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Effects of liming on fisheries

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Liming measures for treating acidified surface waters have been carried out in Sweden for a trial period with the aid of Government grants. The aim was to study whether lime treatment was a possible method of protecting waters of special value for fisheries, nature conservation or recreational uses. In all waters where liming resulted in a sufficient and durable pH increase, the fish started to reproduce again, even if the populations were composed of very few and old individuals at the time of treatment. In waters with weak recruitment one or more rich year classes appeared after liming. Restocking of extinct populations of Arctic char (*Salvelinus alpinus*) and brown trout (*Salmo trutta*) after lime treatment resulted in self-reproducing populations. In populations with intact recruitment, individual growth rates were generally not affected but in weak populations with fast individual growth rates, growth rates decreased after liming. Liming of acidic inlet waters that have high concentrations of aluminium led to heavy mortality in fish farms as did acid spring runoff flowing into a lime treated lake. Rainbow trout introduced into lakes shortly after liming also experienced high mortality. Lime treatment can never be a definite cure for acidified waters, but may protect fish populations in lakes with long turnover times in areas with relatively low acid deposition. Periods of high runoff in streams, rivers and lakes with short turnover times were difficult to treat with lime. In areas with a high acid load and acidified watersheds, liming of lakes and running waters will not prevent acid groundwater with elevated concentrations of toxic metals from entering surface waters.

Introduction

In Europe, liming has been used for a long time as a method of improving productivity and for eliminating various fish parasites in fish ponds (Nees 1946). Different kinds of lime products have also been used in order to try and raise the growth and production of fish in naturally acid and coloured soft-water lakes in Sweden and North America (Waters & Ball 1957). As early as the 1920s, acid waters during periods of high runoff caused mortality in Atlantic salmon (*Salmo salar*) in Norwegian hatcheries, and lime was used to improve the survival of eggs and larvae (Leivestad *et al.* 1976).

In the mid-1970s the degree of acidification in Swedish fresh waters was so severe that the Government initiated and provided grants for a trial period of liming in surface waters. The aim was to study whether liming was a possible means of protecting waters of special value for fisheries, nature conservation or recreational uses. During the years 1976–1981 about 48 million Swedish Crowns were spent on liming measures in surface waters with a total drainage area of 11400 km² and about 8 million Crowns were spent on various follow-up studies (Fiskeristyrelsen & Statens Naturvårdsverk 1981). During the trial period, special attention was paid to effects on fisheries and ecological effects in general (Eriksson *et al.* 1982). Special measures were taken to observe any possible negative effects of liming.

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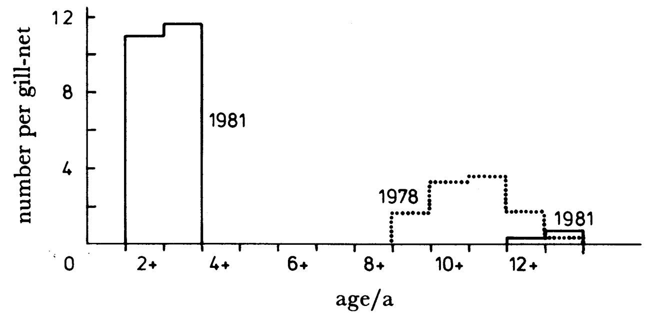

Figure 1. Age composition of the roach (*Rutilus rutilus*) population in Lake Mörtsjön in 1978 and 1981 (Eriksson *et al.* 1983).

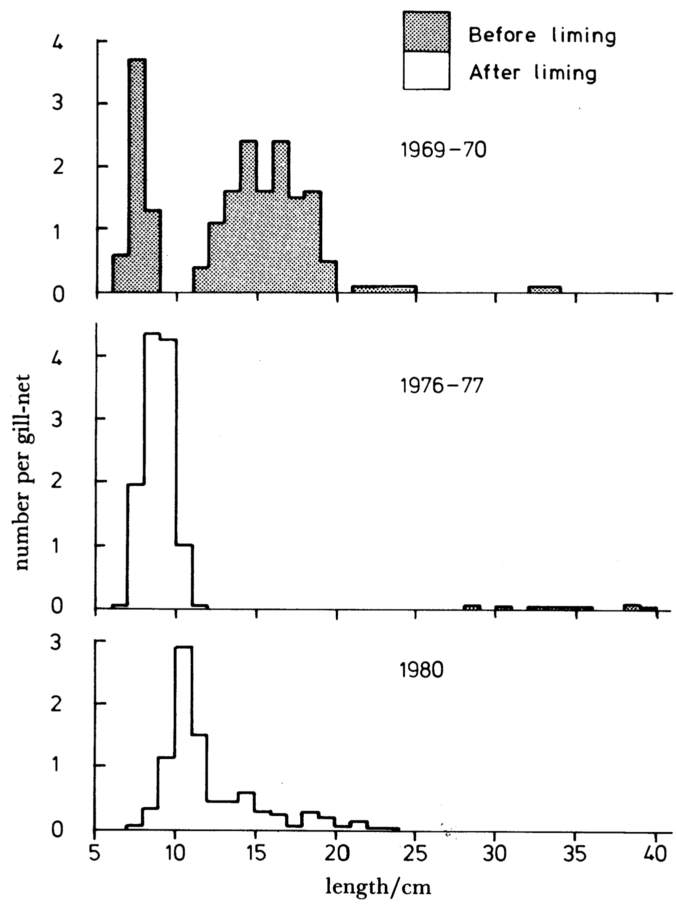

Figure 2. Catch of perch (*Perca fluviatilis*) and length distribution of the population in Lake V. Skälsjön 1969–1970 (19.3 perch per gill-net), 1976–1977 (11.6 young and 0.3 old perch per gill-net in unshaded and shaded region respectively) and 1980 (8.8 perch per gill-net) (Eriksson *et al.* 1982).

Effects on reproduction

The main reason for the reduction in numbers and extinction of fish populations in acidified waters is the mortality of eggs and in particular larvae, which seem to be the most sensitive life history stages (Daye & Garside 1979; Muniz 1981).

In all waters where liming resulted in a sufficient increase in pH, reproduction was successful, even if the remaining individuals were few in number and very old. Such a situation existed

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in the Lakes Mörtsjön and V. Skälsjön before treatment. In Lake Mörtsjön the youngest roach (*Rutilus rutilus*) caught in 1978 were nine years (9+) old and no reproduction had taken place since 1969. After lime treatment in 1977 the population reproduced again the following spring, and test fishing in 1981 yielded a large number of one (1+) and two (2+) year old roach (Eriksson *et al.* 1983) (figure 1). In Lake V. Skälsjön the perch (*Perca fluviatilis*) population was almost eliminated between 1970 and 1975, and the population consisted of 10 mature individuals. Thanks to a small treatment in 1975 these fish were able to produce offspring in 1976, before they were caught in gill-nets, and the population is now recovering (Eriksson *et al.* 1982) (figure 2).

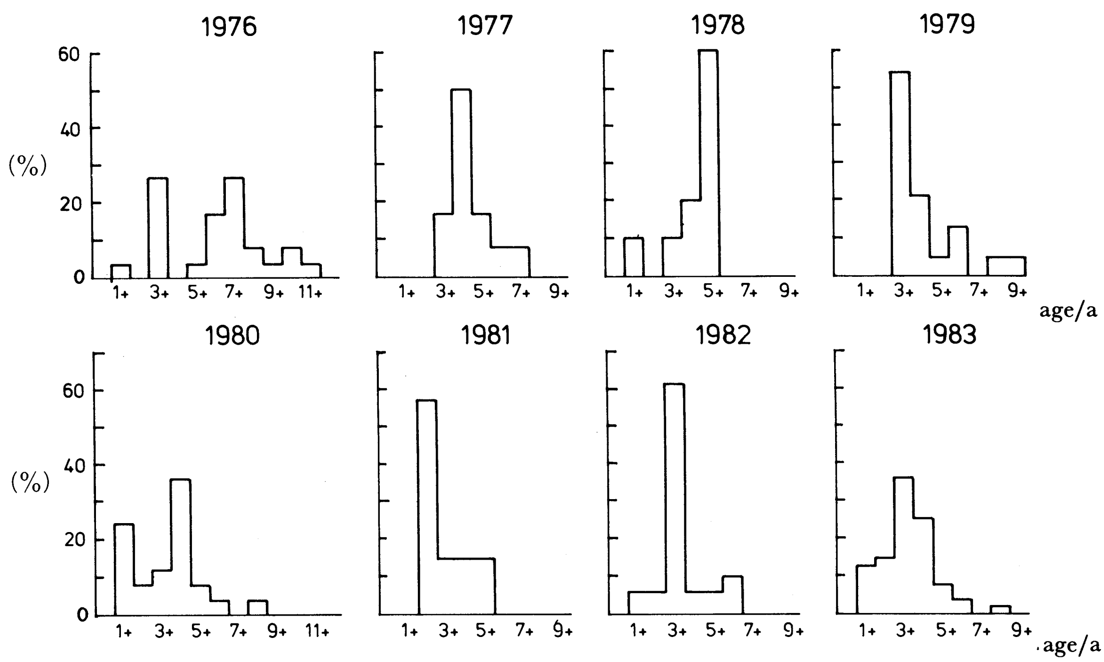

Figure 3. Relative age distribution of the catch of Arctic char (*Salvelinus alpinus*) in Lake Ö. Skälsjön caught in July and September 1976–1980, July 1981 and 1983 and September 1982 (Nyberg unpublished data).

In most of the lakes, the effects of acidification on reproduction were less serious at the time of liming. The population of Arctic char (*Salvelinus alpinus*) in Lake Ö. Skälsjön was made up of old individuals in 1976, but reproduction still occurred during certain favourable years. Lime treatment of the upstream lake in 1975 and on land areas around the lake in 1977 evidently produced favourable conditions for some new and rich year classes. These year classes were caught as three (3+) and four (4+) year olds in 1979 and 1980 and as two (2+) and three (3+) year olds in 1981 and 1982 respectively. Lime, added directly to the lake during winter 1980–1981, resulted in a steady increase in alkalinity and in 1983 the char population was dominated by relatively young fish (figure 3).

Lindström & Andersson (1981) found that liming in combination with the addition of calcium phosphate resulted in an extremely rich year class of char which seven years later still dominated the catch in an Arctic lake. In Nelson Lake in Canada liming resulted in the reproduction of reintroduced smallmouth bass (*Micropterus dolomieui*) (Keller *et al.* 1980; Yan & Dillon 1981) and in an increase of the lake trout (*Salvelinus namaycush*) population (Kelso & Gunn 1982). Gunn and Keller (1980, 1981) found that the survival of eggs and alevins of

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rainbow trout (*Salmo gairdneri*), lake trout and brook trout (*Salvelinus fontinalis*) improved when the eggs were incubated in crushed limestone.

Contrary to these results, Powell (1977) reported that two stocked fish species did not survive after the liming of two lakes near Sudbury, Canada. However, these lakes contained lethal concentrations of copper (Yan *et al.* 1979).

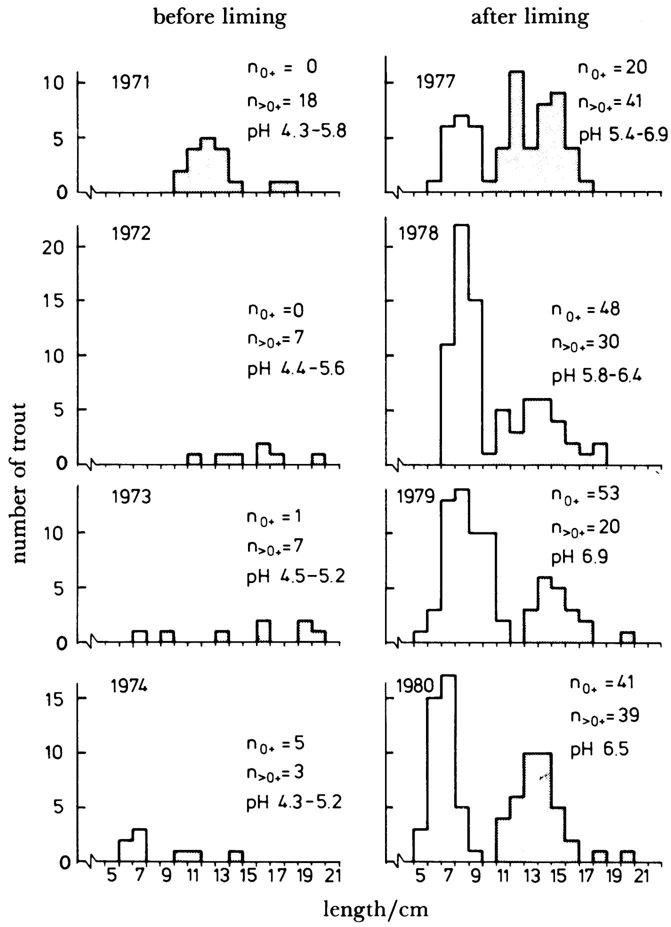

FIGURE 4. Catch of young sea trout (*Salmo trutta*) by electrofishing in the Tjöstelrödsån river before and after lime treatment (after Lundh 1981).

Populations of Atlantic salmon (*Salmo salar*) and, above all, sea-running trout (*Salmo trutta*) in many streams and rivers on the Swedish west coast have been seriously affected by acidification. One such small stream is the Tjöstelrödsån river, where the pH-value and the numbers of juvenile trout, and yearling trout in particular, were extremely low during the years 1971–1974. In 1975 the upstream lake was treated with lime and the pH-value increased in the stream; during 1977–1980 electrofishing yielded 20–53 yearlings and 20–41 older trout (figure 4) (Lundh 1981).

In another river, the Högvadsån river, a very important spawning ground for Atlantic salmon, the liming measures have not yet been completely successful. Figure 5 shows results from electrofishing at two locations (Ullared and Nydala) in the river during several years. The graph from Ullared in 1965 represents the situation before any effects of acidification were

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noted. During 1977 and 1978 one year (1+) olds were totally absent at both locations, despite the fact that yearlings were found the previous year. Low pH-values in combination with elevated levels of aluminium caused by heavy autumn and winter rains were assumed to have caused total mortality in the one year olds. The reason for the occurrence of a new year class every year was probably that the eggs or newly hatched alevins remained in the spawning gravel

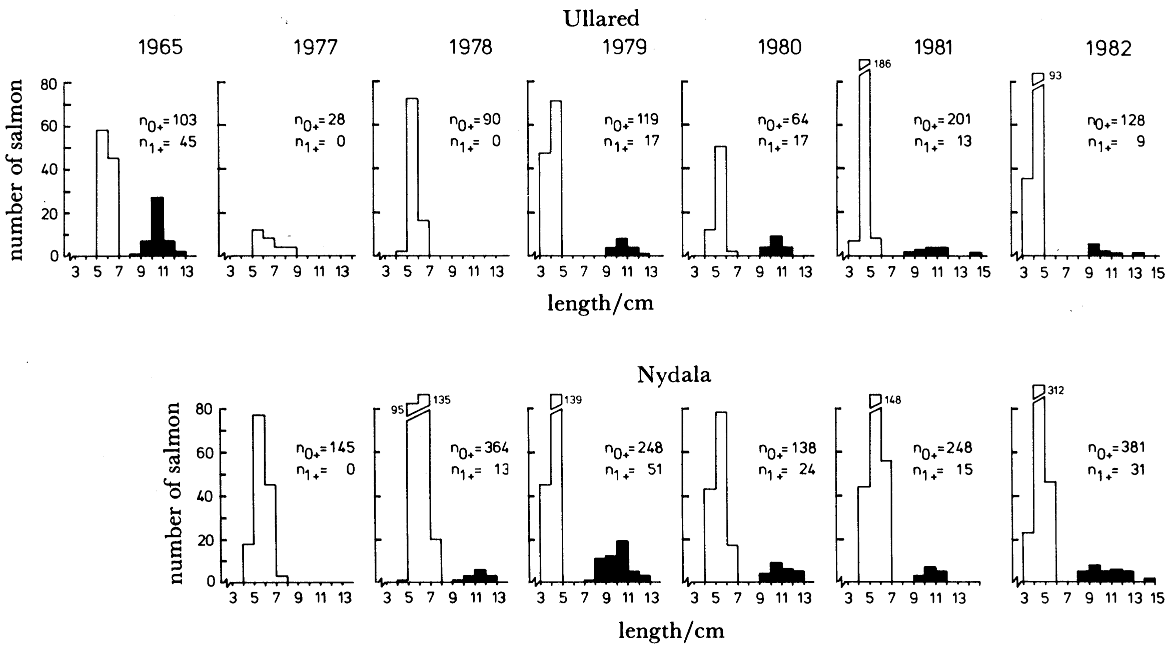

FIGURE 5. Catch of young Atlantic salmon (*Salmo salar*) at two locations in the Högvadsån river (after Edman 1983).

and were thus surrounded by water of better quality. It is also known that eggs are less sensitive to aluminium than young fish (Baker & Schofield 1980). Liming started in 1978 and one year olds started to appear again. Their numbers were, however, still fairly low in 1983 compared with pre-acidification levels. The low number of downstream migrating smolts is also verified by the catch in a stationary trap at Nydala. During the period 1959–1965 an average of about 5200 smolts migrated yearly, compared with about 1000 during 1980–1982 (Edman 1983). The reason for this may be a small number of spawners, but during heavy floods in the winter of 1980–81, yearling salmon incubated in cages showed very high mortality. The liming measures which cost about 2.5 million Swedish Crowns, were not able to create water of suitable quality at all times of the year.

In a number of lakes and rivers the resident fish populations had already been wiped out before liming measures were undertaken. In such waters, liming in combination with the reintroduction of fry, yearlings (Nyberg, unpublished data), one year olds (Lindström & Andersson 1981) or mature Arctic char (*Salvelinus alpinus*) (Andersson & Hultberg 1983), resulted in successful spawning. Hultberg & Alenäs (1981) also showed that the restocking of eggs, fry and mature adults of sea-running trout in a lime-treated stream resulted in the production of offspring.

The recovery or improvement of reproduction of fish after lime treatment probably depends on a reduction in the toxicity of the water. An increase in the pH, i.e. a decrease in the

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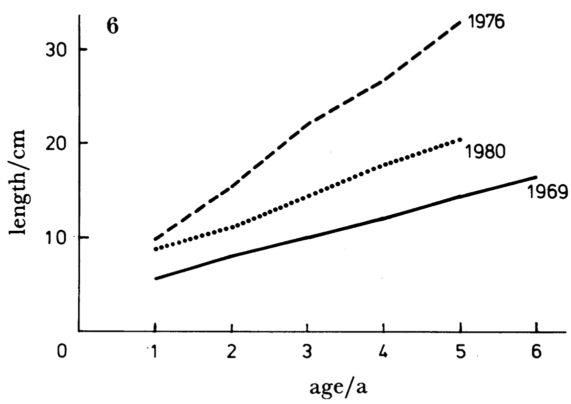
concentration of hydrogen ions, implies less stress on fish (Leivestad *et al.* 1980), and also decreases the toxicity of aluminium to fish (Muniz & Leivestad 1980). Moreover, the higher pH brings about the precipitation and sedimentation of aluminium, thus lowering its concentration in the water (Fiskeristyrelsen & Statens Naturvårdsverk 1981). Liming also raises calcium levels in the water, which has been shown to improve the survival of fish at low pH-values (Brown 1981). Besides these chemical effects, the increased supply of food, e.g. zooplankton, after lime treatment (Eriksson *et al.* 1983), may favour the survival of young fish.

Effects on growth

The effects of liming on the growth of fishes was very much dependent on the status of the populations before treatment. In waters where no recent fish reproduction occurred, resulting in sparse populations with little competition for food, the individuals usually grew very well



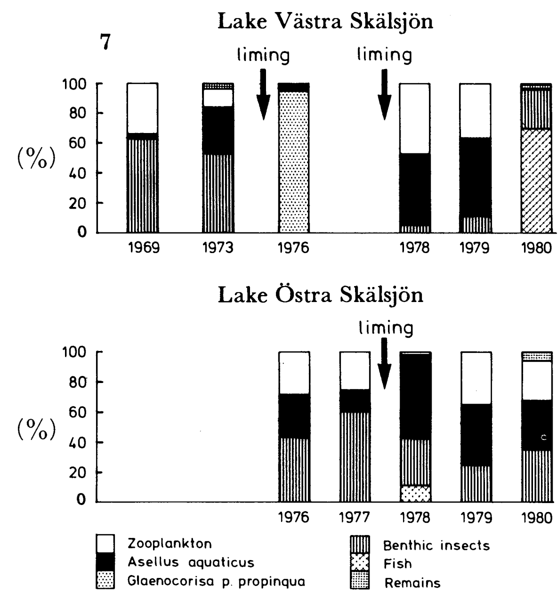


Figure 6. Growth of perch (*Perca fluviatilis*) in Lake V. Skälsjön in 1969, 1976 and 1980 (Eriksson *et al.* 1983).
Figure 7. Diet of older (longer than 15 cm) perch (*Perca fluviatilis*) in Lakes V. and Ö. Skälsjön (Eriksson *et al.* 1983).

before liming. After treatment and the recovery of recruitment, the growth of the offspring was normally very good for the first few years. However, as the population grew, competition for food increased, and individual growth decreased. In 1969, the reproduction of the perch population in Lake V. Skälsjön had not yet been affected by acidification and individual growth was slow, though comparable with that of the perch in other forest lakes in Sweden (figure 6). In the extremely weak population that existed in 1976, the individuals grew very well. After the first lime treatment in 1975 and following 6 years of reproduction, by 1980 the growth rate had decreased and was approaching pre-acidification levels. Similar changes in growth rates after liming have also been observed in several lakes on the Swedish west coast (Alenäs *et al.* 1981). Rapid growth rates in the two first year classes of perch after liming were also noticed in populations with sporadic reproduction during favourable years. In such

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populations the growth rates of the older, predatory perch improved, due to an increased supply of prey after liming. The growth rates of large perch and pike (*Esox lucius*) have also been found to be favoured by a recovery in the reproduction of cisco (*Coregonus albula*) (Alenäs *et al.* 1981) and roach (Nyberg, unpublished data).

In the populations with normal reproduction and age composition, liming has sometimes led to slightly better growth rates, above all for older perch, but most often no effects have been observed. After the liming of a soft-water lake in North America populated by slow-growing yellow perch (*Perca flavescens*), Waters & Ball (1957) found somewhat better growth rates, especially in young perch.

Effects on food habits

Many important fish food organisms, e.g. molluscs, certain crustaceans and insect larvae, are highly sensitive to acidification, and the food supply for fish may decrease before the fish themselves are directly affected. In a later stage of acidification, i.e. when recruitment is affected, the fish population becomes sparse and thus food supplies become abundant. Hence, the effects of lime treatment vary depending on the status of the ecosystem at the time of liming.

Figure 7 illustrates the food habits of older perch (longer than 15 cm) in Lake V. Skälsjön, where the perch population was extremely weak for several years. During 1969 and 1973, however, the population was intact and the perch fed on benthic insect larvae, zooplankton and to a certain degree on *Asellus aquaticus*. In 1976 only a few perch remained and *Glaenocorisa p. propinqua*, an insect species highly susceptible to fish predation, occured in a dense population and almost exclusively formed the diet of perch. After liming and the recovery of perch reproduction, *Glaenocorisa p. propinqua* was eliminated from the lake and zooplankton and *Asellus aquaticus* were again the most important food items in 1978 and 1979. In 1980, however, a rich class of yearlings appeared and the larger perch switched to a diet of fish (Eriksson *et al.* 1983).

The perch population in Lake Ö. Skälsjön was not affected by acidification at the time of lime treatment and as a consequence the food habits of perch were very much the same during all of the five years studied (figure 7) (Eriksson *et al.* 1983).

Several species of invertebrates which are sensitive to acidification have been found to recolonize waters after lime treatment and subsequently to be exploited by fish populations. Thus *Daphnia longispina* and the mayfly *Cloeon dipterum* occurred in the diet of brown trout (*Salmo trutta*) in several lakes (Nyberg unpublished data). Hultberg & Andersson (1981) found the same mayfly and *Lymnaea peregra* in the stomachs of this fish species.

The increased supply of young perch, roach and cisco after lime treatment was exploited by predatory fish such as pike, perch and large Arctic char (Eriksson *et al.* 1982).

Long term development of some fish populations

Even though liming has been used for a long time as a method for improving the production of fish in natural waters, there is very little information on the results of these treatments. As fisheries have been of primary interest during the Swedish trial period, studies on the effects on fish populations have been carried out in a number of liming projects. Most of these studies were, however, started around 1980 and there are still too few results to enable an evaluation.

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This means that the present results are based on studies from a lesser number of waters in which liming was carried out 5–8 years ago.

The perch population in Lake V. Skälsjön was, as mentioned earlier, almost extinct at the time of the first lime treatment, and according to the results from test-fishing, only 10 mature perch remained (figure 2). A new year class was produced in spring 1976 and these reached maturity and were able to reproduce three years later. In 1980 and 1983 the catch was 8.8 and 14.5 perch per gill-net compared with 19.3 in 1969–1970. Even if neither the catch nor the size distribution of the population has reached the levels found before the effects of acidification (1969–1970) (figure 2), the population seems to be recovering.

The perch population in Lake St. Skarsjön was made up of large, old and non-reproducing individuals in 1971 (figure 8) but after lime treatment in the spring of 1975 the population was able to reproduce again. The individuals of the first two year classes after liming had a very fast growth rate and were caught in 1976 as yearlings and one (1+) year olds with lengths of 7–11 cm and 13–15 cm respectively. In 1981, the number caught had increased 8–9 times (figure 8) and the population consisted of perch of length 7–15 cm, in spite of the fact that most of them were four (4+) to six (6+) year olds.

In lakes where intraspecific competition, mostly for zooplankton, is weak or non-existent owing to lack of young year classes, liming may create conditions favourable for very high survival rates in some new year classes. As a consequence, the population density and competition for food increase rapidly, and growth stops at a small individual size. Many oligotrophic forest lakes in Sweden are, however, inhabited by perch with stunted growth (Alm 1946), and thus it is possible that the structure of the population of Lake St. Skarsjön in 1981 is about the same as before the effects of acidification.

Different fish species show different susceptibilities to acidification, and thus acidification may affect interspecific interactions in fish communities. For example, roach is a very strong competitor in lakes in Sweden, except in very cold water (Svärdson 1976), but the species is very sensitive to acidification (Almer *et al.* 1978). The reproduction of roach is affected at an early stage of acidification, which may favour an increase in many other less susceptible fish populations. The food supply of predatory species may, however, decrease. Liming, on the other hand, makes it possible for sensitive fish species to reproduce again. Subsequently, interspecific interactions will change and the changes in the fish community will be experienced by people as positive or negative, depending on the species composition of the lake.

The Arctic char is susceptible to both acidification (Almer *et al.* 1978) and interspecific competition (Svärdson 1976). The char population of Lake Ö. Skälsjön was made up of old individuals in 1976 and during some years offspring were totally absent (figure 3). In July 1976 the catch of char was about 1 per gill-net and, owing to a high individual weight (640 g), about 0.75 kg per gill-net (figure 9). Mortality was, however, high in the old population and catches were very low during 1977–1982, as regards both weight and number. The liming of an upstream lake in 1975, liming on land areas in 1977 and above all liming in the lake itself in winter 1980–1981 increased the alkalinity to less than 0.01, 0.02 and 0.09 meq l^{-1} respectively (figure 9) and recruitment slowly recovered. In 1983, the weight of the catch of char was about the same as in 1976 and the number of char was about four times greater. Owing to a dominance of young fish in the catch (figure 3), the individual mean weight was low.

The perch population on Lake Ö. Skälsjön was not directly affected by acidification in 1976, but was instead probably favoured by the sparse char reproduction, as both species feed mainly

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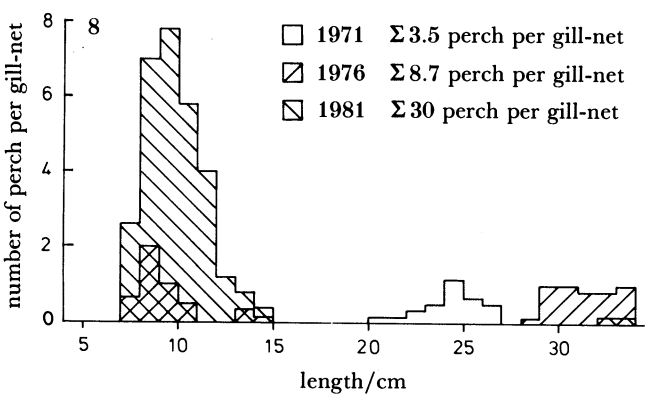

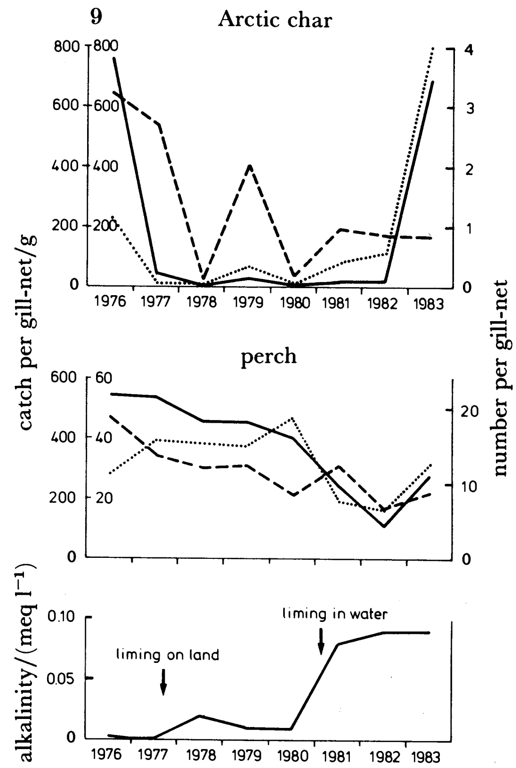

FIGURE 8. Size distribution and catch of perch (*Perca fluviatilis*) in Lake St. Skarsjön in 1971, 1976 and 1981 (Eriksson *et al.* 1983).

FIGURE 9. Catch (——), number (·····) per gill-net and individual mean mass (inner ordinate, mass in grams) (––) of Arctic char (*Salvelinus alpinus*) and perch (*Perca fluviatilis*), and alkalinity of surface water in Lake Ö. Skälsjön in July 1976–1983 (Nyberg unpublished data).

on zooplankton and benthic invertebrates. The perch population seems to have decreased somewhat during the period 1976–1983, even though the gill-net catch increased again during the last year (figure 9). The apparent decrease of the perch may depend on increased competition for food with numerous young Arctic char.

In lakes with populations of roach and perch, roach is the dominating species (Svärdson 1976). Liming, and recovered reproduction in roach, should thus result in an increase of the roach population. Eight lakes on the Swedish west coast which were limed from 1971–1976 were sampled by test-fishing in 1971, 1976 and 1981. The relative strength of the roach population, in numbers and weight of the total catch per gill-net, was, however, about the same after lime treatment (figure 10). This may at least partly depend on the fact that test-fishing was performed relatively soon after treatment, which means that the roach in some lakes were too small to be caught in the gill-nets, and thus the new year classes only contributed to a small extent to the total catch. In Lake L. Väktor the roach population increased after lime treatment and large numbers of roach were caught in the pelagic zone of the lake. Interspecific competition for food with cisco (*Coregonus albula*) probably increased, and the cisco population decreased (Alenäs 1982).

Figure 11 shows the results of test-fishing before and 3–7 years after lime treatment in 20 lakes on the Swedish west coast. The dominating fish species caught were roach and perch,

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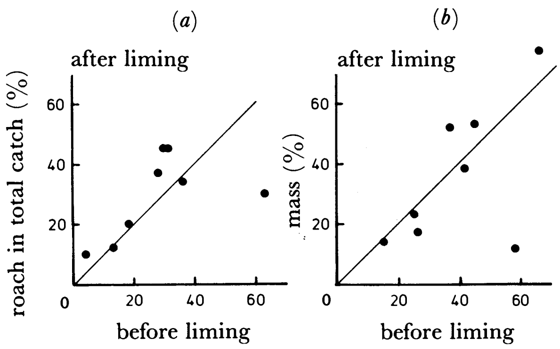

FIGURE 10. Percentage of roach (*Rutilus rutilus*) in total catch in numbers (*a*) and mass (*b*) in eight lakes before and after lime treatment (Eriksson *et al.* 1982).

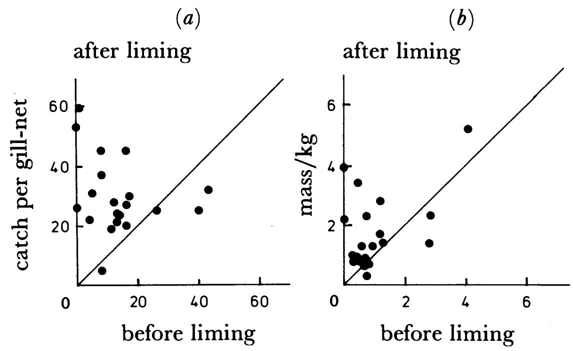

FIGURE 11. Total catch per gill-net in numbers (*a*) and mass (*b*) in twenty lakes before and after lime treatment (Eriksson *et al.* 1982).

although a few specimens of pike (*Esox lucius*) and tench (*Tinca tinca*) affected the weight of the catch in some lakes. As can be seen the number of fish caught increased in all lakes except four (figure 11*a*) and the average yield was 14 and 30 individuals per gill-net before and after treatment respectively. The most marked increase was observed in lakes where the catch was very low before treatment, due to weak or non-existent reproduction. Owing to the relatively large percentage of young fish in the catch after liming, the difference between pre- and post-liming yields in weight was smaller than that in number (figure 11*b*). Before treatment an average of 1 kg of fish was caught per gill-net and the corresponding figure after liming was 1.8 kg. As many fish were young and small in size, this difference should increase in the future.

These results show an increase in the yield of fish after treatment. True studies on the effect of liming on fish production are missing, but the results from Lake O. Skälsjön (that is approximately a fourfold increase in char with an unchanged growth rate) indicate that the production of char has increased. Moreover, Hultberg & Alenäs (1981) found that the abundance of young brown trout approximately doubled after liming measures in streams that were only slightly acid before treatment. These increases may, however, depend on a mobilization of organic material that has accumulated during acidic conditions and may in this case only be of temporary duration.

The results of Broberg & Persson (1981) indicate that in the long run, the leaching of phosphorus from acidified watersheds decreases, which should lead to decreased productivity in the surface waters.

NEGATIVE EFFECTS

The negative effects of liming that have been observed in surface waters so far are believed to depend on the rise in pH and the elevated levels of aluminium in the water. Thus, severe fish-kills have occurred in a number of hatcheries after the liming of acidic inlet water. On another occasion, acid runoff with high concentrations of aluminium into a lime-treated lake caused aluminium poisoning in a downstream fish farm. Finally, the stocking of rainbow trout (*Salmo gairdneri*) 1–2 weeks after lime treatment was followed by total mortality in some lakes.

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Conclusions

It must be pointed out that the results presented here represent effects in waters where liming resulted in a stable pH-value of at least 6. In many Swedish liming projects, this has not been achieved and very small effects, or none at all have been noticed.

Nevertheless, lime treatment seems to be a possible method of keeping fish populations alive, especially in lakes with long turnover times and in areas with relatively light acid loads. Liming in lakes with turnover times of a few months, and especially in streams and rivers, did not prevent the ecosystems in many waters from being affected by acidic water during periods of high runoff.

Liming can probably never be used as a method for protecting fish populations in streams in the northern part of Sweden, or in streams and rivers in the southern and western parts of Norway because of lack of lakes in the catchments, a high yearly runoff and extreme variation in runoff. For example, in the northern part of Sweden, streams running over calcareous bedrock have an alkalinity of 0.5–1.0 meq l^{-1} during 50 weeks of the year, but during the spring thaw the water is toxic to fish (Bjär-n-borg 1983; Nyberg, unpublished data). Such spring spates seem to be impossible to treat by means of liming.

In areas with a heavy acidic load, the liming of surface waters will not prevent acid groundwater with elevated levels of potentially toxic metals from entering surface waters. Hultberg & Andersson (1981) also showed that runoff with a high concentration of aluminium affected the growth and condition of brown trout, in spite of a summer pH greater than 6 in the lake water.

In such areas the liming of lakes will result in the precipitation and accumulation of metals in the sediment of the lakes. If the pH of the lake water drops during some period, these metals will be mobilized in the water and may cause serious effects in the ecosystem. The only way to try to prevent toxic metals from entering surface waters is probably intensive liming on land in the drainage area, which would cost 5–10 times as much as the liming of surface waters.

In a highly acidified area on the Swedish west coast, Broberg & Persson (1981) found the leaching of phosphorus from the watershed to be very low, and Hultberg & Andersson (1981) noticed decreased concentrations of this nutrient in acidified and lime-treated lakes. This implies that even if the fish populations are kept alive by liming, the productivity of the already very oligotrophic waters, exposed to acid deposition, will be still lower.

Finally, we still do not know what the effects of liming will be in the long run. In any case, liming can not be considered as a definite cure for acidified waters but only as a method of saving valuable fish stocks, ecosystems and fisheries, while awaiting a reduction in the acid load.

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