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A systematic review of the effectiveness of liming to mitigate impacts of river acidification on fish and macro-invertebrates☆

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ABSTRACT

The addition of calcium carbonate to catchments or watercourses – liming – has been used widely to mitigate freshwater acidification but the abatement of acidifying emissions has led to questions about its effectiveness and necessity. We conducted a systematic review and meta-analysis of the impact of liming streams and rivers on two key groups of river organisms: fish and invertebrates. On average, liming increased the abundance and richness of acid-sensitive invertebrates and increased overall fish abundance, but benefits were variable and not guaranteed in all rivers. Where B-A-C-I designs (before-after-control-impact) were used to reduce bias, there was evidence that liming decreased overall invertebrate abundance. This systematic review indicates that liming has the potential to mitigate the symptoms of acidification in some instances, but effects are mixed. Future studies should use robust designs to isolate recovery due to liming from decreasing acid deposition, and assess factors affecting liming outcomes.

1. Introduction

In the 1970's widespread environmental concern developed over the effects of acid deposition – widely known as "acid rain" – on base-poor streams, rivers and lakes (Menz and Seip, 2004). Sulphur and nitrogen oxides released into the atmosphere from industrial emissions decreased rainfall pH over affected areas and increased sulphate and nitrate concentrations in deposition. Where rocks and soils were base-poor, base-cation depletion and soil acidification followed, runoff pH declined, and concentrations of aluminium and other metals increased in soil and stream waters as explained by the well-known 'mobile anion' hypothesis (Reuss and Johnson, 1986). Surface-water acidification also changed many aspects of freshwater ecosystems, with altered invertebrate taxonomic composition and reduced fish populations, notably salmonids, among the best known effects (Moiseenko, 2005; Sandøy and Langåker, 2001; Schindler et al., 1985; Watt, 1987). At its peak, acid deposition was one of the most widespread pollution problems affecting rivers, and in base-poor locations such as Wales around half the stream length – some 12,000 km – were impacted (Firth et al., 1995).

Since the 1970s, industrial emissions have declined both in Europe and North America as a consequence of de-industrialisation and improved regulation leading to reduced concentrations of (non-marine) sulphate in runoff (Evans et al., 2001; Reynolds et al., 2004). However, emissions of nitrogen oxides have not decreased to the same extent (Fowler et al., 2007), and there are regions where acid deposition still exceeds soil neutralizing capacity (Matejko et al., 2009). Moreover, biological recovery in watercourses has been patchy or partial even in locations where mean runoff pH has increased (Ormerod and Durance, 2009). Currently, the best explanation for these circumstances is that episodic acidification still occurs during high discharge and is sufficient to offset biological recovery (Evans et al., 2008; Kowalik et al., 2007). At other locations, chronic acidification still remains a problem (Ormerod and Durance, 2009). Additionally, as industrialisation has shifted from Europe into South Asia, acid deposition has become an issue in other parts of the world (Kuylenstierna et al., 2001). In combination, these circumstances raise the possibility that liming – long advocated as a means of treating the symptoms of acidification (Clair and Hindar, 2005) – might be suggested more widely to protect waters where acidic deposition is a growing problem or to aid recovery where this is impaired.

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Liming – the addition of calcium carbonate – is intended to raise the pH of rivers and/or lakes and occurs through a range of different methods. Limestone can be added directly in bulk into the river channel (termed point application in this review), applied continuously by mechanical dosers, applied directly to lakes within river catchments (lake liming) or distributed over river catchments (catchment liming). The latter is potentially effective in reducing the release of potentially toxic metal ions (e.g. Al^{3+}) from catchment soils (Clair and Hindar, 2005). Catchment liming can also be expected to have longer-term effects than individual direct applications although there are risks to the functioning and diversity of wetland systems that might be naturally acidic (Donnelly et al., 2003). With all liming methods, the most commonly used material is ground limestone gravel or powder, although dolomite, $CaMgCO_3$, is also used occasionally (Clair and Hindar, 2005). The dose applied can vary and is generally calculated by modelling the neutralizing requirements (Donnelly et al., 2003).

Liming has been implemented in North America and many European countries with some of the largest programs in Norway and Sweden (Clair and Hindar, 2005). The practice is still widespread in Europe despite reductions to some liming operations in Scandinavia as acid deposition has abated (Barlaup, 2004). For example, Sweden invested 3.8 billion SEK (approximately 0.4 billion Euros) on liming between 1983 and 2006 (Bostedt et al., 2010). Moreover, with the EU Water Framework Directive requiring member states to "protect, enhance and restore all bodies of surface water" to "good ecological status" (EU, 2000), there is the possibility that liming might be advocated through 'programmes of measures'.

For all the above reasons, it is timely to assemble the best evidence about liming effects to guide future applications and policy. While several long-term experiments have been carried out (e.g. Ormerod and Durance, 2009), there has previously been no systematic review appraising whether liming effectively restores fish and invertebrate populations in acidified rivers. In this paper, we provide such a systematic review, aiming to source, analyse and summarise the best available data. Specifically, we posed the question: "What is the impact of liming streams and rivers on the abundance and richness of fish and invertebrates?"

2. Materials and methods

2.1. Search for studies

A systematic review methodology was employed following standard guidelines (CEE, 2010). An a-priori protocol was completed and deposited in the Collaboration for Environmental Evidence Library (Mant et al., 2010). A systematic search for papers relevant to the question was then carried out using terms relevant to the focal ecosystem (i.e. streams/rivers), the biota (i.e. fish/invertebrates) and the intervention (liming). For each category, different variations of the terms were used in order to capture all relevant papers (Table 1). The search was conducted within ten databases including the Web of Knowledge and Scopus (Mant et al., 2011). Wherever the search engine allowed it, all search terms were used simultaneously. Terms within categories were linked with the Boolean operator 'OR', and terms between categories were linked with the Boolean operator 'AND' (Mant et al., 2011). No time, language or document type restrictions were applied. The use of English search terms could have biased the findings against papers in other languages. However, any such bias will have been reduced due to non-English language papers often still providing an English abstract and/or title.

Table 1
The search terms used to retrieve relevant papers, "*" denotes wildcard.

Population – ecological	Stream, river, catchment, brook, creek, burn, fluvial, source area, gravel.
Population–- biota	Fish* (includes fishes, fishery etc.), salmo*, trout, macroinvertebrate*, invert*, macrofauna, meiofauna, insect*, ephemeroptera, plecoptera, trichoptera, mollus*, crustacea*, microcrustacea*, bivalve*, gastropod, zooplankton, coleopteran, chironomid.
Intervention	Liming, lime*, chalk*, calcium carbonate, dolomite.

To find additional reports not retrieved by the database search, general web searches were conducted along with searches of the websites of relevant organisations including each of the Scandinavian, the US and the UK environment agencies (Mant et al., 2011). Bibliographies of material included were searched further for relevant references. Although review articles do not normally contain primary data, they were searched for any primary studies. No geographic restriction was applied to this review.

2.2. Study inclusion

Articles were assessed by their title, abstract then full text to identify those most relevant to the review using specific criteria. They were required to investigate change in abundance, density or richness of fish or invertebrates in any stream, river, or catchment where calcium carbonate (or dolomite) had been added to ameliorate the effects of anthropogenic acidification. Separating natural from anthropogenic effects on surface-water pH can be challenging, but relevant studies were those where liming was carried out to mitigate acidification that was assumed to be of human origin. Liming to mitigate acid mine drainage was not included. No particular method of liming was excluded. All primary studies that compared both limed and un-limed subjects were included, i.e. those which compared a limed river to the condition before liming or to a non-limed control (or both). At each stage, if there was insufficient information to exclude an article it was retained until the next stage. In order to assess and limit the effects of between-reviewer differences in determining relevance, two reviewers applied the inclusion criteria to 200 articles (over 20%) at the start of the abstract filtering stage. Analysis of agreement between the two was reasonable based on a kappa statistic of 0.6 (Edwards et al., 2002). Studies were excluded from the meta-analysis if relevant data could not be extracted due to incomplete reporting, lack of appropriate controls or multiple interventions being applied at the same time (6 articles). Additionally, for each river studied, the impact of liming was only recorded once for each outcome of interest, excluding 33 articles from analysis due to overlap in reported data.

Thirty-three relevant articles where included in the analysis, plus the main survey of the Norwegian environment agency (Direktoratet for naturforvaltning), and the main dataset of the Swedish environment agency (Naturvårdsverket). In total these 33 articles and 2 datasets covered 47 studies, 19 of which were rivers in the Norwegian survey and one of which was the main Swedish study that covered 18 limed rivers and 8 acid control rivers; details of all studies are given in Mant et al. (2011). Of the main 28 studies not in the Norwegian survey the majority (15) were on single rivers or streams and only three (all from Sweden) were on 10 or more rivers or streams. The studies included lake liming ($n = 4$ studies), catchment liming ($n = 6$), point applications into rivers ($n = 9$) and continuous dosing into rivers ($n = 9$). There were also 19 studies in which the liming method was unclear or multiple methods were used in different or the same river. In total there were 33 studies on fish and 27 studies on invertebrates, though in several both groups were assessed.

2.3. Data extraction and synthesis

All 47 studies included were appraised critically according to their study design and quality. Well-conducted studies of high quality have less potential for bias than their poorer counterparts. The presence of control and base-line data was recorded along with the level of replication, how the treatments and controls were allocated and the presence of confounding factors. Study outcomes were also recorded. Data on changes in invertebrate and fish abundance and species richness were extracted. Data on acid sensitive invertebrates, as defined by the study author, were also extracted. The impact of liming was calculated for each outcome (fish, invertebrates, acid sensitive invertebrates, richness and abundance) as the log ratio of limed to unlimed sites. The raw mean difference could not be used because units varied among studies. For fish population estimates units included density estimates of number of adult fish per 100 m^2 or number of fry and par per 100 m^2, fish biomass in kg/ha and fish biomass in total kg caught per year.

Meta-analyses were carried out on the extracted effect sizes using the *R* package 'metafor' (Viechtbauer, 2010). Random effects meta-analyses, weighting by inverse variance, were carried out using the DerSimonian–Laird estimator method. The weighted mean effects, confidence in the mean effect and prediction interval were calculated for each of the variables analysed. The confidence interval for the mean effect was the interval in which we were 95% confident that the mean effect occurred (i.e. the average effect across multiple studies). As several factors varied between studies, including physical, chemical and ecological characteristics of the rivers, not all liming operations will have produced the mean effect; the study-specific "true effect" varied between studies. Hence, the prediction interval was also calculated: the interval giving the distribution of effects across studies/liming operations/rivers, within which 95% of true effects were predicted to occur. Additionally, the percentage of true effects predicted to be negative was calculated for fish abundance, assuming a normal distribution of true effects of the log ratio.

Where there were sufficient data, the impacts of potential effect modifiers were tested including type of study, type of liming, presence of stocking and the mean