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Research Paper

The response of the rotifer community in Loch Leven, UK, to changes associated with a 60% reduction in phosphorus inputs from the catchment

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Abstract

Lakes across the world are suffering from anthropogenically induced nutrient enrichment problems and many attempts are being made to improve their water quality and ecosystem function. Most metrics that are being used to monitor recovery are based on relationships that have been established across a range of lakes. These may not respond quickly to in-lake changes in water quality when nutrient management strategies are put in place. This paper uses data routinely collected from Loch Leven, UK, to examine the immediate and longer-term responses of the rotifer community to a 60% reduction in phosphorus input from the catchment in the early 1990s. We conclude that changes in rotifer abundance and relative species composition are sensitive indicators of lake-specific changes in water quality, responding more quickly than more widely used metrics, such as total phosphorus and chlorophyll *a* concentrations. However, like all indicators of change, such indices must be used with care in situations where rotifer populations are subject to multiple stressors.

1. Introduction

Lakes across the world are suffering from anthropogenically induced nutrient enrichment problems and many attempts have been made to improve their water quality and ecosystem function by reducing inputs from the catchment. However, only in a small number of case studies have the results of such interventions been recorded for long periods of time after nutrient management strategies have been put in place (e.g. see examples reviewed by Jeppesen et al. 2005). Even fewer studies have reported the impacts of management intervention on the rotifer community of specific lakes.

Rotifers have long been recognised as good indicators of water quality across a range of lakes (e.g. Maemets 1983; Pejler 1981; Pejler 1983; Sladeček 1983; Matveeva 1991; Duggan et al. 2001; Ejsmont-Karabin 2012), but it is unclear whether they can be used as indicators of temporal change within a single site in response to restoration measures. This is because most of the relationships between rotifer species composition and abundance, and lake trophic state, have been based on contemporary comparisons of rotifer communities across multiple lakes (e.g. Berzins & Pejler 1989; Jeppesen et al. 2000; Duggan et al. 2001; Tasevska et al. 2012) rather than in-lake changes over time. In general, although the rotifer community is an important component of lake food webs, the way that it responds to change is poorly understood. This is because our knowledge is limited to the results of relatively few long-term studies (e.g. Matveeva 1986; Walz et al. 1987; Balvay & Laurent 1990; Ejsmont-Karabin 1996), some of which have not linked the responses of the rotifer communities that they describe to changes in environmental pressures over time (e.g. Muirhead et al. 2006; Steinberg 2009).

Rotifer communities have been shown to respond quickly to a wide range of environmental stresses such as acidification, climate change, eutrophication and metal pollution (Walz et al. 1987; May & O'Hare 2005; Havas et al. 1995; Svensson & Stenson 2002; Vbra et al. 2003; Waeervagen & Nilssen 2003; Dupius & Hann 2009). Of these, the impacts of changing eutrophication pressures have received the most attention (Matveeva 1986; Walz et al. 1987; Ejsmont-Karabin & Hillbricht-Ilkowska

1994). Once these pressures have been reduced, as with other freshwater biota, 'recovery' may not necessarily be characterised by the reversal of the patterns that were observed during degradation. For example, recent studies have suggested that zooplankton community responses in lakes can be delayed for many years, and by a number of confounding factors, when phosphorus (P) inputs from the catchment are reduced. These include changes to other chemical stressors (e.g. acidification), fish stocking practices, climate change, persistent internal P loading and (e.g. Jeppesen et al. 2005).

With a few notable exceptions (e.g. Lake Peipsi – Haberman et al. 2010), most long term studies of rotifers have focused on the impact of eutrophication, but not of re-oligotrophication, on the planktonic community. So, reports on the recovery of the rotifer community, once nutrient inputs have been reduced, are relatively rare. This paper documents the responses of the rotifer community in Loch Leven, UK, over a 34 year period that is characterised by three key periods of eutrophication and nutrient management: (1) pre-management (1977-1982); (2) nutrient reduction and immediate post-management (1991-1998); and (3) longer-term post-management (2010-2011). Routine monitoring at this site since 1968 has provided a long time series of physical, chemical and biological variables with which to explore the response of the rotifer community to the nutrient reduction process.

2. Methods

Study site

Loch Leven (56^{o} 10' N, 3^{o} 30' W) is a large (13.3 km^2), shallow lake in the east-central Scotland, UK, with mean and maximum depths of 3.9 m and 25.5 m, respectively (Kirby 1971). The lake has an average hydraulic retention time of about 5.2 months (Smith 1974) and drains a predominantly agricultural catchment of about 145 km^2. Several small towns and villages within the catchment have a total population of about 11,000 people (Frost 1996).

Loch Leven is, primarily, phosphorus (P) limited and has a long and well documented history of eutrophication and recovery (May & Spears 2012). Between 1985 and 1995, total phosphorus (TP) inputs from the catchment were reduced by about 60% (May et al. 2012). So, TP inputs fell from about 20 t y^{-1} (1.5 g m^{-2} yr^{-1}) to about 8.5 t y^{-1} (0.64 g m^{-2} yr^{-1}). This lower level of TP input was sustained until at least 2005, when a TP load of 8 t y^{-1} (0.6 g m^{-2} yr^{-1}) was recorded (May et al. 2012).

Most of the reduction in TP input was due to better control of effluents from waste water treatment works and industrial sources, between 1987 and 1993 (May et al. 2012). However, minor changes aimed at addressing inputs from diffuse sources (such as the installation of buffer strips) were also made (Castle et al. 1999). Key changes in the physics, chemistry and biology of Loch Leven over the pre-management, management and post-management periods have been reported elsewhere (May & Spears, 2012). In summary, these include an increase in growing depth and areal coverage of submerged macrophytes (May & Carvalho 2010; Dudley et al. 2012), a decrease in macroinvertebrate abundance and an increase in the number of taxa (Gunn et al. 2012), improvements in fish populations (Winfield et al. 2012), and an increase in the abundance of aquatic birds that depend on the lake for food and habitat (Carss et al. 2012). Little information on the response of the rotifer community has been published to date.

Sample collection

Water samples were collected at weekly intervals between 1977 and 1982, and fortnightly intervals 1991-1998 and 2010-2011. Sampling methods remained more or less consistent throughout the study period, with plankton and water chemistry samples collected from an open water site with a water depth of about 4 m ("Reed Bower", Figure 1) using a weighted PVC tube with an internal diameter of 25 mm. Surface samples were also collected close to the outflow ("Sluices", Figure 1). On some occasions, e.g. during bad weather, these were the only samples collected.

On return to the laboratory, water samples for chemistry and chlorophyll *a* analyses were shaken and sub-sampled. Those for TP analysis remained unfiltered; those for chlorophyll *a* analysis were filtered through a Whatman® GF/C grade filter within 6 hours of collection. Filter papers were stored frozen at -18^{o}C prior to analysis.

Total phosphorus and chlorophyll* a *analyses

Total phosphorus concentrations were determined on samples that were digested with a solution of sulphuric acid and potassium persulphate, following the method described for TP by Wetzel and Likens (2000), with an additional acidification step. This involved adding 0.1 ml of 30% H_2SO_4 to the samples before adding persulphate. Phosphorus concentrations were determined on a spectrophotometer following the method of Murphy and Riley (1962).

For chlorophyll *a* determinations, the frozen filter papers were submerged in 90% methanol overnight in a dark refrigerator. After centrifugation, the extracted chlorophyll *a* was measured spectrophotometrically at 665 nm with a turbidity correction conducted at 750 nm. Concentrations were determined using equation 1 of APHA (1992).

Rotifer community analysis

Rotifer samples were narcotised in the field by adding sufficient procaine hydrochloride ($NH_2.C_6H_4.COO.CH_2.CH_2.N(C_2H_5)_2.HCl$) to give a final concentration of 0.2 g l^{-1} (May 1985). This ensured that soft bodied species, such as *Synchaeta*, would be recognisable in the fixed samples. Samples were then preserved in 4% formaldehyde and concentrated by sedimentation. Multiple sub-samples of the concentrate with an individual volume of 3 ml (1977-1982, and 1991-1998) or 5 ml (2010-2011) were counted under ×100 magnification until at least 200 rotifers, or the whole sample, had been counted. Species identifications (following Koste 1978) were carried out on live specimens collected separately from the preserved samples, because many species cannot be fully identified, in preserved samples.

3. Results

The 60% reduction in P input to Loch Leven led to a slow but steady decline in annual average open water TP concentrations (Figure 2). Before restoration, these values were about 63 µg P l^{-1}. During and shortly after the P reduction period, the average concentrations rose to about 71 µg P l^{-1}. In the longer term, this value fell to about 34 µg P l^{-1}.

Annual mean chlorophyll *a* (chl*a*) concentrations showed a similar pattern of reduction (Figure 3). Before restoration, these values were about 31 µg chl*a* l^{-1}. During and immediately after management intervention, these values increased to about 47 µg chl*a* l^{-1}. In the longer term, the values fell to about 23 µg chl*a* l^{-1}.

Similar to P and chlorophyll *a* concentrations, total annual mean rotifer densities followed a steady decline throughout the restoration period (Figure 4). Before restoration, average annual rotifer population densities were about 1000 ind. l^{-1}. During the P reduction phase and shortly afterwards, these values fell to about 630 ind. l^{-1}. Although the rotifer data are less complete than the TP and chlorophyll *a* data, these lower population densities appeared to be maintained in the longer term, with the equivalent value for 2010-2011 being about 604 ind. l^{-1}. This represented an overall reduction in rotifer numbers of about 40%. However, while both TP and chlorophyll *a* concentrations initially increased before showing appreciable decreases from 2000 onwards, rotifers densities responded to the change in P load almost immediately. Their numbers had declined by about 40% by the mid 1990s.

Changes in species diversity over the study period are shown in Table 1. The 13 most common and more abundant species remained in the lake over the entire study period. Although their absolute abundances fell, in line with the overall reduction in total rotifer numbers, their relative abundances remained similar throughout (Figure 5). The most noticeable exceptions to this were the relative proportion of *Keratella tecta* in relation to the total number of rotifers, and of the ratio of this species to the abundance of *Keratella cochlearis*. Both of these values decreased over time. The proportion of *Pompholyx sulcata* within the rotifer community as a whole also decreased.

The main changes in species diversity were observed amongst the less common species, which represented only 14%-17% of the rotifer community. Of these, *Colurella adriatica* and *Polyarthra euryptera* were lost in the longer term. *Collotheca mutabilis*, *Conochilus hippocrepis*, *Polyrathra major* and *Synchaeta oblonga* were recorded for the first time during the period of P load reduction and remained in the lake thereafter. *Kellicottia longispina*, *Polyarthra vulgaris* and *Synchaeta tremula* were recorded during the P load reduction period, only, but not in the longer term.

4. Discussion

When the P input to Loch Leven was reduced by about 60%, the rotifer community responded almost immediately with a reduction of 40% in its annual mean densities. This was in contrast to TP and chlorophyll *a* concentrations, which showed a lag of several years before beginning to decline. The reduction in rotifer abundance associated with the reduction in TP inputs to Loch Leven is consistent with expectations based on earlier studies of eutrophication impacts. These showed that higher levels of rotifer abundance are associated with increasing levels of eutrophication across a range of different lake types (Blancher 1984, Karabin 1985, Walz et al 1987, Berzins & Pejler 1989; Matveeva 1991; Jeppesen *et al.* 2000; Duggan et al. 2001; Tasevska et al. 2012) and within individual lakes (Matveeva 1986; Walz et al. 1987; Balvay & Laurent 1990; May & O'Hare 2005; Ejsmont-Karabin 1996; Muirhead *et al*. 1996; Ejsmont-Karabin 2003; Steinberg et al 2009). The results suggest that total rotifer abundance is a good indicator of both eutrophication and recovery, and that it responds more rapidly to change than other determinands that are used to measure change in water quality more routinely, such as TP and chlorophyll *a* concentrations.

At the species level, many authors have reported a strong relationship between certain rotifer 'indicator' species and lake trophic state. For example, based on contemporary studies across a number of lakes, it has been reported that more eutrophic environments are more likely to have species such as *Brachionus angularis*, *Filina longiseta*, *Keratella cochlearis*, *Keratella tecta*, *Keratella quadrata*, *Pompholyx sulcata* and *Trichocerca pusilla*, than less eutrophic environments (Pejler 1983: Karabin 1985; Berzins & Pejler 1989; Matveeva 1991; Ejsmont-Karabin 2003). Many authors have also reported a greater proportion of *Keratella tecta* in rotifer communities as an indicator of increasing lake trophic state (Hillbricht-Ilkowska 1972; Pejler 1981; Karabin 1985; Berzins & Pejler 1989; Ejsmont-Karabin 2012). However, Ejsmont-Karabin & Hillbricht-Ilkowska (1994) suggest that it is unlikely that all of these indicators of trophic state determined across a range of lakes will also reflect in-lake changes in water quality when conditions change. The current study on Loch Leven provides an opportunity for this hypothesis to be explored. In general, the results suggest that the species composition of the rotifer community in Loch Leven, and the proportional contribution of each species to overall abundance, changed very little during the recovery period. However, there was some evidence that the proportion of *Keratella tecta* increased in relation to overall rotifer abundance as water quality improved, as did the ratio of *Keratella tecta:Keratella cochlearis*. So, the results of this study support the hypothesis posed by Ejsmont-Karabin & Hillbricht-Ilkowska (1994) that, although overall rotifer abundance is a good, dynamic indicator of change in the level of trophy of a given lake, other indicators – such as species composition – are less useful. The results also suggest that the proportion of *Keratella tecta* in relation to total rotifer abundance, and in relation to the abundance of *Keratella cochlearis*, may be a suitable indicator for monitoring in-lake change in water quality, especially trophic state.

The results of this study suggest that even simple measures of rotifer abundance and relative species composition could provide sensitive indicators of changing water quality within a lake in response to the control of eutrophication by management intervention. They also suggest that the rotifer community responds to change at a much faster rate than the more commonly used metrics of TP and chlorophyll *a* concentration, both of which may actually increase during the early stages of recovery. However, such rotifer-based indices must be developed and applied with care, as recent studies have also suggested that the response of zooplankton communities in recovering lakes can be subject to a number of confounding factors, such as changes in fish predation, climate change and other chemical stressors, such as acidification (e.g. Jeppesen et al. 2005), that make results difficult to interpret. This is especially true where water quality in general, and rotifer populations in particular, are influenced by multiple stressors.

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7. Tables

Table 1. Rotifer species found in Loch Leven over different time periods

Species	**1977-1982**	**1991-1998**	**2010-2011**
Asplanchna priodonta Gosse	**X**	**X**	**X**
Brachionus angularis Gosse	**X**	**X**	**X**
Conochilus unicornis Rousselet	**X**	**X**	**X**
Filinia longiseta (Ehrenberg)	**X**	**X**	**X**
Keratella cochlearis (Gosse)	**X**	**X**	**X**
Keratella quadrata (Müller)	**X**	**X**	**X**
Keratella tecta (Gosse)	**X**	**X**	**X**
Notholca squamula (Müller)	**X**	**X**	**X**
Polyarthra dolichoptera Idelson	**X**	**X**	**X**
Pompholyx sulcata Hudson	**X**	**X**	**X**
Synchaeta grandis Zacharias	**X**	**X**	**X**
Synchaeta kitina Rousselet	**X**	**X**	**X**
Trichocerca pusilla (Jennings)	**X**	**X**	**X**
Colurella adriatica Ehrenberg	**X**	**X**	-
Polyarthra euryptera Wierzejski	**X**	**X**	-
Conochilus hippocrepis (Schrank)	-	**X**	**X**
Collotheca mutabilis Hudson	-	**X**	**X**
Polyarthra major Burckhardt	-	**X**	**X**
Synchaeta oblonga Ehrenberg	-	**X**	**X**
Kellicottia longispina (Kellicott)	-	**X**	-
Polyarthra vulgaris Carlin	-	**X**	-
Synchaeta tremula (Müller)	-	**X**	-

8. Figure legends

Figure 1. Map of Loch Leven, showing routine sampling sites (squares), inflows and outflow (River Leven) ( ), major roads ( ) and urban areas (grey). Map data from Ordnance Survey Strategi dataset. Contains Ordnance Survey data © Crown copyright and database right 2012.

Figure 2. Annual mean total phosphorus (TP) concentrations in Loch Leven, 1977-2011.

Figure 3. Annual mean chlorophyll *a* concentrations in Loch Leven, 1977-2011.

Figure 4. Annual mean total rotifer densities in Loch Leven, 1977-1982, 1992-1998 and 2010-2011.

Figure 5. Relative abundances of common and less common (‘other’) rotifer species in Loch Leven, 1977-1982, 1992-1998 and 2010-2011.

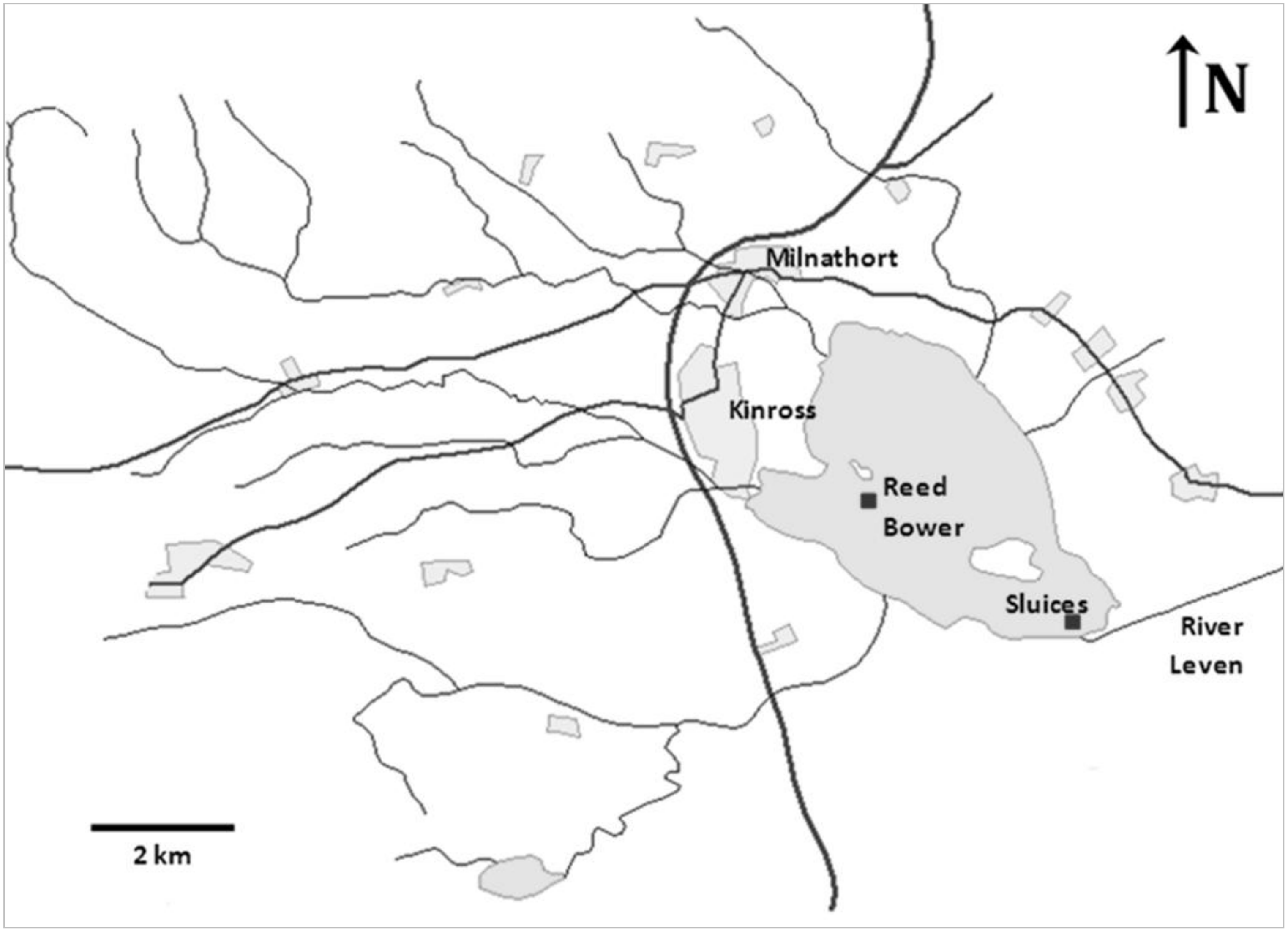
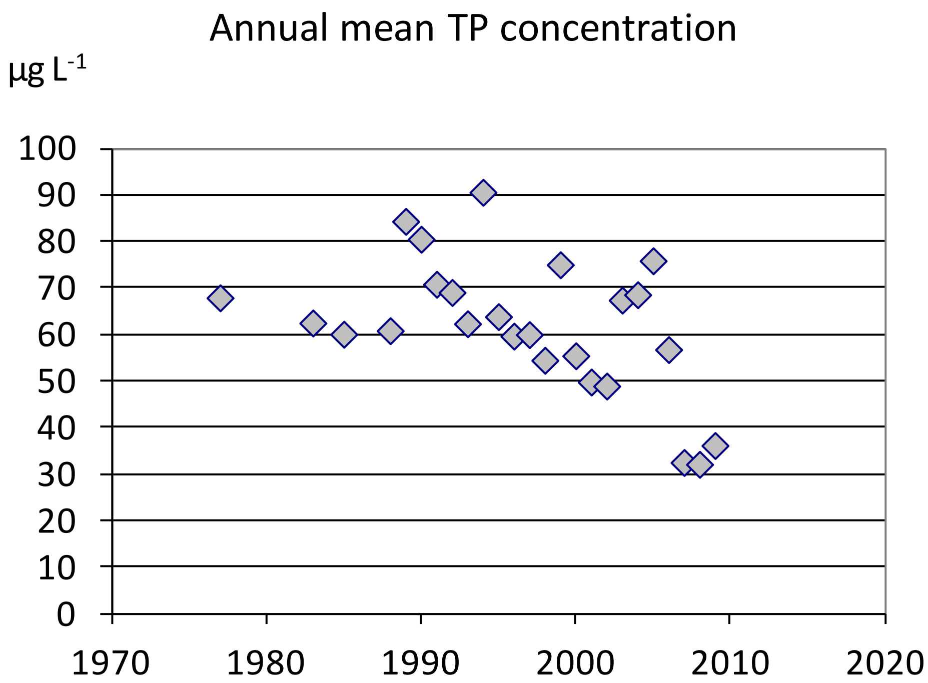


Figure 1.



Annual mean TP concentration
µg L-1
100
90
80
70
60
50
40
30
20
10
0
1970
1980
1990
2000
2010
2020

Figure 2

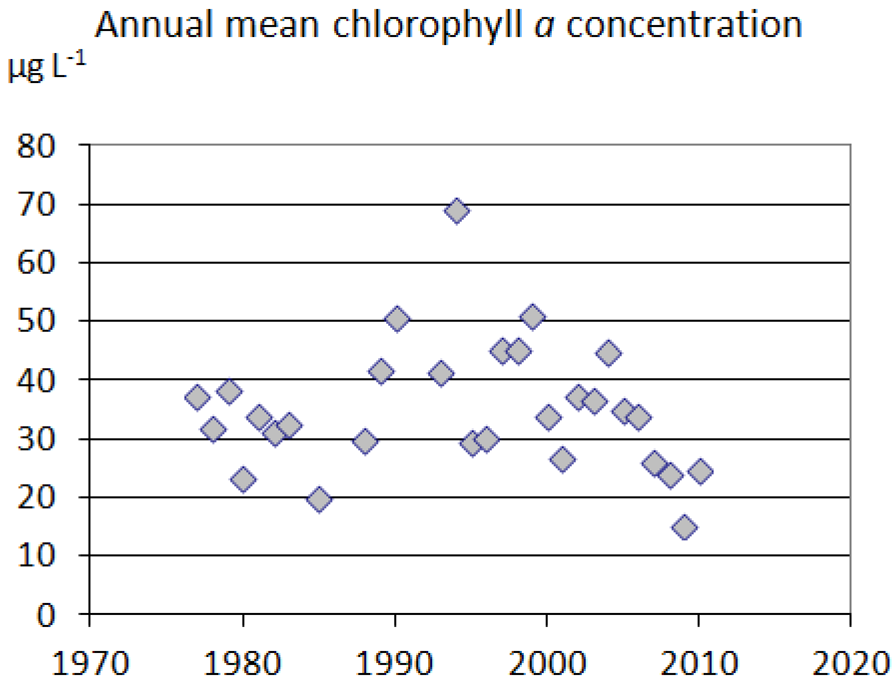

Annual mean chlorophyll *a* concentration
µg L-1
80
70
60
50
40
30
20
10
0
1970
1980
1990
2000
2010
2020

Figure 3

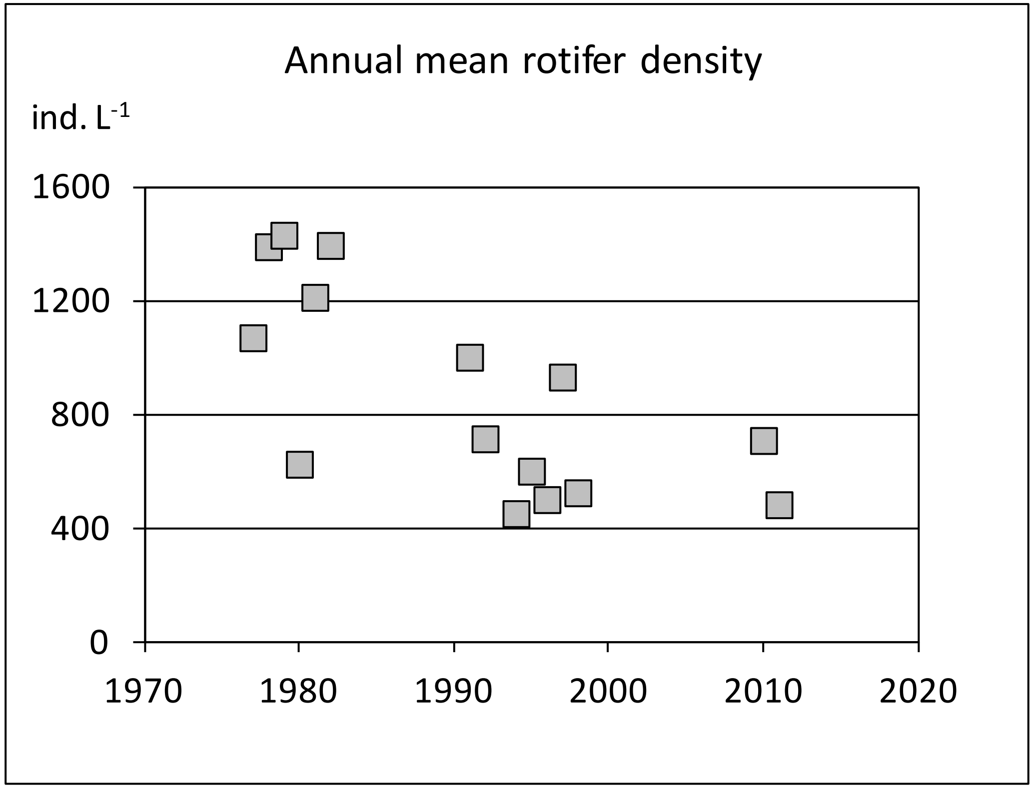

Annual mean rotifer density
ind. L-1
1600
1200
800
400
0
1970
1980
1990
2000
2010
2020

Figure 4

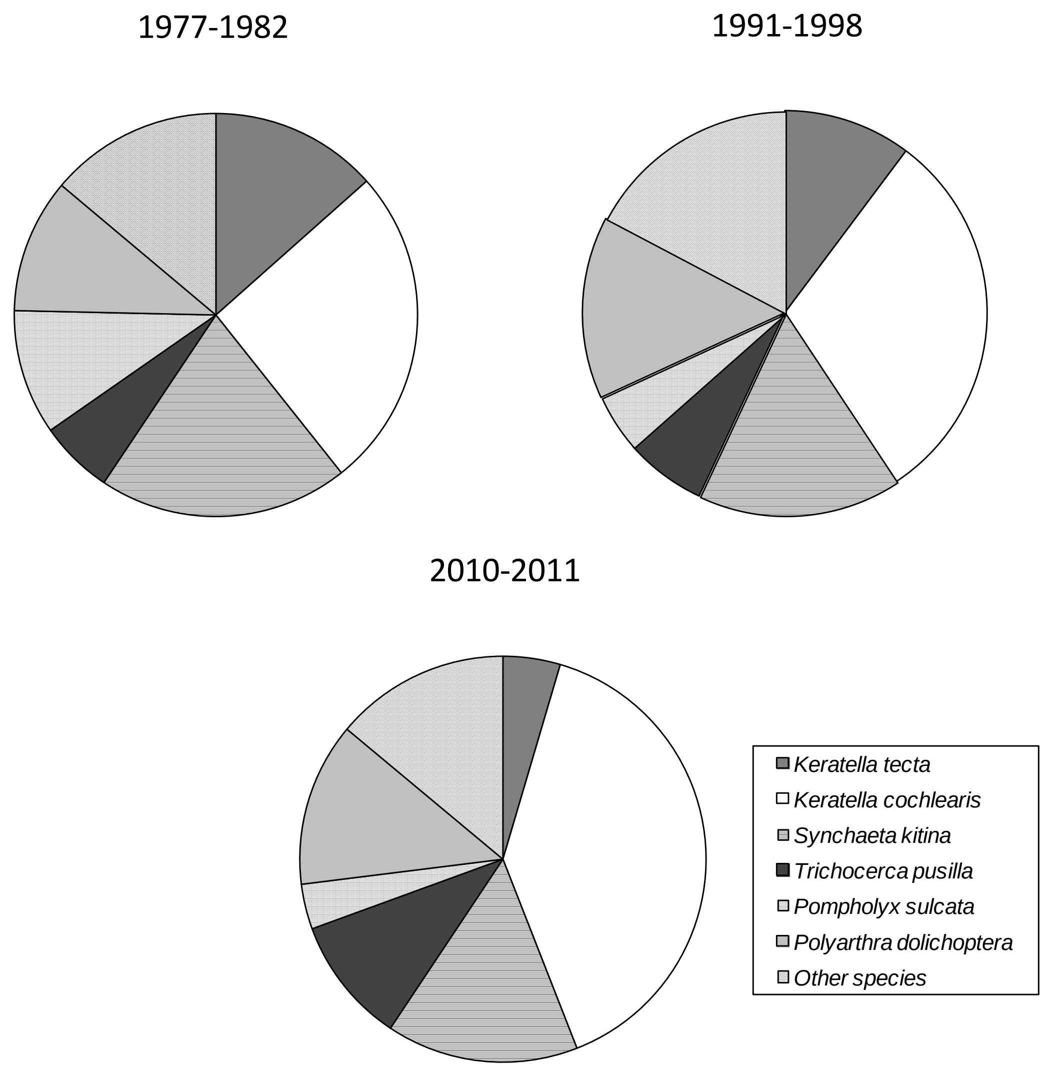

1977-1982
1991-1998
2010-2011
Keratella tecta
Keratella cochlearis
Synchaeta kitina
Trichocerca pusilla
Pompholyx sulcata
Polyarthra dolichoptera
Other species

Figure 5