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The effects of acidification on Scandinavian freshwater fish fauna

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Acidification of freshwaters have inflicted a major perturbation on Scandinavian aquatic ecosystems as indicated by severe regional loss of fish populations. This decline was first noted in the early 1920s but became particularly severe after World War II in the 1950s and 1960s. In southern Norway regional damage is now documented in an area of 33000 km², 13000 km² of which are devoid of fish. Several major southern salmon rivers are now barren. In Sweden more than 2500 lakes are documented to be affected. This corresponds to 3–4 % of the total lake surface area. An additional 6000 lakes are assumed to be affected by acidification. Population losses are also found in thousands of kilometres of running water as well as in salmon and seatrout rivers on the southwest coast. This paper describes the early observations, chronology of this decline and reviews possible causes and mechanisms. The acidification and the associated loss of fishstocks over vast areas is apparently the most devastating change recorded for the fish fauna of Scandinavia.

The first indications

The association between acid water and death of fish is an old and established experience in Scandinavia. Several papers on the subject were published in the 1920s (Dahl 1920, 1922, 1926; Huitfeldt-Kaas 1922; Sunde 1926). This sudden interest was clearly related to observations of a gradual decline in the landings of Atlantic salmon that had occurred in several of the southernmost Norwegian rivers, with several instances of fish kills of adult salmon or brown trout and heavy mortalities of egg and fish larvae in local hatcheries (Leivestad *et al.* 1976). It was also noted that brown trout populations in a few high mountain lakes had disappeared, and that some populations were much reduced and dominated by old and large fish (Dahl 1920).

The heavy mortalities in the hatcheries could largely be remedied by using lime to neutralize the water. Several experiments were conducted in which brown trout yolk sac larvae were exposed to different pH values in water acidified by letting it pass through peat (Dahl 1927; Sunde 1926). These authors also noted that there was a fair correspondence between the 'critical pH values' found in their experiments and pH measurements in field situations where changes in fish status had occurred. They concluded that the low pH values were presumably the main cause for the observed changes in the salmonid stocks in watercourses of southernmost Norway (Dahl 1926). Scattered measurements of pH in the field also indicated that pH could fluctuate daily and seasonally and that 'the acidity of the rivers is roughly associated with, in addition to the climatic conditions, the geological composition of the catchment'. Aagård (1953) stated further that 'the present "acidic period" will gradually therefore sooner or later be relieved'. But the salmon in the rivers continued to decline. In the 1950s it was found that the brown trout population in the same region was strongly reduced; in some districts the species were practically eliminated (Dannevig 1959). This trend continued into the 1960s, when

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it was reported that fish populations from a large number of lakes and rivers in the high mountain areas of southernmost Norway had lost or were in the process of losing their fish stocks (Kjos-Hanssen 1971; Jensen 1972).

In Sweden, one of the first observations of changes in fish fauna associated with acidic water goes back to 1964. A fishery consultant, Lundin, found that different fish species had successively disappeared from a strongly acidified headwater lake in the Härryda district near Gothenborg: the roach in the 1930s, the pike in the 1950s, and the perch and eel in the early 1960s. Lake Trolltjärn was a headwater with no known supplies of pollutants, so Lundin concluded that these fish changes had to be caused by atmospheric fallout (Almer 1972).

When Hultberg & Stenson (1970) treated two small oligotrophic lakes, Kroksjön and Mörtevatten in Svartedalen, approximately 40 km north of Gothenborg, with rotenone in 1969, they found an exceptionally low density of fish. The two lakes had a surprisingly low pH value (pH 4.6–4.8) and high contents of sulphate ions in the lake water. They also revealed low pH values in neighbouring lakes, which in some cases had dropped by approximately 1 pH unit during the previous decade. The former perch population in Lake Mörtevatten had completely disappeared, and there were only remnants of the former population of pike, which at that time were between 4 and 7 years old. The authors pressed for intensive biological and physiochemical studies to ascertain if similar changes of the environment had occurred in other lakes. The objective was to implement adequate counter measures (Hultberg & Stenson 1970).

Increasing problems with the maintenance of fish populations in lakes in the high mountain region of central Sweden go back to the 1960s (Andersson *et al.* 1971). Acidification was suspected to be the cause, and strong evidence supporting this was later found by chemical analyses of snow and water (Dickson 1973, 1975; Lindström & Andersson 1981).

Regional loss of scandinavian fish stocks

Sweden

We have already dealt with some of the early field observations on changes in fish stocks in Norway and Sweden. A regional survey of the chemistry in 384 lakes in 5 counties in the southern and southwestern parts of the country (Göteborg and Bohus, Älvsborg, Kronoberg, Halland and Jönköping) revealed that many of these lakes were acid, for historical records indicated that the pH of these lakes had dropped significantly in recent decades. Interviews with the local fishermen also indicated that fish stocks had declined drastically. Based on this information, 50 representative lakes in 6 areas were surveyed by test fishing. These lakes covered a pH range from 4.4–7.5 (Almer 1972; Almer *et al.* 1974). It was then found that 10 roach populations had disappeared. Several roach and perch populations were much reduced and dominated by a few older fish close to extinction. Based on this and other surveys, which included 100 lakes south of River Dalaälven in southern Sweden, it was documented that 63 (15%) out of 444 species populations had disappeared, and that many populations were now sparse and declining (table 1) (Almer *et al.* 1978).

The 50 lakes on the west coast were resampled after 5 years (in 1976) together with 5 more lakes with historical records or records of present day occurrence of Arctic char. It was found that 10 of the former study lakes had been limed between the two sampling periods, and that 6 more roach and 2 vendace populations had disappeared. Only 2 of the former populations of Arctic char were still present, one of them probably because the lake had been limed. None of the perch populations had vanished during these 5 years, but some had become more sparse, and some had even recovered. The perch recovery was probably because of intermittent reproduction associated with improved water quality in 2 of these 5 years (Almer & Hansson 1980).

Table 1. Effects of acidification in 100 Swedish lakes (pH 4.3–7.5) south of Dalaälven River

(Source: Almer *et al.* 1978.)

family	species	number of previous stocks	number of remaining stocks	stocks acidification (number)	exterminated by (%)	pH critical for reproduction
Cyprinidae	minnow (*Phoxinus phoxinus*)	28	16	12	43	⩽ 5.5
Cyprinidae	roach (*Rutilus rutilus*)	77	52	25	32	⩽ 5.5
Salmonidae	Arctic char (*Salvelinus alpinus*)	36	25	7	19	⩽ 5.2
Salmonidae	brown trout (*Salmo trutta*)	28	24	4	14	< 5.0
Coregonidae	cisco (*Coregonus albula*)	21	19	2	10	< 5.0
Esocidae	pike (*Esox lucius*)	79	72	7	9	4.4–4.9
Percidae	perch (*Perca fluviatilis*)	99	95	4	4	4.4–4.9
Anguillidae	eel (*Anguilla anguilla*)	76	73	2	4	≈ 4.5

Similar observations of a decline in pH and in fish species, concurrent with low total biomass of fish, were reported from three lakes along the coast in southwest Sweden, and for three inland lakes in the province of Värmland (Grahn *et al.* 1974). Loss of roach from an acidified lake near Stockholm has been documented (Milbrink & Johansson 1975). Dickson (1975) points out that several more populations of this species had vanished before in the 1920s and 1930s. We lack historical material on water chemistry from these lakes, which were found to be acid in the early 1970s (Almer 1972).

In addition to loss of inland fish species, acidification of brooks and rivers on the west coast of Sweden has affected anodromous populations of sea trout (Hultberg 1977*b*), and efforts are being made to rescue Atlantic salmon populations in one of the west coast rivers (Edman & Fleischer 1980).

As a consequence of such regional changes in fish stocks, the Swedish government in 1977 launched a 4 year programme to study possible countermeasures to restore and rescue valuable freshwater fish resources. They also provided funds to subsidize liming projects throughout Sweden, particularly in the most affected districts (Fiskeristyrelsen & Statens Naturvårdsverk 1981). To assess the future need for such operations, a major regional survey was conducted in 1981 to map the extent of the acidification problem through the provinces and their fishery boards. Eight thousand lakes were sampled for chemical composition. Fish data from lakes and rivers were collected from questionnaires, field surveys and by test fishing. In cases where fish data were lacking, the effects on fish were estimated from water quality criteria for sensitive

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species (Johansson & Nyberg 1981). This survey showed that several fish species were affected, particularly lake populations of roach and perch, brown trout populations in running water, and sea trout and Atlantic salmon in rivers on the west coast. Although this study gave no exact figures for number of extinct populations, effects of acidification were documented (D) for 1600 populations of roach and 900 populations of perch; some 2500 lakes are clearly affected. Based on water samples and water quality criteria for the most sensitive species, another 6500 lakes were assumed (A) to have declined. Corresponding figures for lake areas ((D)/(A)) are 1250/1450 km^2 for roach, 195/330 km^2 for perch. This is equivalent to 3–4 %/7 % of the total lake area in Sweden. In addition to these effects, there are effects on 200 km of running water with sea trout and Atlantic salmon, 1500/1800 km with brown trout, 400 km of rivers where populations of pike, perch, and roach are affected, and approximately 120 km of running water where minnows are affected (Johansson & Nyberg 1981). These data clearly show that loss of inland fish species is a major regional problem in Sweden.

Norway

During the 1960s there was growing public concern in the southernmost counties in Norway because of the gradual disappearance of fish from lakes and rivers. After receiving numerous water samples for chemical analysis the Directorate for Wildlife and Freshwaterfish (D.W.F.) implemented more systematic monitoring programmes on water chemistry in several of our declining salmon rivers in 1965 (Snekvik 1972). Parallel to this, the D.W.F. collected data on the fish populations from local fishermen and landowners. In 1971 a more systematic survey was done by sending questionnaires to 80 fishery boards in our 4 southernmost counties (Rogaland, Aust-Agder, Vest-Agder, and Telemark) (Jensen & Snekvik 1972; Snekvik 1974). By 1972 the D.W.F. had received replies from 40 boards. From that material it was evident that 741 out of 2083 lakes (35.5 %) had lost their fish after 1940. pH values collected from 260 lakes in the same region showed that stunted or good populations were not found at pH below 4.5 but these populations were generally found at pH values above 5.5. Sparse, and in many cases declining, populations of fish were found at pH 4.5–5.5. The D.W.F. also noted that the frequency of empty lakes increased with increasing acidity and concluded that the population decline was closely associated with the acidity in the lakes.

These surveys were extended during 1974–1979 to include all Norway. It was now done in a more detailed way, i.e. by touring the countryside, interviewing the landowners, local fishermen and local fishery boards, fishing clubs, the county boards and farmers' organizations. The information was then checked and water samples for chemical analyses were collected from many of the lakes (Sevaldrud & Muniz 1980).

A subset of 88 lakes was then test fished as a control (Rosseland *et al.* 1980). The survey lakes are all larger than 0.5 km^2. No data on fish populations in running water were collected. Priority was given to the most affected areas. The aim of this study was to continue the collection of data on fish stocks, to check and correct old data and to identify and map new areas. Detailed information was also collected on fish species populations in individual lakes.

Regionally, this study has confirmed earlier findings (Jensen & Snekvik 1972; Leivestad *et al.* 1976; Muniz *et al.* 1976; Wright & Snekvik 1978).

Inland fish stocks are now affected in a land area of 33000 km^2. In 13000 km^2 of this area fish stocks are virtually extinct (figure 1). Affected areas are found in all counties of southern Norway south of the 62° line. The only exception is the county of Møre and Romsdal. No effect

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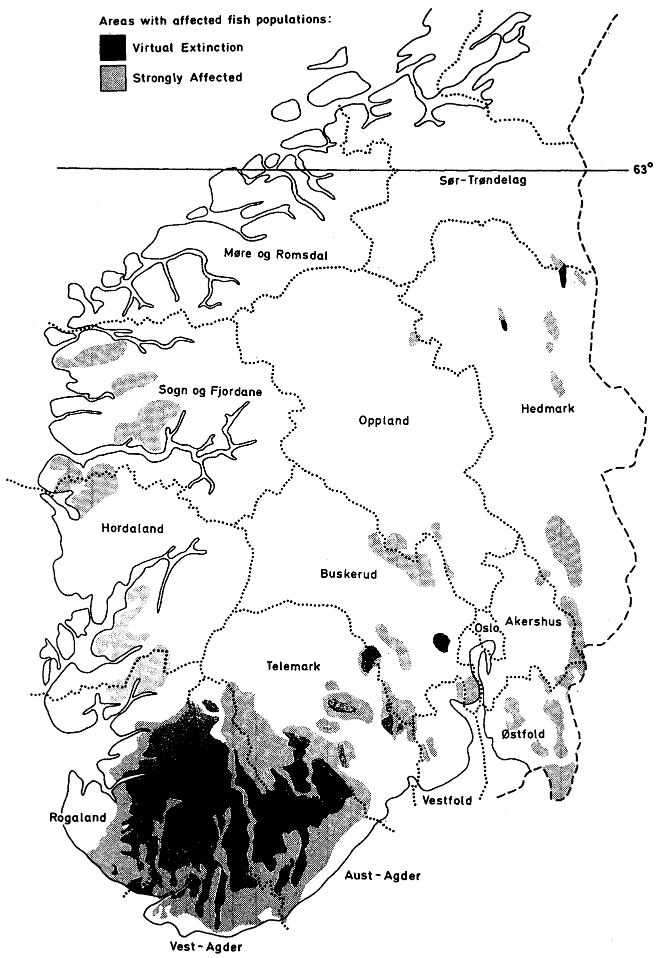

FIGURE 1. Regional distribution of areas with affected fish populations in southern Norway. (Source: Sevaldrud & Muniz 1980.)

TABLE 2. PRESENT STATUS FOR 3365 FISH POPULATIONS FROM 2840 LAKES IN THE 23800 KM^2 AFFECTED AREA IN THE FOUR SOUTHERNMOST COUNTIES OF NORWAY

(Source: Sevaldrud & Muniz 1980.)

	brown trout	perch	char
good populations	597	200	47
sparse populations	760	97	25
loss of populations	1454	118	30
no data on status	12	16	8
total	2823	431	110

has been documented in counties further north. The most severely damaged regions are in the four southernmost counties, where 12800 km^2 are strongly influenced, 1711 fish populations are lost and 941 populations are decreasing. Adverse effects are documented for 9 species of freshwater fish. The losses are particularly heavy for brown trout, our most wide-spread species, perch and Arctic char (table 2).

The Atlantic salmon in our southernmost rivers continued to decline during the 1960s and

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early 1970s, when the last salmon were caught. Scattered pH measurements all point out that these rivers are now more acidic than the other salmon rivers of Norway, which still harbour self-sustaining salmon stocks (Muniz 1981). From the 20 years of water quality monitoring in our southern rivers, we know that these slamon rivers have become more acidic and that the hydrogen-ion concentrations have approximately doubled in the years 1966–1976 (Henriksen *et al.* 1981). The present day water quality with the current levels of hydrogen ions and aqueous aluminium is obviously too acidic for the survival of sensitive stages of Atlantic salmon (Muniz 1981; Rosseland & Skogheim 1982; Skogheim *et al.* 1984).

By analysing the distribution of the brown trout, we observe that the frequencies of lost populations increase with acidity and that increasing salinity in terms of conductivity plays an important role because fish are found at a lower pH in lakes with higher salinity (Leivestad *et al.* 1976; Wright & Snekvik 1978). This phenomenon can be interpreted in two ways. We know that certain cations, such as calcium, have an ameliorating effect on acid stressed fish (Leivestad *et al.* 1980), and that since calcium is probably associated with the ability of individual catchments to neutralize acid loading, we can use it as an indicator for the historic sensitivity of the surface water (Henriksen 1983). If we accept that a fish population is an integrator of all the lake processes and that information on both changes and loss of population can be used as an indicator for the acidification process as a whole, both in space and time, it is noteworthy that small and medium sized dilute lakes at higher altitudes were the first to be affected and that the loss of stocks has since then gradually spread downsteam towards the coast to include larger lakes with higher salt content. Several authors have commented on this general observation (Dannevig 1959; Jensen & Snekvik 1972). This downstream loss of fish has to be interpreted in the context of chemical loading and the physiochemical and physiographical characteristics of the catchments. The catchment ability to neutralize and transform the chemical inputs as well as the water chemistry with its temporal and spatial variations within the catchment is also important (Muniz *et al.* 1983).

We have no long term data series on water quality for all our lakes, but again the available measurements seem to indicate that acidification has taken place (Wright 1977; Henriksen 1983). The most convincing evidence, however, comes from the large scale decline in our fish populations in waters which are now acidic and have toxic levels of aqueous aluminium. For brown trout 150 μg Al l^{-1} (17 μeq l^{-1}) is shown to be acutely toxic for adults, a value which is commonly exceeded in our acidic water courses (Muniz & Leivestad 1980*a*, *b*; Henriksen 1983).

An elevated level of aluminium is nearly always associated with acid water in Scandinavia (Wright & Gjessing 1976; Dickson 1978, 1980). The recent discovery that aluminium leaches from catchments into surface and ground water is of crucial importance for our understanding of the acidification process and the linkage between the edaphic and aquatic environments.

Fish populations have been found to be small and even miniscule in acidified lakes (Harvey 1982). The population estimates from some of the lakes on the southwest coast of Sweden (Hultberg & Stenson 1970) and three more inland lakes in the same region were low. The total fish biomass varied between zero and 600 kg km^{-2} (Grahn *et al.* 1974) and the remaining populations were dominated by older individuals.

We have no continuous population estimates by mark and recapture technique from any lakes before and during the decline, until the phase where the last individuals went extinct. Some historical data are available. Catch statistics, in terms of number of fish captured or catch

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per effort (number of fish per gill-net) can illustrate this decline. For example, Lake Holmevatn, an acidified lake (pH 4.7–4.8) in lower Telemark, lies in an area where a majority of the trout lakes and streams are now barren. There has been a gradual decline in the fish catches (figure 2), and the landowner tried to remedy this by stocking yearlings, but the decline continued. He then used adult wild trout from the neighbouring River Tovdal, and when this failed, the lake was finally abandoned (Overrein *et al.* 1980).

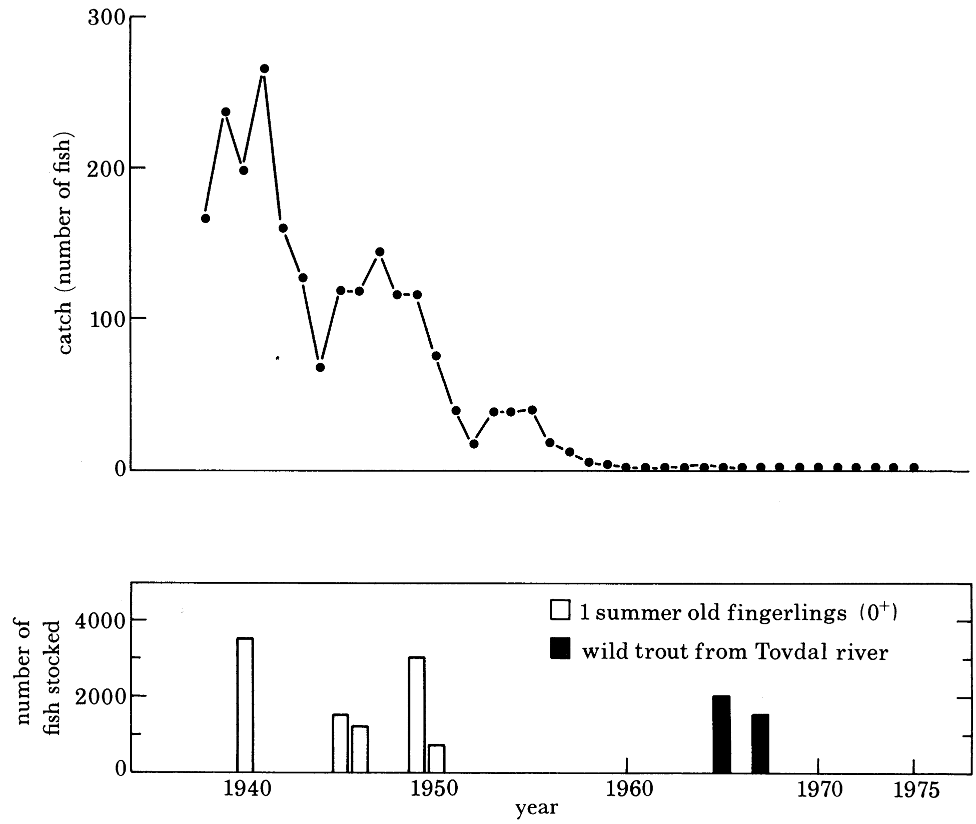

FIGURE 2. Stocking and catch of brown trout in Lake Holmevatn (Telemark). The catch statistics are 3-year moving average, based on notes by the land owner. (Source: Overrein *et al.* 1980.)

In Södra Boksjön, a 9 km² lake in the western parts of Sweden, the Arctic char population had for years been regularly fished with gill-nets during the spawning period (100–150 nettings per year). The catch was approximately 500 fish every year from 1850 till 1963. Then it dropped rapidly, and the last char was captured in 1968. The pH of the lake during 1970–1971 was 4.5–4.7 and in 1973 4.2–4.5 (Almer 1972; Almer *et al.* 1974) (table 3). In this lake the roach disappeared in the 1930s and the crayfish population at the beginning of the 1940s.

Several fish surveys with standardized gill-nets in lakes that cover a wide range of pH values have shown that the catch per effort is much lower in the acidic lakes and that it is positively associated with pH (Almer 1972; Almer & Hansson 1980; Rosseland *et al.* 1980).

The regional material on brown trout from southernmost Norway, shows that more than half of the populations in the most affected areas have been lost (figure 3). This decline started shortly after World War II and has been particularly rapid since 1960. With the present trend,

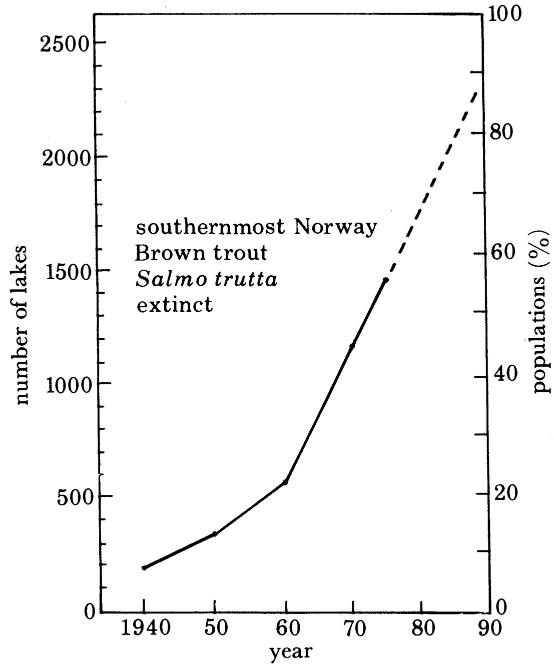

FIGURE 3. Time trend for losses of brown trout in the affected areas in southernmost Norway. (Source: Sevaldrud & Muniz 1980.)

TABLE 3. CATCH OF SPAWNING ARCTIC CHAR IN LAKE SÖDRA BOKSJÖN

(Source: Almer 1972; Almer *et al.* 1974.)

		mean mass/kg	
year	number of fish	♂	♀
1956–58	at least 500 per year		
1959–63	*ca.* 500 per year	0.2–0.25	0.15
1964	*ca.* 175	0.3	0.15
1965	*ca.* 70	0.5	0.25–0.3
1966	*ca.* 20	0.7	0.3
1967	*ca.* 8	0.7	0.3
1968	*ca.* 6	1.1	0.3
1969	0	—	—

this species is indeed seriously affected and close to extinction in many areas (Muniz & Leivestad 1980*a*).

The loss in terms of sustainable yields from these lakes is variable but generally low, particularly in the high mountain areas, and is largely associated wih the overall low productivity at high altitudes. But even in such situations the yield would not vary more than by a factor of 5 (100–500 kg km^{-2}) (Jensen 1977). Even our most oligotrophic lakes in non-affected areas produce high quality fish. These lakes are harvested by using gill-nets, and by recreational fishing with rod and line. The production loss of Atlantic salmon may be estimated from catch statistics from the affected rivers, which amounted to 30000 kg at the turn of the century. These landings are approximately 20% of the total output because some 80% of the salmon are caught at sea (Muniz 1981) (figure 4).

The populations in our acidified lakes show large perturbations in their age class composition, which are related to intermittent or chronic reproduction failure (Almer 1972; Hultberg 1977*b*; Almer & Hansson 1980). Changes in growth are often observed, and can be understood as changes in competition, food availability and physiological stress (Muniz & Leivestad 1979; Rosseland *et al.* 1980). Lack of food organisms has rarely been found to be critical for fish survival in such lakes, and the few remaining individuals will often be quite fat (Almer 1972; Rosseland *et al.* 1980). In one case it has been documented that the condition factor for trout in a limed lake declined in addition to the catchability (number of fish per netting) during the process of reacidification (Hultberg & Andersson 1982). This was reversed shortly after the lake had been relimed. In general, several of these effects may be remedied when the lakes are treated to obtain a circumneutral pH.

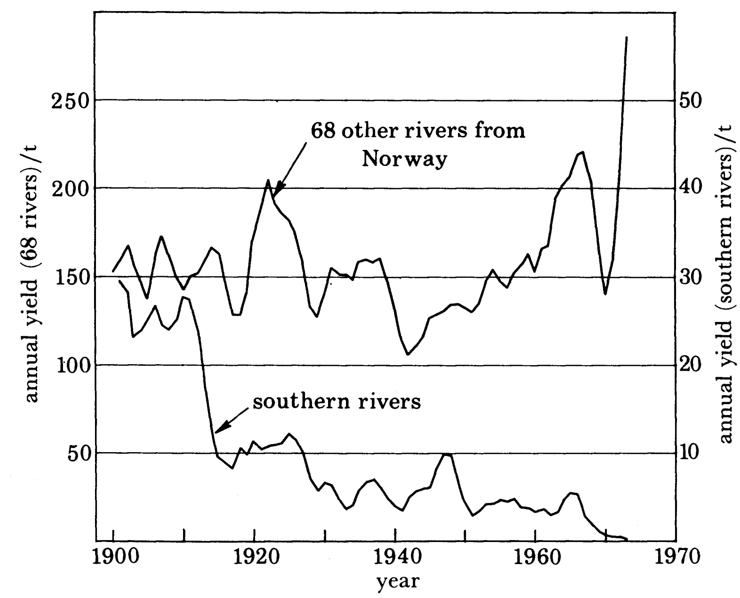

FIGURE 4. Salmon fisheries statistics for 7 southern acidified rivers and from 68 rivers from the rest of the country. (Source: Leivestad *et al.* 1976; Muniz 1981.)

Several regional studies have also indicated elevated levels of metals in acid lakes, particularly aluminium, manganese, and zinc, and in some regions copper, cadmium, lead, and nickel (Dickson 1975; Wright & Henriksen 1978). The sources, behaviour and sinks for these metals are not always understood. But acidification probably results in increased solubility and bioavailability for some of these metals (Dickson 1978). The mercury contents in fish from acidic lakes in Sweden are now reaching high levels. Some of these lakes have no local source for mercury, and several lakes are now blacklisted and their fish banned for human consumption (Hultberg 1977*a*; Johannsson & Nyberg 1981). The same phenomenon has been observed for cadmium (Swedish Ministry of Agriculture 1982).

Concluding remarks

The effects of acidification on aquatic life, particularly fish populations, in lakes and rivers in southern Scandinavia, have been documented in an extensive and varied literature (Overrein *et al.* 1980; Swedish Ministry of Agriculture 1982). The evidence is complex and includes historic records of declining or extinct fish stocks, population studies based on present-day surveys, data on success and failure of stocking experiments and *in situ* exposures of fish in field and laboratory situations (Leivestad & Muniz 1976). We have studied survival, growth, behaviour and physiological responses of fish typically associated with acidified water as well as evalulating the regional extent of the problem (Muniz & Leivestad 1980*a*). These observations have in most cases included water quality parameters like pH, conductivity (salinity) and alkalinity, and more recently aqueous aluminium and other metal cations. It should, however, be pointed out that these data vary in quantity and quality, but this often quite heterogeneous body of information still provides us with enough information to conclude that acidification has had, and is still having, a detrimental effect on our freshwater fish populations. This deterioration appears to be one of the major changes, probably the single most devastating, in the natural history of the fish fauna of Norway and Sweden.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

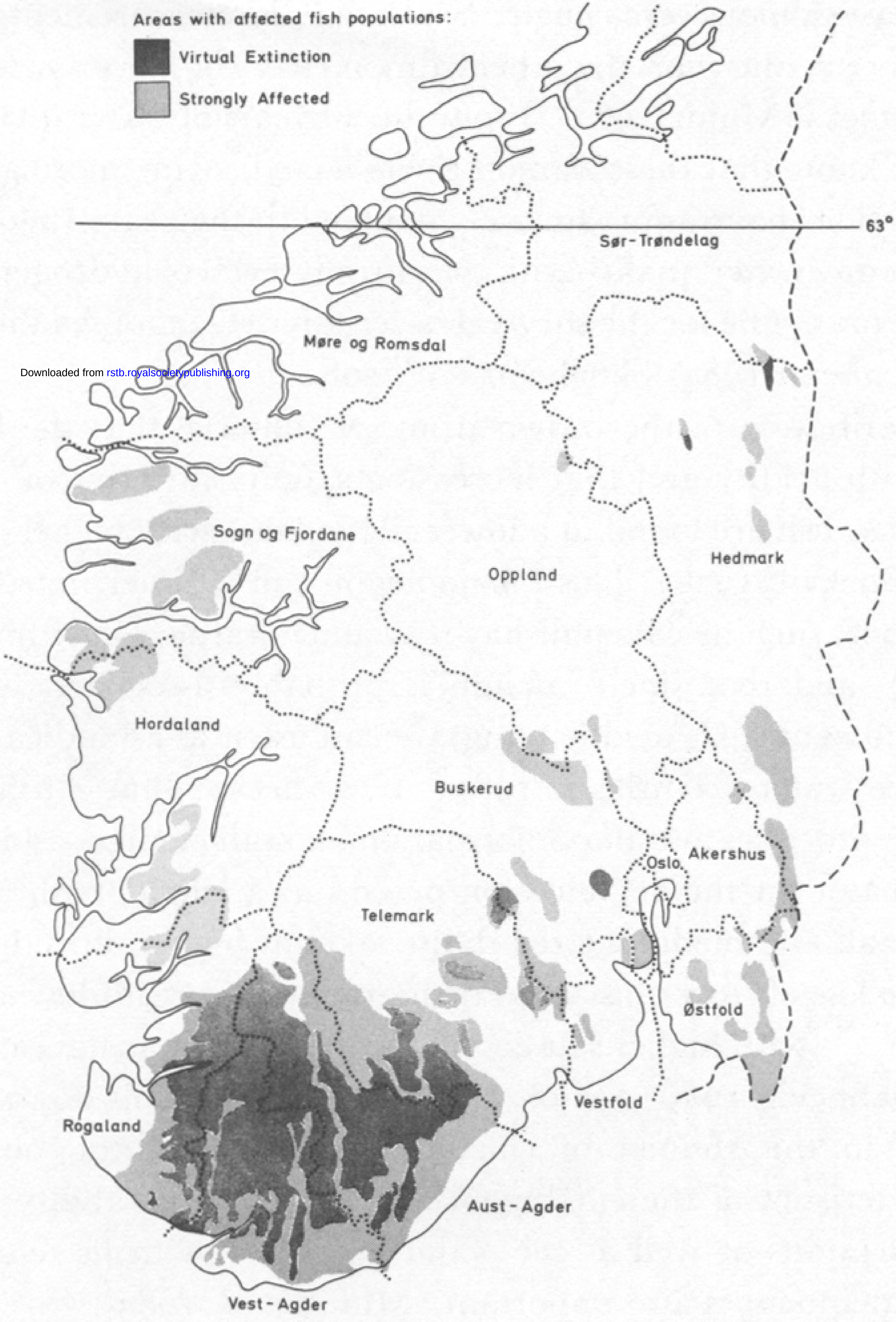

FIGURE 1. Regional distribution of areas with affected fish populations in southern Norway. (Source: Sevaldrud & Muniz 1980.)