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Long term trends of fish after liming of Swedish streams and lakes

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HIGHLIGHTS

- Fish was monitored at 1779 lakes and streams up to 42 years since first liming.
- Large-scale liming and monitoring revealed clear improvement at the national scale.
- Stream fish occurrence, species richness and abundance increased after liming.
- Few acid sites were left non-limed to permit consistent monitoring at reference sites.
- Species richness and abundance did not improve in lakes as in streams after liming.

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ABSTRACT

Thousands of Swedish acidified lakes and streams have been regularly limed for about 30 years. Standard sampling of fish assemblages in lakes and streams was an important part of monitoring the trends after liming, i.e. sampling with multi-mesh gillnets in lakes (EN 14757) and electrofishing in streams (EN 14011). Monitoring data are nationally managed, in the National Register of Survey test-fishing and the Swedish Electrofishing Register. We evaluated long-term data from 1029 electrofishing sites in limed streams and gillnet sampling in 750 limed lakes, along with reference data from 195 stream sites and 101 lakes with no upstream liming in their catchments. The median year of first liming was 1986 for both streams and lakes. The proportion of limed stream sites with no fish clearly decreased with time, mean species richness and proportion of sites with brown trout (*Salmo trutta*) recruits increased. There were no consistent trends in fish occurrence or species richness at non-limed sites, but occurrence of brown trout recruits also increased in acid as well as neutral reference streams. Abundance of brown trout, perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*) increased significantly more at limed sites than at non-limed reference sites sampled before and after 1986. The mean species richness did not change consistently in limed lakes, but decreased in low alkalinity reference lakes, and fish abundance decreased significantly in limed as well as in non-limed lakes.

1. Introduction

Thousands of Swedish lakes and streams have been regularly treated with limestone to mitigate acidification (Svenson et al., 1995). Liming became a large-scale and governmentally supported restoration program in the 1980's, and the number of local liming projects increased at the same time as large-scale measures were taken to decrease airborne emissions of sulfur and nitrogen compounds. The annual amount of limestone spread peaked at more than 200,000 tons during 1998–2002. As an adjustment to decreasing acidification, the amount of lime decreased and recently stabilized at about 120,000 tons per year (Abrahamsson et al., 2013).

Deposition of sulfur and nitrogen has now decreased over Europe, although non-linearly related to reduced emission at regional scale (Fowler et al., 2007). Swedish soils are just slowly becoming less acid (Akselsson et al., 2013). Similarly, sulfate and acidity has decreased in streams and lakes (Fölster and Wilander, 2002; Futter et al., 2014), but many of the non-limed lakes are still acidified as compared to estimated reference pH. Slow and insufficient chemical recovery is probably one reason for slow or inconsistent biological recovery in Swedish lakes (e.g. Angeler and

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Johnson, 2012; Holmgren, 2014), but there are relatively few reports of evidence for partial biological recovery in non-limed streams (e.g. Monteith et al., 2005; Kowalik et al., 2007; Battarbee et al., 2014; Murphy et al., 2014).

Acid precipitation led to recruitment failure, declining abundance and eventually extinction of many fish populations in Scandinavia and North America (Schofield, 1976). Experiments revealed that fish species differ in sensitivity to low pH and acidity-associated aluminum (e.g. Skogheim and Rosseland, 1984; Poleo et al., 1997), and that reproductive and early life stages were most critically affected (e.g. Rask, 1984; Mc Cormick and Leino, 1999).

A main goal of the liming programs in Sweden was initially to restore waters identified as being of special value for fish and fishery (Bengtsson et al., 1980). Fish was also targeted in large-scale liming in Norway (Sandøy and Romundstad, 1995), and in other more recent plans to promote recovery of acidified waters (e.g. Josephson et al., 2014). Site-specific chemical targets for liming in Sweden currently focus on the most acid-sensitive species (Abrahamsson et al., 2013), in practice often Atlantic salmon (*Salmo salar*) in rivers, and roach (*Rutilus rutilus*) in lakes.

General results of liming projects have been reviewed (e.g. Henrikson and Brodin, 1995; Clair and Hindar, 2005), and reports on biological impacts of liming were recently synthesized both for rivers and streams (Mant et al., 2013) and lakes (Mant and Pullin, 2012). Positive effects on fish included increased diversity, with or without re-stocking of lost populations, and sometimes increased abundance or improved reproductive success. However, many reported liming projects were non-replicated case studies, without baseline and/or control sites, and often of short duration in terms of lime treatment and/or monitoring.

Bradley and Ormerod (2002) stressed the need for long-term monitoring of liming of acidified surface waters. The large-scale Swedish liming program offers a unique possibility to evaluate long term effects on fish at a national scale. Governmental funds support not only regular lime treatment, but also chemical and biological monitoring with standard methods (e.g. CEN, 2003; CEN, 2015), as long as the monitoring results are reported to national data hosts. Results from some Swedish fish studies of varying duration were included in the reviews mentioned above (e.g. Degerman and Appelberg, 1992; Degerman et al., 1992; Holmgren, 2001), but a national-scale analysis over more than 30 years of liming has not previously been presented.

In this study, we extended our perspective from just a few well studied sites, to evaluate more extensive monitoring data in large national fish databases. We expected that positive national-scale effects of liming on fish populations would, in most cases, dominate over any local site-scale changes. More specifically, we expected increasing fish occurrence and species richness, due to re-establishment of species that were previously lost during acidification. We further expected more regular recruitment of acid-sensitive species, and overall increased fish abundance. All predicted responses were tested using electrofishing data from streams. Responses on fish species richness and abundance in lakes were similarly explored using data from gillnet sampling.

2. Material and methods

2.1. Stream data

The main part of this study was based on stream fish data stored in the Swedish Electrofishing Register (SERS, Sers, 2014), representing autumn samples on annual basis or less frequently, with each site covering a wadable stream reach of at least 100 m^2 (CEN, 2003). Abundance was expressed as number of fish per 100 m^2, within each species caught, separately for age 0 + and >0 + for brown trout (*Salmo trutta*) and Atlantic salmon (inferred from length frequency distributions), and for the sum of all occurring species.

Electrofishing sites were initially selected based on the following criteria; 1) samples from at least five occasions, 2) time span of at least seven years between first and last sampling date, 3) first sampling performed before year 2000, and 4) no known stocking of fish.

Catchments of selected electrofishing sites were delimited by using national digital elevation data. Limed sites and their first year of liming were identified, and information on amounts of limestone spread in the catchments methods of liming was retrieved by matching of electrofishing sites with the national database on liming (http://kalkdatabasen.lansstyrelsen.se). County administration boards provided existing data on pH and alkalinity from limed as well as non-limed reference streams. Electrofishing sites in non-limed streams were kept if available data made it possible to classify them in one of three reference groups; 1) acid (mean pH < 6.0 or minimum pH < 5.4), 2) low alkalinity (minimum pH > 5.4 and mean alkalinity < 0.5 meq L^{-1}), or 3) high alkalinity (mean pH > 6.0 and mean alkalinity > 0.5 meq L^{-1}).

2.2. Lake data

An additional part of the study was on lake fish data from the National Register of Survey test-fishing (NORS, Kinnerbäck, 2015), including sampling with benthic multi-mesh gillnets in late summer (generally after mid-July or in August). The prevailing type of multi-mesh gillnet changed gradually through time, during 1968–1990 from Lundgren type S (12 panels, bar mesh 10–75 mm, total area 54 m^2) to Lundgren revised type S (14 panels, bar mesh 6.5–75 mm, total area 63 m^2, Hammar and Filipsson, 1985), and from 1991 the older types were increasingly replaced by the Nordic type (12 panels, bar mesh 5–55 mm, total area 45 m^2, Appelberg et al., 1995), used in a depth-stratified random design according to the current European standard (CEN, 2015).

Lakes were first selected based on the following criteria; 1) multi-mesh benthic gillnet samples representing the whole lake and all of its available depths, 2) samples from at least two years, 3) time span of at least five years between first and last sampling date, and 4) first sampling performed before year 2000.

The dataset was further reduced to include only lakes with recorded status as limed or non-limed, and limed lakes were kept if the first year of liming was available in the fish database NORS. Available data on pH and alkalinity were retrieved from a national database managed by the Department of Aquatic Sciences and Assessment (http://webstar.vatten.slu.se/db.html). As for streams, non-limed lakes were kept if available data made it possible to classify them in one of three reference groups; 1) acid (mean pH < 6.0 or minimum pH < 5.4), 2) low alkalinity (minimum pH > 5.4 and mean alkalinity < 0.5 meq L^{-1}), or 3) high alkalinity (mean pH > 6.0 and mean alkalinity > 0.5 meq L^{-1}).

2.3. Data analysis

The following fish metrics were retrieved for each stream sample; 1) fish occurrence (yes = 1 or no = 0), 2) species richness (number of caught fish species), 3) occurrence of brown trout recruits (age 0 + estimated from length distribution, yes = 1 or no = 0), and 4) abundance (estimated number of fish per 100 m^2). Abundance was estimated separately for each species, separately for age 0 + and >0 + within brown trout and Atlantic salmon, and for the sum of all observed species.

Only two fish metrics, species richness and total fish abundance, were retrieved for each lake sample; i.e. 1) species richness as for