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# The response of stream-dwelling fish to liming

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The fish fauna in 22 limed and seven unlimed small streams was monitored using yearly electrofishing to assess the effects of liming on species occurrence and abundance. The liming techniques were divided into three main methods, lake liming, doser liming and wetland liming, to evaluate whether different strategies had different effects on the fish fauna. The predominant species at the investigated stations were salmonids, mainly brown trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*). Other species generally occurred in low numbers. The average number of fish species did not increase significantly after liming, which was probably due to recolonization difficulties caused by the frequent occurrence of migration obstacles in the streams. After liming the density of salmonids increased significantly, irrespective of the liming method. Other fish species showed no general increase, but in individual streams significant increases of European minnow (*Phoxinus phoxinus*) and bullhead (*Cottus gobio*) occurred. Some unlimed streams had acid spates with a pH below 6, which immediately lowered the numbers of salmonid parr. Other unlimed streams lost fish species progressively due to increasing acidification. pH, and probably increased levels of metals, were the major factors regulating the fish fauna. Few examples of biotic interactions were observed, but with an increase of Atlantic salmon parr after liming, brown trout abundances decreased in three streams.

## INTRODUCTION

Lake liming has been proved to be a successful method for mitigation of the negative impact of anthropogenic acidification on fresh waters (Olem, 1990). The response to liming of fish communities is mainly determined by abiotic factors, such as acidification status and habitat heterogeneity, although species interactions have been shown to influence the fish fauna after liming (Nyberg *et al.*, 1986; Appelberg & Degerman, 1991). Owing to large and rapid fluctuations in water flow, small running waters are often more difficult to lime. The response of the fish community in streams should be more dependent on abiotic factors, as biota in small running waters are considered to be highly dependent on their environment (Vannote *et al.*, 1980).

In Sweden, the liming of acidified lakes with fine-grained limestone has been carried out on a large scale since 1977 (Nyberg & Thörnelöf, 1988). Several studies have reported the effects on water chemistry and on various groups of biota (e.g. Eriksson *et al.*, 1983; Raddum *et al.*, 1984; Hörnström & Erkström, 1986; Nyberg *et al.*, 1986) or on their combined effects on the ecosystem (Dickson, 1988*a*; Appelberg *et al.*, 1990*a*).

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Running waters are often a main target for many liming operations, since they represent the breeding grounds for acid-sensitive salmonid species. Although an overall positive effect on the abundance of salmonids after liming of acidified running waters has been reported earlier (Nyberg *et al.*, 1986; Appelberg *et al.*, 1990b), the effect of liming on other stream dwelling species has not been studied to the same extent. Nor has any study evaluated the response of fish to different limiting strategies.

Liming of running waters is carried out in upstream lakes (if any), by wetland liming and by lime dosers. The value of the latter method has been questioned, as toxic effects of various metal fractions have been found immediately downstream (<200 m) (Lessmark *et al.*, 1986). Wetland liming is highly controversial since land vegetation, especially *Sphagnum* mosses are affected and sometimes killed (Aronsson, 1990). It is not known if these problems with toxic metal fractions and the mineralization of vegetation, eventually causing increased transportation of nutrients and organic matter, will affect fish after liming in such a way that they must be taken into consideration when determining liming strategy.

The chemical objective of the Swedish liming operations is to keep the pH above 6, since it is considered that biota in general is harmed at lower pHs (Engblom

& Lingdell, 1983; Appelberg, 1987; Hultberg, 1988; Nyberg & Thönelöf, 1988; Degerman & Nyberg, 1989).

The aim of this present paper is to assess the effect of liming on fish in streams, and to study the effects of different liming methods. It is hypothesized that the response of the fish community should be mainly a direct effect of acidification status and hydrologic events, while biotic interactions should play a minor role.

## MATERIALS AND METHODS

### Streams studied

In total, 22 limed streams and seven unlimed streams in southern and central Sweden have been included in the study (Fig. 1). In each stream, electrofishing was carried out at one to seven stations. The average width and depth of the streams at the stations was 5·1 m and 0·28 m, respectively. The catchment areas upstream varied from 1 to 1321 km², and the proportion of the catchment area occupied by lakes averaged 4·4%. The bottom substrate was dominated by stones at 46% of the stations, and by finer substrate (silt, sand, pebbles <10 cm) at 31·3% of the stations. The average annual water flow was generally within 0·1–0·6 $m^3 s^{-1}$. Only six streams had flows higher than 1 $m^3 s^{-1}$.

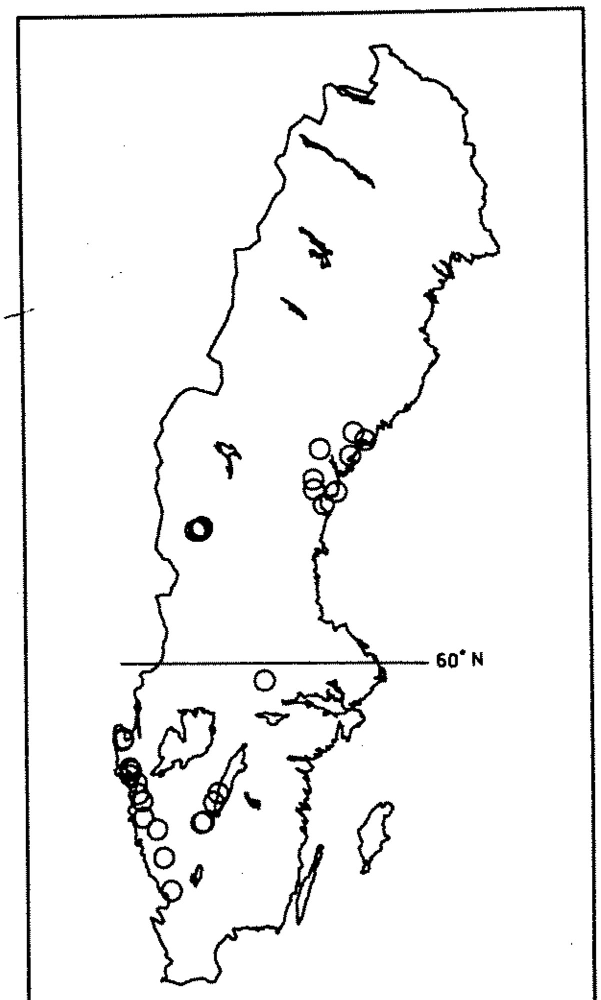


**Fig. 1.** Map of Sweden indicating the streams studied (circles).

### Water chemistry

Water chemistry was sampled 2–12 times a year at 1–5 stations in the streams studied. All analyses were performed according to Swedish standard methods (SIS, 1981). Variables included were pH, alkalinity, conductivity and water colour.

### Liming operations

The streams were characterized according to the main liming method used; lake liming, wetland liming, or lime doser liming. Lake liming was the most common strategy, being the main method in 11 (50%) of the limed streams (Table 1). Lake liming was undertaken either as liming on the water surface during the ice-free season, or as liming on ice during winter (three streams). In six of the streams, wetland liming was the only liming method. However, during the 1980s wetland liming became a common practice for most liming targets. Also, in the late 1980s wetland liming has become a common supplement to lake liming (Table 1). Lime dosers were the main lime distributors in five of the streams, and were used as a supplementary method in another two streams. The lowest found pre-treatment pH was 3·8–6·0 in the limed streams (Table 1). While approximately half of the streams treated with lake or doser liming had a lowest pre-treatment pH above 5, only one out of six streams treated with wetland liming had a lowest pH before liming above 5. This makes the comparison of dominating liming methods difficult.

The first liming operations started in 1974–75 in two streams (lake limings), and 15 other liming operations started in 1977–1984. Five streams have recently been added to the liming programme (1985–1987). This means that there has been a follow-up period of 11–15 years for the first limings, but only 3–4 years for the most recent. The doses of grained limestone used have varied between projects, but in general doses recommended by the National Environmental Protection Agency (Thörnelöf & Degerman, 1991) were used.

### Electrofishing

Electrofishing was carried out, quantitatively at all stations, by successive removals of fish (Bohlin, 1984, Bohlin *et al.*, 1984). After counting and weighing the fish, all fish were released back into the stream. The current used was 400–1000 V (DC). The electrofishing stations were chosen in shallow, hard bottom areas, suitable as breeding grounds for salmonids. The stations chosen represent parts of the rivers with an average water velocity over 0·2 m $s^{-1}$. Electrofishing was

**Table 1. Start of liming, predominant method, supplemental method, predominant fish species, their main migratory behaviour, the catchment area and the lowest recorded pH before liming of the 22 lined streams and the seven unlimed streams studied**

| Stream | Liming started | Predominant method | Supplementary method | Predominant species | Catchment area ($km^2$) | Lowest pre-pH |
|---|---|---|---|---|---|---|
| Djursvasslan | 1983 | Wetland | — | Trout (stream) | 30 | 4·0 |
| Hammarbäcken | 1983 | Wetland | — | Trout (stream) | 6 | 4·5 |
| Ådalsån | 1987 | Wetland | Lake | Trout (stream) | 588 | 4·9 |
| Gagnån | 1985 | Wetland | — | Trout (lake) | 32 | 4·4 |
| Brodalsbäcken | 1981 | Wetland | Doser | Trout (sea) | 16 | 4·0 |
| Veån | 1986 | Wetland | — | Trout (sea) | 9 | 5·8 |
| Grissleån | 1985 | Lake | Wetland 1989 | Trout (stream) | 25 | 4·4 |
| Skuggälven | 1974 | Lake | Wetland 1975 | Trout (lake) | 11 | 4·6 |
| Ekelidbäcken | 1975 | Lake | Wetland 1975 | Trout (lake) | 4 | 4·8 |
| Taskeå | 1980 | Lake | — | Trout (sea) | 30 | 5·5 |
| Resteån | 1981 | Lake | Wetland 1989 | Trout (sea) | 16 | 5·4 |
| Grössbyån | 1977 | Lake | Wetland 1984 | Trout (lake) | 17 | 3·8 |
| Solbergsån | 1982 | Lake | Wetland 1989 | Trout (sea) | 20 | 4·3 |
| Haraldsjöån | 1983 | Lake | Doser 1984– | Trout (stream) | 52 | 5·5 |
| Bjässjöån | 1984 | Lake | — | Trout (stream) | 56 | 5·2 |
| Forsån | 1987 | Lake | — | Trout (stream) | 43 | 5·5 |
| Strinneån | 1984 | Lake | — | Trout (sea) | 65 | 6·0 |
| Nykyrkebäcken | 1984 | Doser | Wetland 1988 | Trout (lake) | 6 | 4·4 |
| Surtan | 1984 | Doser | Lake 1981 | Trout/Salmon | 210 | 5·0 |
| Högvadsån | 1978 | Doser | Lake 1978– | Salmon (sea) | 476 | 4·5 |
| Fylleån | 1982 | Doser | Lake 1982– | Salmon (sea) | 401 | 5·2 |
| Idbyån | 1984 | Doser | — | Trout (sea) | 222 | 6·0 |
| Örekilsälven | — | Unlimed | | Salmon (sea) | 1321 | 6·1 |
| Skredsviksån | — | Unlimed | | Trout (sea) | 30 | 6·4 |
| Helgaboån | — | Unlimed | | Trout (stream) | 9 | 5·4 |
| Glötån | — | Unlimed | | Trout (stream) | 62 | 5·0 |
| Häggingbäck | — | Unlimed | | Trout (stream) | 14 | 4·7 |
| Bänkåsbäcken | — | Unlimed | | Trout (sea) | 5 | 5·1 |
| Byån | — | Unlimed | | Trout (sea) | 40 | 5·9 |

generally carried out in August–September, each or every other year. In total, 447 electrofishing occasions at 78 stations have been included in the study.

### Statistical analysis

Fish abundance has been normalized using $\log_{10}(x + 1)$ transformation. Also, all physical and chemical variables (excluding pH) have been normalized using $\log_{10}$. The stations were divided into one of three major liming methods. In addition, the salmonid fish at each station were classified into three categories; stream dwelling, lake migrating and sea migrating (Table 1).

Data before and after liming have been analysed in two main ways. Firstly, all observations before and after liming have been used. These have been analysed using multivariate linear regression and ANOVA. Secondly, the average value before and after for each station has been used. This has usually been analysed using the Wilcoxon matched pair rank test.

Although fish sampling was supposed to take place at the end of the summer, some stations were sampled so late in the season that temperature/season significantly affected the catch. This was noted for brown trout (*Salmo trutta*) and European minnow (*Phoxinus phoxinus*) in one mountain stream. In one coastal stream in the east of Sweden, there was a significant correlation between the catch of crayfish (*Astacus astacus*) and the water temperature, and in a nearby stream the same was found for bullhead (*Cottus gobio*) and water temperature. Comparing all streams, however, the average temperature in each stream at sampling did not differ significantly before and after liming (Wilcoxon $P = 0{\cdot}23$).

## RESULTS

### Water chemistry

The average annual pH, as well as the lowest measured pH and alkalinity over a year, increased significantly after liming (ANOVA, $P < 0{\cdot}05$). However, the chemical objective of the liming operations, to avoid a pH below 6, was achieved in only half of the observed years after liming (Table 2). Although no difference was observed between the different liming methods, it was obvious that pH downstream of lime dosers was seldom extremely low. In spite of comparatively low pre-treatment pH in the streams where wetland liming was carried out, the effect on the alkalinity was slightly better than with the other two methods used.

**Table 2. Number of water sampling occasions after liming where the annual lowest pH value was below 5 and 6, and the alkalinity was below 0·1 meq litre⁻¹, depending on main liming method**

| | Wetland liming (%) | Lime doser (%) | Lake liming (%) |
|---|---|---|---|
| Lowest pH < 5·0 | 15·4 | 2·2 | 11·8 |
| Lowest pH < 6·0 | 38·5 | 50·6 | 51·6 |
| Lowest Alkalinity < 0·1 meq litre⁻¹ | 46·2 | 57·8 | 53·9 |

Only in three projects was a pH of below 6 not detected after the first liming. Typically, these three projects represented each of the three main methods of liming. Two of these projects were only slightly acidified, infrequently exposed to acid spates. The third stream, River Fylleån, was part of a large liming programme mainly involving two lime dosers, but also subjected to additional liming within the catchment (Table 1).

Conductivity increased significantly after lake and doser liming (ANOVA, $P < 0.005$ and $P < 0.05$), while no significant change was recorded after wetland liming. Water colour remain unchanged after liming, irrespective of method. There was a significantly lower water colour in streams where lake liming had been conducted, as compared with the other two methods (58 vs. 87 mg Pt litre⁻¹, ANOVA, $P < 0.001$). This is to be expected, since lake liming is undertaken if lakes are available, and lakes act as sinks for humic materials.

For liming projects that had been running for more than six years, annual mean pH and lowest measured pH over a year did not fall below 6, i.e. liming performance improved with time, irrespective of dominating liming method.

## Number of fish species

The number of species, which varied between one and eight per sampling occasion, was not significantly different before liming, compared with after liming, mean values being 2·81 and 2·96, respectively (Wilcoxon, $P = 0.57$). The number of species was positively dependent on the cross-sectional area of the station, and the annual mean pH at the station (multiple, linear regression, $r^2 = 0.46$, $P < 0.001$). The lack of change in number of species after liming may be due to the fact that migration obstacles between the sampled station and lakes upstream occurred at 57% of the stations, and between the stations and downstream lakes at 32%. Thus, the possibility for recolonization was severely reduced.

The average number of species in the unlimed streams was 5·0, significantly higher than the value in limed streams (ANOVA, $P < 0.001$, with cross-sectional area as covariate). The average pH did not differ significantly (average 6·52 and 6·34, respectively).

## Fish abundance

The overall abundance of fish and crayfish increased significantly after liming (Wilcoxon, $P < 0.007$). The main part of the increase could be attributed to an increase in the number of salmonids. If they were excluded, no overall increase in fish abundance was recorded. However, in some streams, species other than salmonids increased significantly after liming.

## Atlantic salmon (*Salmo salar*)

Atlantic salmon, which was found in 10 limed streams, predominated only at seven stations in three streams. In all three streams, salmon increased significantly after liming (ANOVA, $P < 0.05$, Fig. 2). This increase was positively correlated to the increase in pH, whereas no correlation was found with water temperature or water discharge. Salmon was also the dominant species in the unlimed, non-acid, River Örekilsälven, where no correlation between salmon parr abundance and time or water chemistry was found. The importance of pH for the development of salmon may be exemplified by the development of salmon in the limed River Fylleån (Fig. 3). Not until the lowest annual measured pH exceeded 6 did the Atlantic salmon population increase. This population was considered to be severely threatened by acidification before liming, and on several occasions during the 1980s no parr were caught during electrofishing.

## Sea-run brown trout

Sea migrating brown trout were caught in 12 limed streams, and in four unlimed streams. The liming

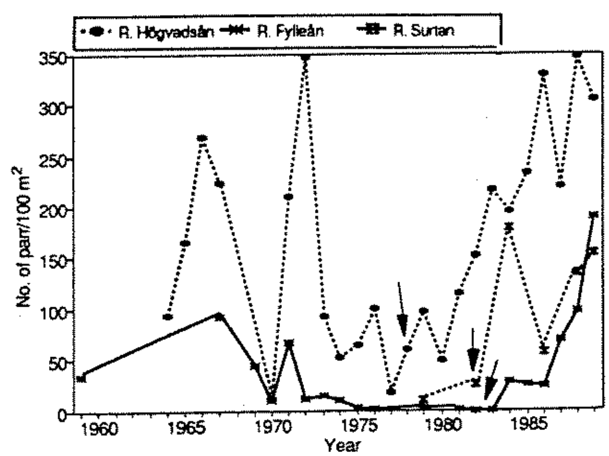


**Fig. 2.** Abundance (number/100 m²) of Atlantic salmon parr in three streams on the west coast of Sweden. Arrows indicate the start of liming. The line consists of averages of three, two and two stations per stream.

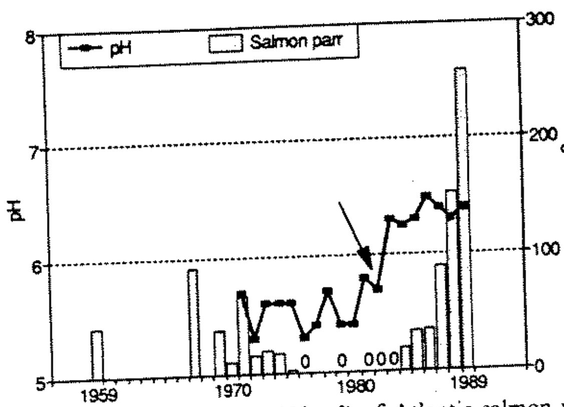


**Fig. 3.** Abundance (number/100 m²) of Atlantic salmon parr at station Tolarp in River Fylleån and the lowest measured pH each year. Liming started in 1982 (indicated by arrow).

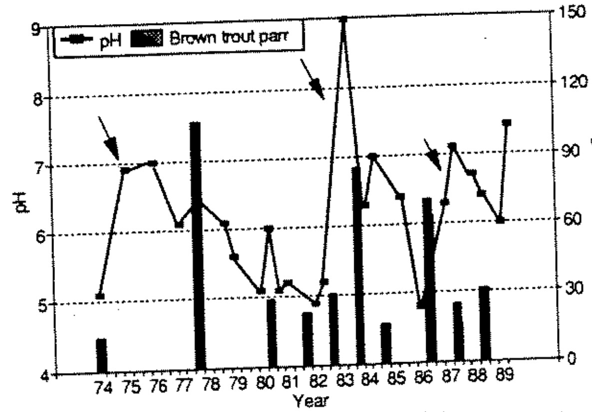


**Fig. 5.** Abundance (number/100 m²) of brown trout parr (lake-migrating) in River Ekelidbäcken in relation to the pH in the lake immediately upstream (line). Liming indicated by arrows. Yearling parr (0+) black portion of the bars.

methods used were either mainly lime dosers or lake liming. Both methods were successful, as indicated by an overall increase of brown trout abundance before liming, as compared with after liming (ANOVA, $P < 0{\cdot}01$). As a strong indication of competition between brown trout and Atlantic salmon, the former species decreased in abundance in the three limed streams where the Atlantic salmon regained its strength (Fig. 4).

In the unlimed streams, no significant changes in the abundance of fish with time were detected (linear regression). In these streams pH was above 6 until spring 1986, when a sudden pH drop was noted in two of the streams. As a consequence, the number of yearlings was low that year, although both populations soon recovered.

## Lake-run brown trout

Six limed streams were inhabited by lake-migrating brown trout at nine stations. No unlimed streams were sampled. In the streams Skuggälven and Ekelidbäcken, lake liming operations were undertaken in 1974–75 (Table 1). The lakes were deliberately allowed to re-acidify before the second and third liming operations, which resulted in drastic fluctuations of the abundance of parr (Fig. 5). The abundance of parr was significantly correlated with pH and alkalinity (linear regression, $P < 0{\cdot}05$).

## Stream-dwelling brown trout

Non-migratory populations of brown trout were found at 31 stations in 12 limed streams. Liming of lakes within the catchment resulted in a significant increase of the abundance of brown trout (parr and older fish) (ANOVA, $P < 0{\cdot}05$). It was also noted that the positive effect on fish abundance decreased with the distance from the nearest limed upstream lake, and increased with an increased proportion of lakes in the catchment. In streams where wetland liming (three streams), or doser liming (two streams), were the predominant methods, the densities of brown trout increased. However, the overall changes were not significant, although significant increases were recorded in individual streams.

Three unlimed streams were inhabited by resident brown trout when the studies started. In one mountain stream all fish disappeared after a severe acid spate in

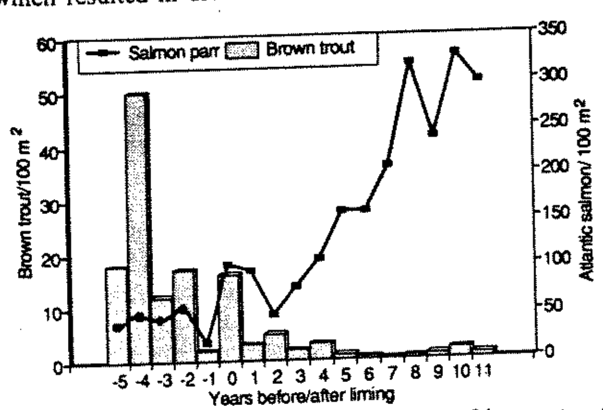


**Fig. 4.** Average abundance (number/100 m²) of brown trout (bars) and Atlantic salmon parr (line) coexisting in three lime streams (see Fig. 1) before and after liming.

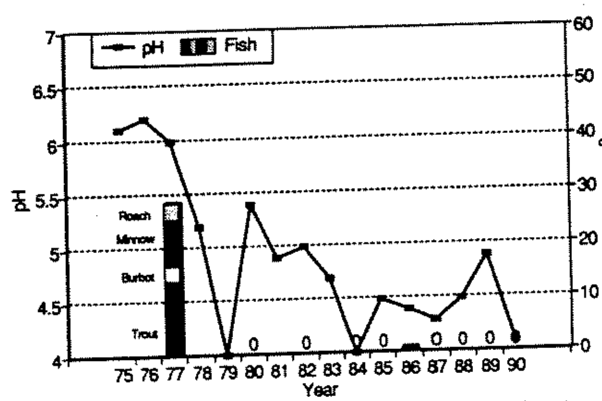


**Fig. 6.** The abundance (number/100 m²) of fish (bars) and the lowest annual pH (line) in the unlimed stream Häggingbäcken subjected to severe acidification. 0 indicates that no fish were found.

1977. This coincided with high deposition of unusually acid snow and consequent low pH in the stream (Fig. 6). Another nearby unlimed stream had declining trout numbers from 1984 to 1990 (linear regression, $P < 0{\cdot}05$). In this case the decrease in abundance was also correlated with decreasing pH. In the third unlimed stream, R. Helgaboån in southern Sweden, the population of brown trout also decreased with time (linear regression, $P < 0{\cdot}01$) and pH (not significant).

**Non-salmonid species**

In general, the abundance of species other than salmonids was low. Mean abundance for all species was 61·6 per 100 $m^2$. Brown trout constituted 71% of this figure. Atlantic salmon 19%, and other species 10% (6·2 individuals per 100 $m^2$). In five streams, bullhead, together with brown trout, were the predominant species. Four of these streams were limed, and the abundance of bullhead increased with time (linear regression, $P < 0{\cdot}01$) together with increased abundance of brown trout. In the unlimed stream, the lowest recorded pH was 5·9, and no trends in the abundance of fish was observed.

Burbot (*Lota lota*) occurred in 11 streams at densities between 0·1–8 per 100 $m^2$. In the limed streams with burbot there was an insignificant increase in abundance (average 0·9 before vs. 2·0 per 100 $m^2$ after liming). In two of the unlimed mountain streams with resident brown trout (see above), burbot declined significantly or disappeared from the streams during acidification (Fig. 5). European minnow was found in 13 streams at densities of between 0·4 and 183 per 100 $m^2$ at different stations. The overall abundance of this species was only correlated with water temperature (linear regression, $P < 0{\cdot}05$). The species is known to be acid-sensitive, and it disappeared during acidification in three streams (e.g. Fig. 5). It recolonized stations in some streams after liming. In Rivers Högvadsån and Surtan, the increase at certain stations was significant (linear regression of density versus alkalinity after liming, $P < 0{\cdot}01$ and ANOVA of the density before vs. after liming, $P = 0{\cdot}015$).

## DISCUSSION

The choice of sampling stations in hard bottom areas partly explains why the abundance of fish species other than salmonids was generally low. Stretches with slow flowing water were severely under-represented. However, studies by Degerman *et al.* (1985) show that in these small streams the number of species is low and does not differ between hard and soft bottom substrates. The same species were found on both types of substratum, and the frequency of certain species (brown trout, Atlantic salmon, eel, European minnow, perch, northern pike, other species taken as a group) did not differ between the substrates (Degerman *et al.*, 1985). The only difference was noted for roach. Extensive studies of two of the streams included in this study (Rivers Skredsviksån and Taskeå) revealed that the surface areas of the hard bottoms, classified as mainly gravel or coarser bottom substrate, were 77% and 94%, respectively (Thörnelöf, 1983).

The results clearly demonstrate that liming increases the abundance of fish in small acidified streams. The abundance of species present increased, whereas the number of species did not. The number of species was dependent on habitat heterogeneity and the average pH of the stream. The multiple regression indicated that an average of 1·6 species was regained when pH increased from 5·5 to 6·5. Since unlimed streams held more species, it is suggested that a loss of species has occurred, and that this loss has not been compensated for by liming, except in certain streams. Recolonization should be a product of acidification status and migration obstacles. Even if the low pH is counteracted by liming, the high proportion of migration obstacles, usually dams, calls for active reintroduction if the fish communities in several rivers are going to be fully restored.

The main liming methods were compared by simply using achieved water quality and abundance of fish. Probably differences at a more detailed level are to be expected for water chemistry. For instance, wetland liming might keep toxic metals in the surrounding soils instead of letting them enter the water. However, no variations in the effect on fish of different liming methods could be seen. Instead, the pH achieved in the stream and the duration of the liming were of importance. Re-acidification rapidly led to lowered abundance (Fig. 5). As most projects were subjected to occasional pH values below 6, the chemical objective of the limings was not achieved. However, performance improved with time as lime doses or strategies were slightly altered.

Although several of the unlimed rivers were chosen as unacidified reference streams, acid spates occurred in some of them in the 1980s, resulting in significant losses of fish. Acid spates occurred during snow melt even in streams where the average alkalinity was above 0·20–0·25 meq $litre^{-1}$ which has previously been pointed out (Degerman *et al.*, 1985; Appelberg *et al.*, 1990*b*). The results imply that a large proportion of running water in Sweden might be subject to the negative effects of the acidification on fish. Dickson (1988*b*) has estimated that running water in a quarter of the country area is negatively affected by acid run-off.

The response of certain species to liming was generally seen as an increase with pH, alkalinity or just time after liming. A general observation was that both brown trout and, for instance, bullhead or European minnow, increased at the same station. Significant increases in Atlantic salmon and crayfish have also previously been noted at the same stations after liming (Appelberg & Odelström, 1990). This indicates that the fauna was under severe stress, and that pH, and possibly pH-related increased levels of toxic metal fractions, were the major regulating factors for population abundances. However, the decrease of brown trout in streams where Atlantic salmon parr increased (Fig. 4), is probably an effect of competition. During the acid stage, brown trout, being less acid-sensitive, could expand in stretches normally inhabited by Atlantic salmon parr. After the improvement of water quality, Atlantic salmon regained its strength, and brown trout decreased. These observations indicate that biotic interactions do play a role in the fish community after liming.

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