trophic state indicated a return of the ecosystem to its pre-restoration state. High variability in the rotifer abundance indicated a continuous imbalance of the ecosystem. Previous restoration treatments using several methods simultaneously showed better effectiveness. The change of strategy of restoration before obtaining a stable improvement of water quality destroyed previously achieved effects.

Key words: zooplankton, sustainable lake restoration, biomanipulation, limited restoration, deep water aeration

Introduction

All organisms inhabiting aquatic ecosystems respond to environmental changes. Both phytoplankton and zooplankton are good indicators of water quality state because they reflect lake conditions. Grazing pressure of crustaceans on phytoplankton is one of the crucial factors of food web manipulation, especially in eutrophic lakes (Blindow et al. 2000; Tátrai et al. 2005). By observing the species composition and abundance, it is possible to assess the condition of the water body and possibly predict the direction of changes (Ejsmont-Karabin 2012; Ejsmont-Karabin and Karabin 2013; Kuczyńska-Kippen and Basińska 2014; Ochocka and Pasztaleniec 2016). Zooplankton is very sensitive to changes in food availability and predation pressure (Gulati 1983), so it depends on bottom-up and top-down control (Blindow et al. 2000; Ochocka and Pasztaleniec 2016). Therefore, analysis of the zooplankton structure is particularly important in lakes in which restoration treatments are applied.

Usually, these are unstable lakes in which progressive eutrophication is observed due to the increase in nutrient concentration. When the pollutants were discharged into the lake for a long time, the nutrients were accumulated in bottom sediments. As a result of lowering the oxygen content at the bottom, internal loading (release of nutrients to the water column) is intensifying (Jiang et al. 2008). This is often manifested by a deterioration of water transparency, the appearance of water blooms, including potentially toxic cyanobacteria and reduction of biodiversity in the ecosystem (Søndergaard and Jeppesen 2007). The diversion of pollution sources in such cases is necessary. However, this is not always possible (Dunalska et al. 2015, 2018; Søndergaard and Jeppesen 2007). To assist the lake in self-cleaning processes improving water quality, protective measures are used in the catchment area and restoration treatments in the water body (Zamparas and Zacharias 2014). Among the latter, sustainable restoration methods are very promising.

Sustainable restoration is based on the supporting of natural processes, which are responsible for water quality improvement. The applied treatments do not change the conditions in the ecosystem radically and quickly. They involve the simultaneous application of several methods, e.g. wind-aeration, phosphorus inactivation using low doses of chemical substances and biomanipulation (Gołdyn et al. 2014; Kowalczewska-Madura et al. 2020; Rosińska et al. 2018). Oxygenation of bottom waters maintains an appropriate level of redox potential, which prevents the phosphorus release from bottom sediments. Iron sulphate and magnesium chloride causes precipitation of phosphorus from the water column, limiting the phytoplankton growth, especially cyanobacteria. The use of high doses of precipitants brings faster effect but may pose a threat to aquatic organisms (Immers et al. 2014; Rybak et al. 2020; Rybak and Joniak 2018). Thus sustainable restoration is based on repeated application of low doses of chemicals (Gołdyn et al. 2014). Biomanipulation is particularly important because it affects the food-web network. Catching omnivorous fish and stocking with fry of predatory fish (pike and pike-perch) support the development of zooplankton, mainly large cladocerans of the genus *Daphnia*, which can control phytoplankton (Tátrai et al. 2005). These treatments control bottom-up and top-down processes, therefore, an improvement in water quality is observed (Dondajewska et al. 2019; Jeppesen et al. 2007).

An example of a lake, in which the effect of improving water quality during sustainable restoration was visible, is Swarzędzkie Lake (Kowalczewska-Madura et al. 2020; Rosińska et al. 2018). This urban lake was a receiver of untreated sewage for many years. Despite pollution cut-off, the lake was characterised by hypereutrophy (Kowalczewska-Madura and Gołdyn, 2006). Therefore, in autumn 2011, restoration began. As a result of conducted treatments, a slow but gradual reconstruction of the qualitative and quantitative composition of plankton and a decrease in the concentration of nutrients in the water (Rosińska et al. 2019, 2018) as well as decrease of phosphorus release from bottom sediments were observed (Kowalczewska-Madura et al. 2019). Unfortunately, limiting the treatments to only one method (aeration) during the recovery process in the lake resulted in a quick return to the pre-restoration conditions, i.e. an increase in phytoplankton abundance and deterioration of physical and chemical parameters of water quality (Kowalczewska-Madura et al. 2020; Kozak et al. 2018).

The aim of the present study was to determine the structure of zooplankton during limited restoration comparing the results with the analogous from periods of sustainable restoration and before restoration. We hypothesised that limiting the restoration to the aeration method alone is insufficient to rebuild the zooplankton community structure (an increase of cladocerans abundance) to make them able to control phytoplankton effectively. The limitation of restoration will cause a return to the state before the restoration, especially the reduction of the abundance of filter-feeding crustaceans.

Materials and Methods

Swarzędzkie Lake (area 0.94 km^2, average depth 2.6 m and maximum depth 7.2 m) is a natural shallow, polymictic lake. It is elongated in shape, narrowing from half its length towards the outflow. The maximum depth of the lake is in the wider part, while the narrower part does not exceed 2 m depth (Fig.1). Swarzędzkie Lake is located in the northwestern part of Swarzędz town, on the border with the City of Poznań (52°24'49''N, 17°03'54''E). The Cybina River (total length 41 km, catchment area 195.5 km^2, dominated with farmlands) and Mielcuch Stream (small inflow, which drains rainwater and some sanitary sewage from illegal connections) supply the lake with abundant loads of nutrients (Szyper et al. 1994; Kowalczewska-Madura 2003; Kowalczewska-Madura and Gołdyn 2006). An important source of biogenic compounds, especially phosphorus, are also the bottom sediments in this lake (Kowalczewska-Madura and Gołdyn, 2009). The lake was classified as a bream-pikeperch type. The catch was dominated by *Abramis brama* (L.), *Blicca björkna* (L.) and *Rutilus rutilus* (L.). In the 1990s, it was irregularly stocked mainly with *Aristichthys nobilis* (Richardson), *Hypophthalmichtys molitrix* (Valenciennes) and *Anguilla anguilla* (L.) (Rosińska and Gołdyn 2015; Rosińska et al. 2019).

The lake was heavily polluted because until 1991 it was a direct receiver of sewage from Swarzędz town. Despite sewage diversion, the trophic state of the lake did not improve significantly, and the lake ceased to be used for recreation. Cyanobacterial blooms, deoxygenation of the over-bottom waters, high concentrations of chlorophyll-*a* and low transparency were observed in the lake (Kozak et al. 2014; Kowalczewska-Madura 2003; Kowalczewska-Madura and Gołdyn 2006; 2009; Stefaniak et al. 2007).

In 2011, a decision was made on the restoration of Swarzędzkie Lake. Sustainable restoration based on three methods (aeration, phosphorus inactivation and biomanipulation) started in autumn 2011 and was conducted until 2014. The deep-water oxygenation was conducted with the use of a wind-driven aerator (in the deepest part of the lake), without disturbing the thermal stratification (Podsiadłowski et al. 2018; Osuch et al. 2020). The second method was phosphorus inactivation in the water column with iron sulphate ($Fe_2(SO_4)_3$) and magnesium chloride ($MgCl_2$). It was applied with the use of specialised mobile equipment 5-9 times per year (9 times in 2012, 5 times in 2013 and 2014) with small doses (2-5 kg ha^{-1}; 200-300 kg/lake). The third method was the biomanipulation. It consisted of catching an excessive population of planktivorous fish in autumn 2011 (mainly cyprinids, like roach *Rutilus rutilus* and bream *Abramis brama*), stocking the lake with pike *Esox lucius* (L.) 70 kg of autumn fry in years 2011-2013 and 200 kg in 2014 and also early summer fry of pikeperch *Sander lucio perca* (L.) in the amount of 7200 fingerlings in 2014 (Kozak et al. 2014; Rosińska et al. 2017; 2018; 2019; Rosińska and Gołdyn 2015). In the years 2015-2016, the restoration treatments were limited to only one method, i.e. aeration with the use of pulverising aerator (Kozak et al. 2018; Kowalczewska-Madura et al. 2020).

Monitoring of this lake was conducted in the years 2011-16. It consisted of three periods, i.e. before restoration (2011), during sustainable restoration (2012-2014) and after its limitation (2015-2016). Both physico-chemical and biological parameters of water were analysed: biogenic compounds, chlorophyll-*a*, the chemical composition of bottom sediments, phytoplankton, zooplankton, macrophytes and internal loading of phosphorus from bottom sediments. During the period of sustainable restoration (2012-14), a gradual improvement in water quality was observed in the form of reduced concentration of chlorophyll-*a* and increased transparency. There was noted an increase of phytoplankton biodiversity and decrease in the number of cyanobacteria. Unfortunately, as a result of limiting the restoration from three to one method, the water quality of this lake has deteriorated again (Kozak et al. 2014; Kozak et al. 2018; Rosińska et al. 2017; 2018; 2019; Rosińska and Gołdyn 2015; Kowalczewska-Madura et al. 2019; Kowalczewska-Madura et al. 2020). This article includes the results of zooplankton research in 2015-16, i.e. during the limitation of restoration treatments. The results of the impact of biomanipulation and other treatments from 2011 to 2014 (BR – before restoration, SR – sustainable restoration) have already been published (Rosińska et al. 2019) and this article concerns the changes in the structure of zooplankton between 2015 and 2016, i.e. after limitation of the restoration treatments (LR – limited restoration).

Zooplankton was sampled in the water column from the surface to a depth of 6 m, every 1 meter, monthly from January 2015 to November 2016, in the same way as in previous years (Rosińska et al. 2019). The sampling station was located in the central, deepest place of the north-eastern part of the Swarzędzkie Lake, near the aerator (Fig. 1). Water samples for zooplankton community structure determinations were taken using a 5-L water sampler. 10 L of lake water was filtered through a plankton net (mesh size 40 μm). Samples were preserved with modified Lugol's solution (Wetzel and Likens 2000). Zooplankton was analysed (determined, counted and measured) in Sedgwick-Rafter chamber of 1 mL in volume, under a microscope magnification of 100-200x.

The rotifer trophic state index for lakes (TSI_{ROT}) was calculated based on the average abundance in the epilimnion in summer (July and August) (Andronikova, 1996; Ejsmont-Karabin 2012; Rosińska

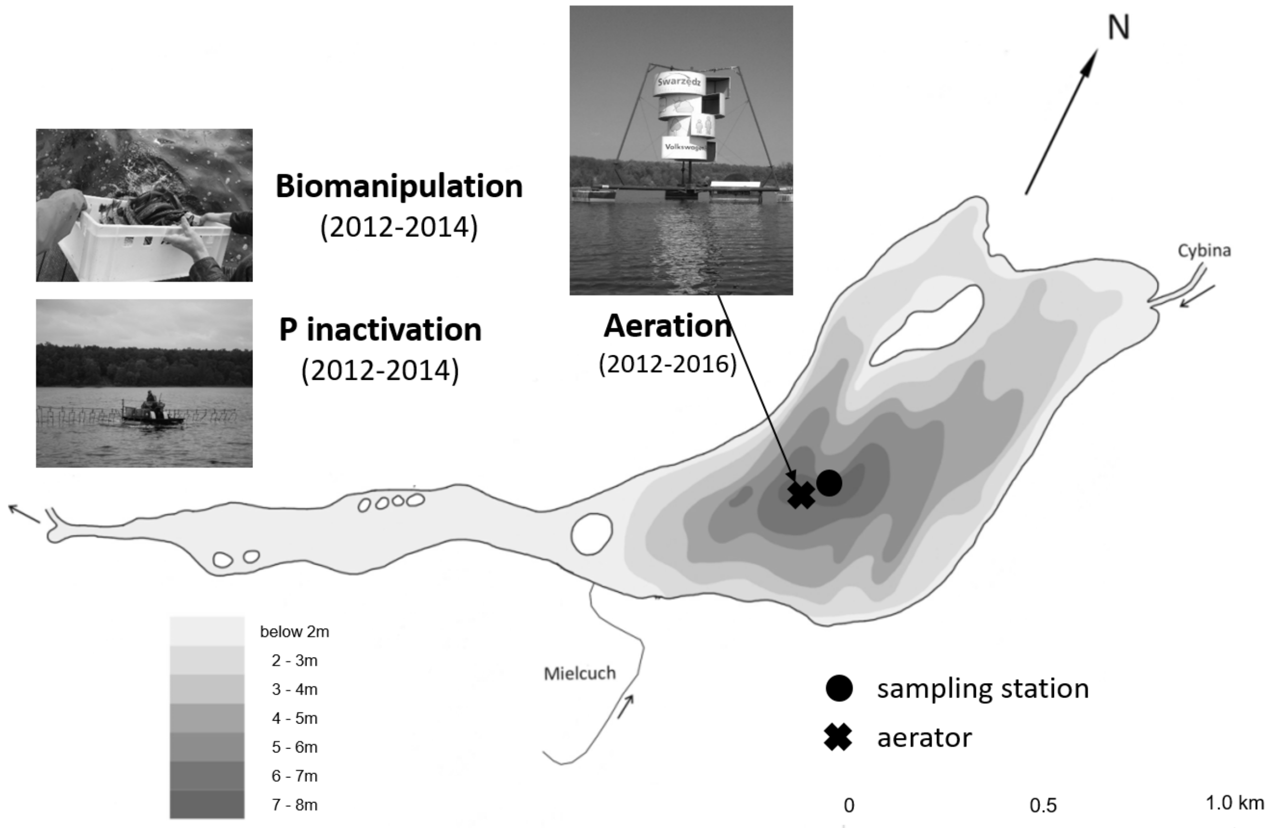

Fig.1.Bathymetric map of Swarzędzkie Lake and location of sampling station

et al. 2019). The epilimnion thickness was determined based on the temperature measured in the water column. The biomass of rotifers was calculated based on standard wet weights, according to Ejsmont-Karabin (1998, 2013). TSI_{ROT} was calculated based on six parameters (Tab.1). The indicators of the eutrophication process based on the zooplankton abundance, according to Andronikova (1996) as well as Haberman and Haldna (2014) were also analysed (Tab.1).

To find out to what extent the zooplankton groups depend on phytoplankton abundance and environmental factors, a set of Canonical Analyses (CCA) was performed using the CANOCO 4.5 software package (terBraak and Šmilauer, 2002). We divided the zooplankton into taxonomical (Cladocera, Copepoda and Rotifera), size and functional groups. Such groups have been awarded like big filtrators (most of *Daphnia* sp. and adult calanoids), small filtrators (e.g. rotifers without *Asplanchna* sp. small daphnids, larval forms of copepods) and predators (*Cyclopoida, Asplanchna* sp. and *Leptodora kindtii*) according to Dawidowicz (1990), Radwan (2004) and Rybak and Błędzki (2010). Statistical significance of the created models, as well as particular factors included in the analyses, were calculated using the Monte Carlo permutation test (999 permutations, $p<0.05$). The Canonical Variate Analysis (CVA) was also applied for the analysis of zooplankton and phytoplankton taxonomic groups, defining the distribution of these groups within the three periods of studies.

Results and discussion

The structure analysis of the zooplankton taxonomic groups in Swarzędzkie Lake, during the period of limited sustainable restoration (LR), showed the presence of 69 species in 2015 and 65 species in 2016. Rotifers dominated in both years over crustaceans (Cladocera and Copepoda), which is often observed in eutrophic waterbodies (Dembowska et al. 2015; Ejsmont-Karabin and Kuczyńska-Kippen 2001; Sługocki et al. 2012, Kozak and Gołdyn

Table 1. The parameters of the Trophic State Index based on Rotifera (Ejsmont-Karabin, 2012) and zooplankton abundance ([1]Andronikova, 1996; [2]Haberman and Haldna, 2014) before restoration (BR), during sustainable (Rosińska et al. 2019) (SR) and limited restoration (LR)

		BR		SR		LR	
	Parameter with formula	2011	2012	2013	2014	2015	2016
	Rotifera						
1	Rotifer numbers (N, ind. L^{-1}) TSI_{ROT1}=5.38 ln(N)+19.28	66.73	65.98	72.65	64.59	70.91	64.24
2	Total biomass of rotifer community (B, mg w.wt. L^{-1}) TSI_{ROT2}=5.63 ln(B)+64.47	70.35	64.83	73.81	68.55	71.38	66.00
3	Percentage of bacterivores in total rotifer numbers (BAC, %) TSI_{ROT3}=0.23 BAC+44.30	57.56	61.21	61.24	57.56	60.01	52.01
4	Percentage of the tecta form in the population of Keratella cochlearis (TECTA, %) TSI_{ROT4}=0.187 TECTA+50.38	68.54	66.99	68.57	61.85	69.05	69.08
5	Ratio of biomass to numbers (B:N, mg w.wt. $ind.^{-1}$) $TSI_{ROT5}=3.85\ (B:N)^{-0.318}$	45.63	59.62	53.27	44.51	55.12	50.37
6	Contribution of species which indicates high trophic state in the indicatory group's number (IHT, %) TSI_{ROT6}=0.203 IHT+40.0	60.18	60.20	60.29	60.06	60.30	60.30
	TSI_{ROT}	**61.50**	**63.14**	**64.97**	**59.52**	**64.46**	**60.33**
	Trophy based on zooplankton indices (55-65 – eutrophy)			**eutrophy**			
	Parameters based on zooplankton abundance						
1	The proportion of Rotifera and Cladocera in total numbers[1]	54	63	245	19	248	90
2	The ratio of numbers of Cladocera to numbers of Copepoda – N_{Clad}/N_{Cop} [1]	0.29	0.10	0.21	0.42	0.21	0.18
3	Rotifer abundance (ind. L^{-1})[2]	6761	5882	20334	4545	14704	4261
4	The percentage share of rotifers in total zooplankton abundance[2]	92.48	84.87	97.68	84.60	97.71	93.19
5	The ratio of crustaceans abundance to rotifer abundance N_{Crust}/N_{Rot} [2]	0.08	0.18	0.02	0.18	0.02	0.07

2014). Rotifers accounted for 67% of the species composition of the zooplankton community (46 and 43 species in 2015 and 2016, respectively), while cladocerans for 17% and 15% of the taxonomic structure (12 and 10 species, respectively). Copepods also represented a small number of species (11 and 12 species), i.e. 16% and 18% of the total number of zooplankton species in the analysed lake. As the previous studies have shown (Rosińska et al. 2019) in the years 2011 (BR) and 2012-2014 (SR) the largest share of rotifers was recorded in 2012 (70%) and the lowest in 2014 (67%). In the case of cladocerans, their share ranged from 15% (2011) to 19% (2014) and for copepods from 12% (2012) to 16% (2011). Comparing the total number of species in particular periods related to the restoration of the lake, it was found that there was an increase in the number of species in the first year of restoration (from 75 to 91 species) (Rosińska et al. 2019) and in the subsequent years, it decreased to 65 species in 2016 (Fig.2a).

Considering the average number of species of particular zooplankton groups in three analysed periods (BR, SR, LR), it was found that only in the case of rotifers the differences between subsequent years of study were statistically significant (Kruskal-Wallis test $p<0.05$). In addition, rotifers showed a decrease in the number of species in subsequent years of the study, cladocerans initially increased until 2014 and then decreased. In the case of copepods, no clear differences were observed between subsequent years of the study (Fig.2b).

The species with the highest abundance in 2015-16 were mainly *Anuraeopsis fissa* (Gosse),

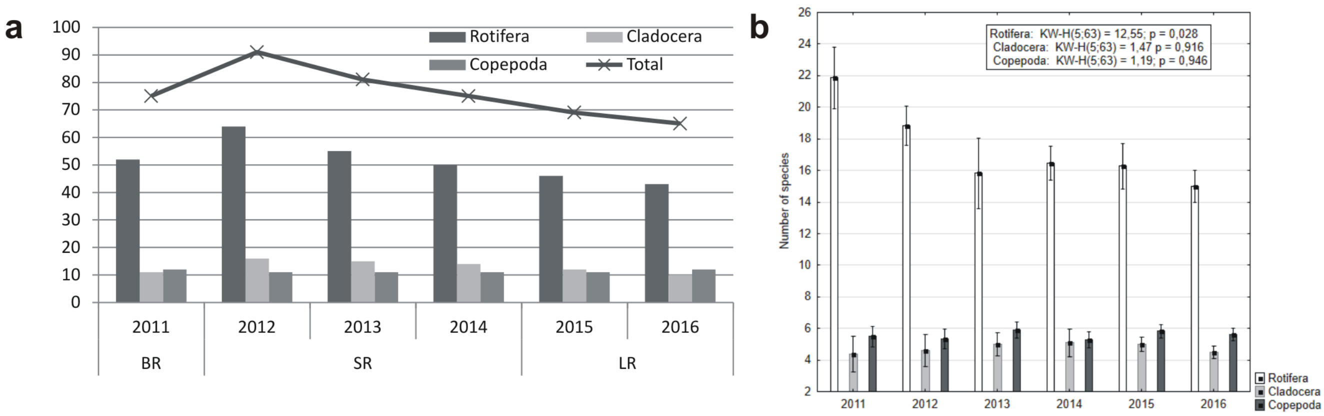

Fig.2. Total number (a) and mean number (with standard error) (b) of species of each zooplankton group in 2011 (BR-before restoration), 2012-14 (SR-sustainable restoration) (Rosińska et al. 2019) and 2015-16 (LR-limited restoration)

Keratella cochlearis (Gosse), *K. Cochlearis f. tecta* (Gosse), *K. quadrata* (Müller), *Pompholyx sulcata* Hudson, *Synchaeta* sp., *Trichocerca pusilla* (Lauterborn) and *Trichocerca* sp. They were species characteristic for waters with the high trophic state (Ejsmont-Karabin, 2012; Ejsmont-Karabin and Karabin, 2013; Kuczyńska-Kippen, 2020), similarly as in the previous years (BR-2011 and SR-2012-14) (Rosińska et al. 2019). A completely different pattern was observed in Lake Trummen in the year after the restoration – the disappearance of *A. fissa* and decrease of *Brachionus angularis*, *T. pusilla*, and *K. quadrata* (Gulati, 1983). Also, two species characteristic of hypertrophy, i.e. *Brachionus diversicornis* (Daddy) and *Trichocerca stylata* (Gosse) (Ejsmont-Karabin, 2012; Ejsmont-Karabin and Karabin, 2013) were present in Swarzędzkie Lake during the restoration process and before. The dominant species among crustaceans were: *Bosmina coregoni* (Baird), *B. longirostris* (Müller), *Daphnia cucullata* (Sars) and *Chydorus* sp. also mostly indicator species for eutrophic waters (Ejsmont-Karabin and Karabin, 2013; Gulati, 1983). Copepods were mainly represented by species such as *Mesocyclops leuckarii* (Claus), *Thermocyclops oithonoides* (Sars), and juvenile forms (nauplii and copepodites).

The total abundance of zooplankton (mean of the vertical profile) during the LR period ranged from 176 ind. L^{-1} in January 2015 to 13253 ind. L^{-1} in August of the same year. The mean total abundance of zooplankton in the first year of the limitation of sustainable restoration was 5478 ind. L^{-1} and in the next year, it decreased almost 3-fold to 1855 ind. L^{-1}. Zooplankton communities usually reach their highest abundance during summer (De Senerpont Domis et al. 2013; Gulati et al. 1992; Ochocka and Pasztaleniec 2016), which was also observed in Swarzędzkie Lake. Rotifers were the dominant group in both years of study. Their mean abundance in 2015 reached 13026 ind. L^{-1} in August and in 2016 until 5268 ind. L^{-1} in September. The abundance of Rotifera of about 5000 ind. L^{-1} was noted in strongly eutrophic lakes (Ochocka and Pasztaleniec 2016). Crustaceans had a much smaller share during the LR period, which amounted to 411 ind. L^{-1} for cladocerans and up to 430 ind. L^{-1} for copepods (Fig.3a).

Although the species composition of zooplankton communities varied very little among the restoration periods, their abundance (especially rotifers) decreased markedly in the second year of LR. In 2016, there was noted the lowest abundance of zooplankton (1855 ind. L^{-1}), while in the second year of sustainable restoration (2013) it was the highest (5512 ind. L^{-1}). It was due to rotifers, which variability was very similar (1663 ind. L^{-1} and 5227 ind. L^{-1}, respectively). Probably the rotifer abundance may be a more sensitive indicator of changes in trophic state, than species composition (May and O'Hare 2005). Cladocerans also showed a clear decrease of abundance in the second year of the limitation of restoration treatment (on average 52 ind. L^{-1}). However, these values were still higher than in the year before restoration (2011), when the density of 34 ind. L^{-1} was recorded. In the case of this group, statistically significant differences were found between subsequent years of research. In 2016, the lowest abundance was also found for copepods (140 ind.

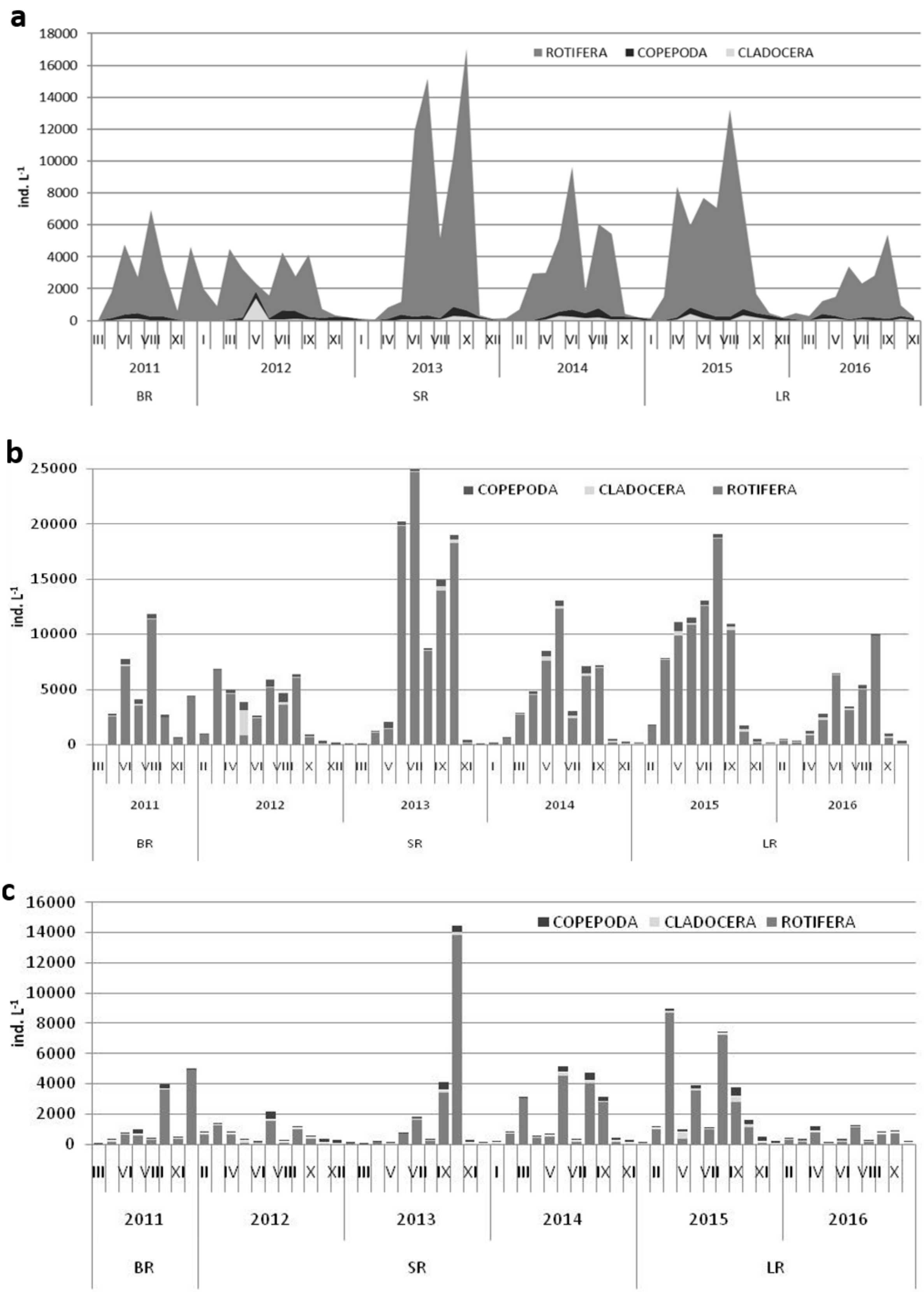

Fig.3. Abundance of zooplankton: mean of vertical profile (a), mean of epilimnion (b), mean of metalimnion (c) of Swarzędzkie Lake in 2011 (BR), 2012-14 (SR) (Rosińska et al. 2019) and 2015-16 (LR)

L^{-1}) (Fig. 4). Such zooplankton composition is often observed, when phytoplankton is dominated by cyanobacteria (Villena and Romo 2003), which was noted in Swarzędzkie Lakes, especially in 2016 (Kozak et al. 2018).

Analysing the total abundance of zooplank-

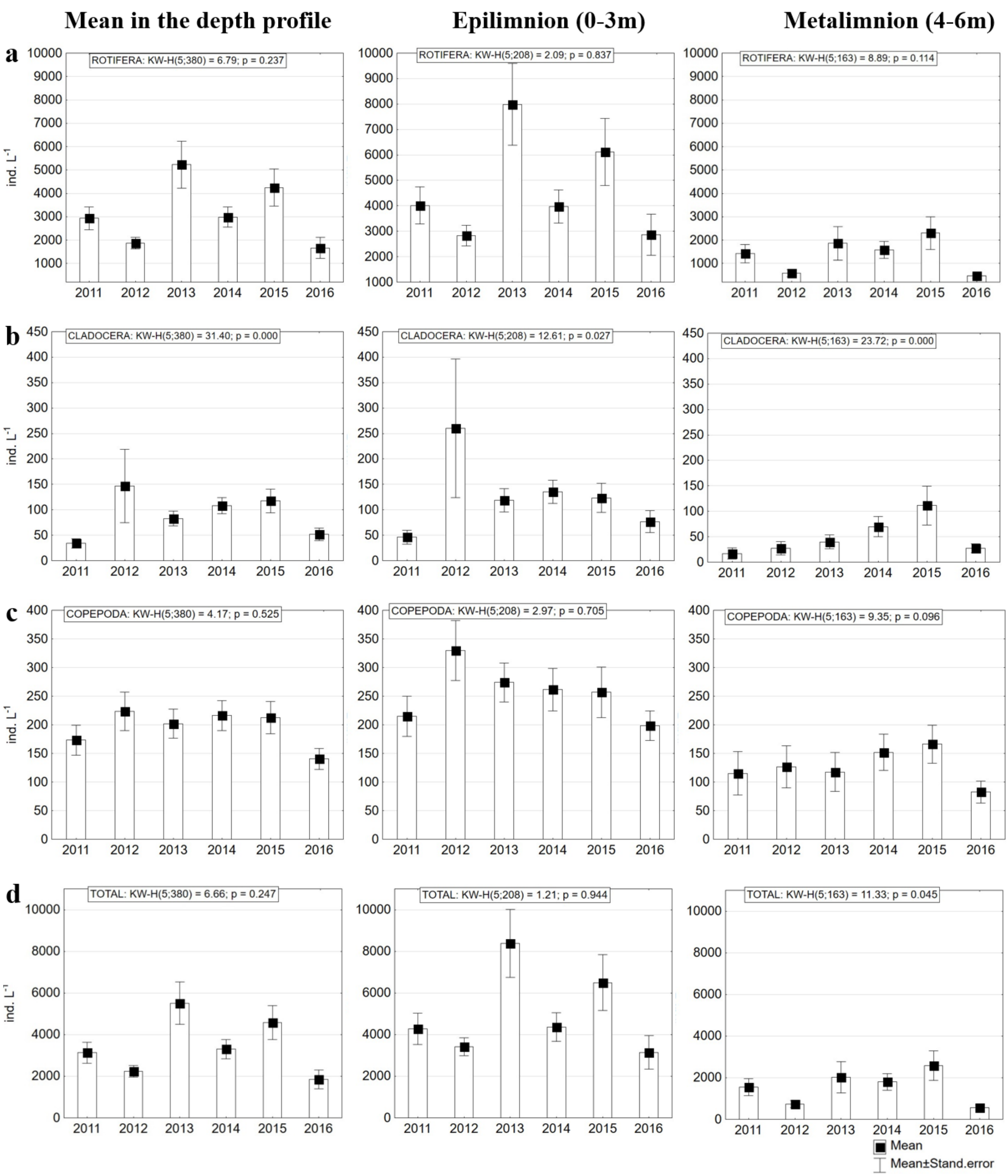

Fig.4.Changes of mean values and standard error of abundance of Rotifera (a), Cladocera (b), Copepoda (c) and total zooplankton (d) in the depth profile, epilimnion (0-3 m) and metalimnion (4-6 m) in 2011 (BR), 2012-14 (SR) (Rosińska et al. 2019) and 2015-16 (LR)

ton in the epilimnion (0-3 m) in the years 2015-2016, after the limitation of restoration treatments (LR) from three to one method, it was found that it ranged from 157 ind. L^{-1} (Jan. 2015) to 19064 ind. L^{-1} (Aug. 2015) (Fig.3b). The dominant group in the whole period 2015-2016 was rotifers, and their maximum abundance reached 18715 ind. L^{-1} in August 2015. In the case of cladocerans, their mean abundance in the epilimnion ranged from 0 to 406 ind. L^{-1} (May 2015) and copepods from 28 ind. L^{-1} to 761 ind. L^{-1} (May 2015) (Fig.3b).

The mean total abundance of zooplankton in the epilimnion decreased from 6496 ind. L^{-1} in the first year of LR to 3141 ind. L^{-1} in the second year. The value noted in 2016 was also minimal from 2011. The maximum was recorded in 2013 (second year of sustainable restoration), reaching 8377 ind. L^{-1}. The same relationship was noted for individual zooplankton groups. Considering the mean abundance of individual zooplankton groups in the three periods (BR, SR, LR), it was found that in 2013 the rotifers reached a maximum of 7984 ind. L^{-1} and a minimum of 2829 ind. L^{-1} in 2012 (Fig. 4). For cladocerans and copepods the maximum mean abundance was found in 2012, i.e. 260 ind. L^{-1}, and 329 ind. L^{-1}, respectively (Rosińska et al. 2019). Only in the case of cladocerans, the differences between subsequent years of study were statistically significant (Kruskal-Wallis test $p<0.05$).

The total abundance of zooplankton in the metalimnion (4-6 m) in 2015-16 (LR) showed lower values than in the epilimnion. They ranged from 124 ind. L^{-1} (May 2016) to 8988 ind. L^{-1} (Apr. 2015) (Fig.3c). In this layer, a significant decrease in the total abundance of zooplankton in the second year of limited restoration was also found. Similarly to the epilimnion, the dominant group was rotifers, whose abundance ranged from 13 ind. L^{-1} to 8741 ind. L^{-1}. Cladocerans and copepods were significantly less abundant and did not exceed 417 ind. L^{-1}, and 564 ind. L^{-1}, respectively (Fig.3c).

The mean total abundance of zooplankton in the metalimnion in the subsequent years of research showed differences. The maximum of 2577 ind. L^{-1} was in 2015 and the minimum of 570 ind. L^{-1} in the next year. Similar variability was noted in the case of rotifers, i.e. 2577 ind. L^{-1} in 2015 and 570 ind. L^{-1} in 2016. Cladocerans, on the other hand, from the beginning of the sustainable restoration showed a gradual increase in the mean abundance up to 111 ind. L^{-1} in 2015, but it was significantly reduced to 27 ind. L^{-1} in the last year of the study. Copepods, similarly to rotifers, and the total zooplankton abundance reached its maximum in 2015, i.e. 166 ind. L^{-1} and the minimum in the following year, namely 82 ind. L^{-1} (Fig.4). The differences between subsequent years of the study were statistically significant only for cladocerans and total zooplankton abundance (Kruskal-Wallis test $p<0.05$). The increase of mean zooplankton abundance in the metalimnion was probably caused by an improvement in oxygen content due to aeration, which enabled zooplankton to use this dark water layer as a refuge against predators (Bormans et al. 2016). Filter feeding zooplankton also avoided layers with high densities of filamentous algae. Therefore they migrated to the deeper water layers (Bürgi and Stadelmann, 2002).

Analysing the parameters of the Trophic State Index, the abundance of species characteristic of eutrophy, classified as bacterivores, i.e. *A. fissa* and *K. cochlearis f. tecta*, were particularly high in the first year of limited restoration (the average number in the epilimnion in summer was 4445 and 5160 ind. L^{-1}, respectively). In the following year, these values decreased 4.5-fold and 10-fold, respectively. The abundance of these species was definitely higher in the second year of sustainable restoration. Despite this, the presence of *T. pusilla*, another species indicating eutrophic conditions was high in both years of limited treatments and amounted to over 1000 ind.L^{-1}. These values were 2-3 fold higher than in 2011-2014. The presence of *Polyarthra major* (Burckhardt), which is a species characteristic of a lower trophy, was not observed in LR period. However, it was recorded before and during sustainable treatments. Comparing the results of TSI_{ROT}, the indicator increased sharply in the first year of the limited treatments, indicating high eutrophy. In the following year, due to the lower abundance of species indicating high trophic state, the value of the index decreased; however, it was still within the eutrophic range (Tab.1).

Most of the parameters of the rotifer trophic state index increased at the beginning of the restoration. This was probably related to the reconstruction of the composition and abundance of phytoplankton, which created better food conditions for rotifers. This was probably associated with an increase in the bacterioplankton abundance, as the abundance of small bacterivorous rotifers increased. It was not until the third year of restoration that these parameters clearly decreased, indicating an improvement in the trophic status of the lake. The limitation of restoration to one method in the following year resulted in a return to the state of intense changes in the ecosystem, which again promoted the development of rotifers and caused an increase in indices of trophic status. However, in the second year of LR, the value of few parameters calculated on a base of rotifers decreased (No. 1, 2, 3, 5 in Tab. 1) indicating the stabilisation of conditions in the lake, except the percentage of *tecta* form in *K. cochlearis* population and the number of species, indicating high trophic state (4, 6 in Tab. 1).

The abundance of crustaceans during limited restoration was almost as low as the values recorded in 2011. The average abundance of cladocerans in the epilimnion in summer did not exceed 60 ind. L^{-1}. The number of copepods (dominated by nauplii) was also lower and did not exceed 300 ind. L^{-1}. Low numbers of crustaceans and high numbers of rotifers caused that the values of parameters were similar to those in the second year of sustainable restoration (Tab. 1) when cyanobacteria bloom occurred (Rosińska et al. 2019, 2017).

Before the restoration, a higher abundance of cyanobacteria was found in the Swarzędzkie Lake (Fig. 5) (Kozak et al. 2014). That was the reason why a sustainable restoration method was applied. During the period of using three methods simultaneously (SR), a clearly higher Cladocera abundance (especially *Daphnia*) was noted (Rosińska et al. 2019), while among phytoplankton groups a clear increase in abundance was found for Bacillariophyceae, Cryptophyceae, Chlorophyceae and Chrysophyceae (Rosińska et al. 2018). This was due to the fact that during the period of using biomanipulation, the pressure of planktivorous fish on cladocerans was limited and zooplankton grazing controlled phytoplankton biomass (Mátyás et al. 2004; Kozak and Gołdyn 2004; van Donk et al. 1993). Cladocerans lead to a reduction in phytoplankton blooms in summer, to some extent, also blooms of cyanobacteria (Kozak et al. 2018). However, the most abundant taxa of cyanobacteria were able to produce cyanotoxins (Kobos et al. 2013), which could cause all kinds of negative consequences for the biota, including impact on zooplankton development (Hilborn and Beasley 2015; Zanchett and Oliveira-Filho 2013). The occurrence of cyanobacterial toxins may also disqualify the lake from recreational and sporting functions, as they are dangerous to humans (Yunes 2019). CVA analysis showed that cyanobacteria were decisive before restoration. During the sustainable restoration, phytoplankton was determined by diatoms, cryptophytes, chrysophytes and green algae, with which cladocerans correlated. Rotifers and copepods from zooplankton and euglenoids from phytoplankton were the most related to the third research period (Fig.5).

Cladocerans highly correlated with chlorophytes, partly also with cryptophytes, throughout the entire 6-year study period (Fig. 6a), while copepods and rotifers correlated with conjugates, dinophytes and euglenoids. The abundance of

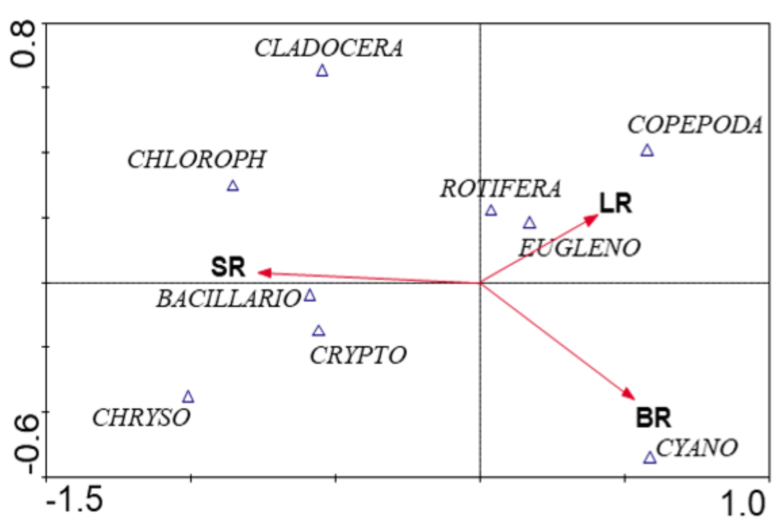

Fig.5. The distribution of the groups within the three periods of the studies (CVA analysis)

phytoplankton groups was determined by water temperature, NO_3, NH_4 and zooplankton groups ($p<0.05$). Water temperature was the crucial factor for rotifer sand generally for smaller-bodied zooplankton, which was often observed in lakes with a high trophic state (De Senerpont Domis et al. 2013; Pociecha and Wilk-Woźniak 2007). The results of CCA indicated that higher abundance of small-bodied zooplankton co-existed with cyanobacteria, as copepods were dominated by juvenile forms, nauplii and copepodites (Fig. 6a), which was often observed in lakes (Ger et al. 2016). Also, planktivorous fish pressure was probably very high, which mostly shifts the zooplankton community structure toward increasing densities of small-sized zooplankton. Meanwhile, big filtrators such as daphnids and calanoids were the important factors in structuring cryptophytes and chlorophytes communities in the study area (Fig. 6b). Predators, especially copepods, affected such groups of phytoplankton as cyanobacteria, conjugatophytes and dinophytes.

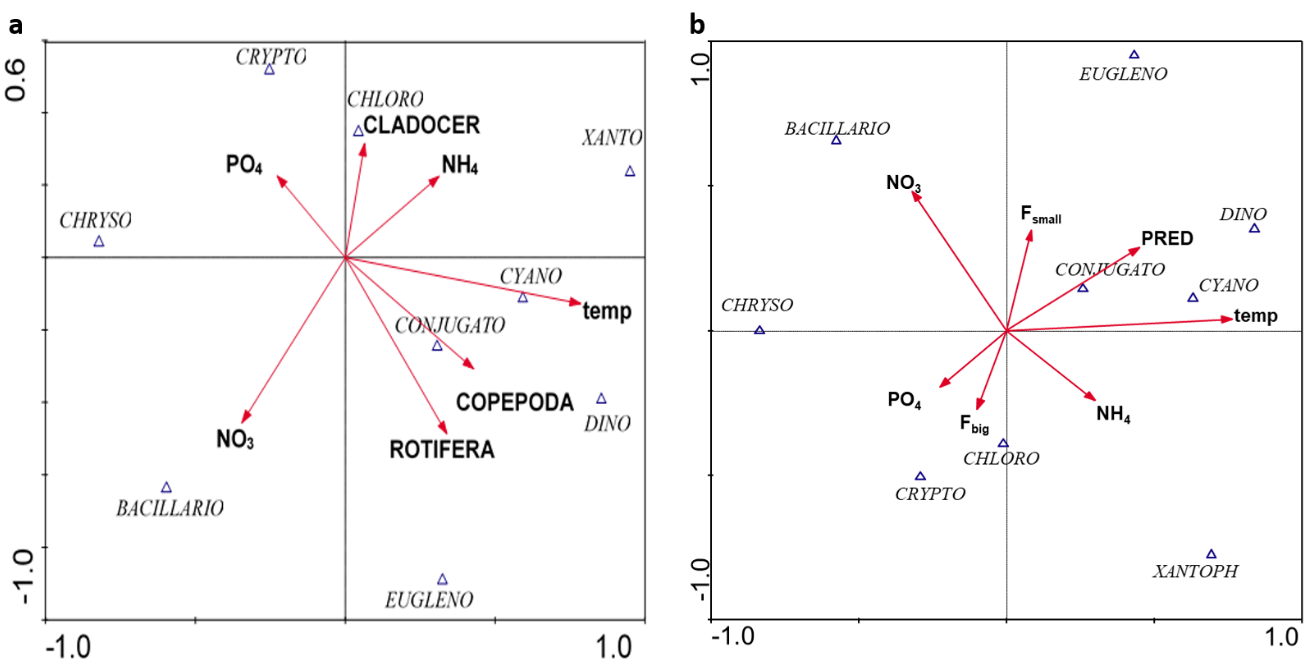

Fig. 6.(a) Biplot of the canonical correspondence analyses (CCA) showing the relationship between phytoplankton groups, physico-chemical parameters and zooplankton taxonomical groups, and (b) spatial ordination resulting from CCA of phytoplankton and physico-chemical parameters, with respect to zooplankton groups (F_{big} – big filtrators, F_{small} – small filtrators and Pred – predators). All vectors, except PO_4, were significant $p<0.05$ (Monte Carlo permutations)

Conclusion

Leaving only one method of restoration (namely, oxygenation of the bottom waters) proved insufficient to support the development of crucial organisms as cladocerans. Despite a reduction in the number of zooplankton species, the same species of rotifers invariably dominated. The abundance of zooplankton during the first year of LR was definitely higher, which indicated the return of the ecosystem to a state similar to that at the beginning of restoration. This abundance significantly decreased in the second year. These changes could have resulted more from seasonal changes than from the effects of aeration. However, a high percentage of the *tecta* form in the population of *Keratella cochlearis* and a high proportion of rotifers typical for a high trophic state, indicate a return of the ecosystem to its pre-restoration state. The confirmation of this statement is the return of cyanobacteria to dominance in phytoplankton. Restoration treatments using several methods simultaneously proved to be more effective, while too early limiting them to one method caused the ecosystem to return to a turbid state.

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