Science of the Total Environment 478 (2014) 36–47

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Does road salting confound the recovery of the microcrustacean community in an acidified lake?

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HIGHLIGHTS

- We examine if road salting modifies the biological recovery of an acidified lake.
- The main driver of changes in microcrustacean community was reduced acidification.
- Biological recovery of the study lake lacked behind an acidified "reference lake".
- Lower pH, Al and Ca did not explain the shift between the two dominating species.
- We suggest that Cl may affect the community indirectly maybe in combination with TOC.

ARTICLE INFO

Article history:
Received 11 October 2013
Received in revised form 20 January 2014
Accepted 21 January 2014
Available online 12 February 2014

Keywords:
Cladocera
Copepoda
Zooplankton
Road salt
Acidification
Indicators

ABSTRACT

Numerous boreal lakes across the Northern Hemisphere recovering from acidification are experiencing a simultaneous increase in chloride (Cl) concentrations from road salting. Increasing Cl may have profound effects on the lake ecosystem. We examine if an increase in Cl from road salting has modified the recovery of the microcrustacean community in an acidified boreal lake undergoing chemical recovery (study lake). Results from the study lake were compared with an acidified "reference lake". The community changed during the study period in the study lake mainly driven by the reduction in acidification pressure. Despite the community changes and an increase in species richness, the absence of several acid sensitive species, previously occurring in the lake, indicates a delayed biological recovery relative to the chemical recovery. Moreover, changes in occurrence of acid sensitive and acid tolerant species indicated that the biological recovery was slower in the study lake compared to the "reference". Although recurrent episodes of high aluminum and low pH and decreasing Ca are likely important factors for the delay, these do not explain, for instance, the shift from *Cyclops scutifer* to *Bosmina longispina* in the study lake. Although the contribution of Cl was not significant, the correlation between Cl and the variation in microcrustacean community was twice as high in the study lake compared to the "reference". We argue that small, sheltered forest lakes may be especially sensitive to increased Cl levels, through changes in pattern of stratification, thus providing a mechanism for the shift from *C. scutifer* to *B. longispina*. The reduction of the acidification pressure seems to override the Cl effects on microcrustaceans at low Cl levels in salt-affected lakes recovering from acidification. However, prognoses for growing traffic and increasing road salting raise concern for many recovering lakes located in proximity to roads and urbanized areas.

1. Introduction

The structure and function of freshwater ecosystems are affected by a multitude of anthropogenic stressors (e.g. Palmer and Yan, 2013). One such stressor is acidification of rivers and lakes, which has been a major environmental problem in North America and Europe for more than 50 years (Schindler et al., 1989; Skjelkvåle et al., 2005). Atmospheric deposition of acid components has significantly impacted water quality, resulting in marked decreases in pH and alkalinity and increases in concentrations of sulfate (SO_4) and a subsequent mobilization of toxic aluminum (Al). Impoverished water quality has been followed by reduced diversity of aquatic organisms, e.g. a general shift in invertebrate assemblages (Larsen et al., 1996; Sandin et al., 2004; Schartau et al., 2008) and the loss of a vast number of fish populations (Gjedrem and Rosseland, 2012). As a result of international agreements and actions, the emission of sulfur (S) has been reduced by more than two-thirds since 1980 in Europe (EMEP, 2011) followed by improvements in surface water quality (Monteith et al., 2014; Skjelkvåle et al., 2005; Stoddard et al., 1999). Although recent studies have attributed recovery of lake biology to

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http://dx.doi.org/10.1016/j.scitotenv.2014.01.076

decreased deposition of acidifying compounds (Hesthagen et al., 2011; Raddum et al., 2004), evidence of widespread biotic recovery is generally lacking (Gray and Arnott, 2009; Gunn and Sandoy, 2003; Skjelkvale et al., 2001). Studies performed in Europe and North America have demonstrated a delay in zooplankton recovery of 3–10 years, even after water quality has reached acceptable levels (see Gray and Arnott, 2009). Thus, acidification is still considered a serious threat to the biodiversity and ecosystem functioning of inland surface waters in northern Europe (e.g. Brodin, 1995; EMEP, 2005; EMEP, 2011).

Biological recovery from acidification is a complex process. A number of biotic and abiotic factors may delay the restitution of the biological communities. Species interactions may prevent or delay the biological response to improved water quality (see Lundberg et al., 2000). For example, acid sensitive grazers may be excluded from their former niche by acid-tolerant generalists that have occupied this role during the period of acidification. Suppression by invertebrate predators may cause failure of herbivorous zooplankton to respond to the improved chemistry of acidified fishless lakes (Arnott et al., 2006). In other lakes, the return of and the predation by fish may impact on biological recovery (e.g. Valois et al., 2010). Dispersal limitation may also constrain or delay the recovery of biological communities (Gray and Arnott, 2011). An example of an abiotic factor that can delay biological recovery is the mobilization and leaching of dissolved organic carbon (DOC, Korosi and Smol, 2012), observed in many lakes of the Northern Hemisphere during the last decades and which may reduce the water clarity. Another example is the declining level of base cations as a consequence of long term acidification, which might affect certain crustacean zooplankton species (Alstad et al., 1999; Hessen and Rukke, 2000).

Increasing salt concentrations may also affect biological recovery from acidification. Higher salt concentrations of surface waters can be caused by deposits from the sea or from runoff of de-icing chemicals from roads. Here we will focus on the latter. The by far most applied de-icing chemical is sodium chloride (hereafter termed road salt). In the Northern Hemisphere sodium (Na) and chloride (Cl) concentrations of surface waters have increased over the last decades due to increasing use of road salt (e.g. Evans and Frick, 2001; Molot and Dillon, 2008). Also, in Norway there has been a significant increase in the amount of applied road salt, and since year 2000 the annual amount has more than tripled (Kronvall, 2013) leading to increasing Cl concentrations in lakes (Bækken and Haugen, 2012).

Increasing salt concentration in lakes affects the ecological structure and functioning of the aquatic ecosystem both directly and indirectly. At high enough concentrations, Cl can increase the acidity of water, causing some of the same negative effects as acid rain (Löfgren, 2001). Higher salt concentrations may also favor more salt tolerant taxa (Blinn et al., 2004; Evans and Frick, 2001; Sarma et al., 2006). However, one of the most evident impacts of road salt on the aquatic environment is increased density stratification followed by altered circulation patterns and oxygen depletion in lakes (Kjensmo, 1997; Koretsky et al., 2012; Novotny et al., 2008; Novotny and Stefan, 2012). A recent survey conducted in Norway revealed that almost 30% of the investigated lakes had developed salt gradients and altered circulation patterns (Bækken and Haugen, 2012). Oxygen depletion of the deep water may in turn lead to mobilization of toxic metals and phosphorus from the sediments (Bækken and Haugen, 2012; Lewis, 1999). Increased salt concentrations may therefore indirectly lead to algal blooms because of increasing nutrient availability. So far most of the literature dealing with the effects of increasing salt concentrations on aquatic freshwater ecosystems has focused on relatively high concentration ranges (e.g. Van Meter et al., 2011). However, Evans and Frick (2001) noted that very small increases in Cl of 2–10 mg L^{-1} can affect phytoplankton community structure in low salinity lakes. In Norwegian calcium poor lakes effects on the phytoplankton community may appear at chloride concentrations of 23–30 mg L^{-1} (Haugen et al., 2011). Growth reductions of individual sensitive phytoplankton species occur at even lower concentrations (10–15 mg L^{-1}, Haugen et al., 2011). A recent study of multiple anthropogenic stressors on Canadian freshwater zooplankton demonstrated effects of rising Cl concentrations on important zooplankton metrics at concentrations below 5 mg L^{-1} (Palmer and Yan, 2013). The effect of Cl at low concentrations may be exacerbated in a multiple stressor environment, e.g. recovering from acidification.

Numerous lakes across the temperate and subarctic zones in North America and Northern Europe undergoing chemical recovery from acidification are also experiencing a simultaneous increase in Cl concentrations due to deicing of roads during winter (e.g. Palmer and Yan, 2013). No studies have investigated if the biological recovery from acidification is affected by the increasing Cl concentrations in these lakes. The Lake Øvre Jerpetjern in Southeastern Norway (Fig. 1) undergoing chemical recovery from acidification is also influenced by road salts. Using monitoring data on water chemistry and microcrustaceans from this lake, we test whether the change in water quality (decreasing acidification and increasing Cl concentrations) over a 17 year period has affected the structure of the microcrustacean community. A comparable lake recovering from acidification but without influence from road salts was used as a reference. We hypothesize that increasing Cl concentration in the lake modifies the recovery of the microcrustacean community from acidification.

2. Materials and methods

2.1. Study site

Lake Øvre Jerpetjern is located in Southeastern Norway in the county of Telemark about 48 km from the sea (N 59.60692°, E 9.42168°). The lake is situated at an altitude of 457 m.a.s.l. It has a surface area of 0.12 km^2, and the maximum depth is 17 m (Fig. 1). The catchment area is 1.85 km^2, mainly covered by forest consisting of spruce (*Picea abies*) and pine (*Pinus sylvestris*). The bedrock of the catchment consists of granite. One of the main roads between Southeastern and Western Norway, the E134, passes south of the lake at a distance of 150 m. The annual average daily traffic (ADT) on this part of E134 is approximately 5000 vehicles. In relation to the E134 a resting place was established southwest of the lake in the beginning of the 1980s. Except for the road, the resting place and a few cottages, the catchment is undeveloped. Two inlet streams enter the lake, the larger one from the north east (Fig. 1), draining the forested area north of the lake. A smaller stream enters the lake in the southwestern corner (Fig. 1), receiving runoff from the road and the rest area. This part of E134 receives on average 20 t of NaCl from road salt per km per winter (range 13–28). The rest area is also salted but to a lesser degree than the road. While the Cl concentration in the lake has reached levels around 10 mg L^{-1}, measurements in the southwestern inlet stream show values that are 20 times higher (T.C. Jensen unpublished results). The lake is fishless due to acidification but originally contained a population of perch (*Perca fluviatilis*). An attempt to re-establish the population during the 1990s failed. Brown Trout (*Salmo trutta*) has also been introduced to the lake twice during the study period (2004 and 2005). The stocked trout survived, but no reproduction in the tributaries has been observed.

During the period 1986 to 2010, Lake Øvre Jerpetjern was part of a national long term monitoring program. The purpose of the program is to document the ecological effects in freshwaters due to acid deposition, and record improvements due to reduced sulfur emissions in Europe. The improvement of the water quality caused by reduced emissions is also evident in Lake Øvre Jerpetjern. For the period 1986 to 1995 water chemistry has been measured once per year after circulation in autumn. In 1996 this monitoring was intensified including additional sampling periods. In addition the development of the microcrustacean community has been followed since. As a result of increasing chloride concentration due to road salting, the lake was removed from the monitoring program in 2011. However, the monitoring of the lake was continued by the Norwegian Institute for Nature Research in 2011 and 2012.