Ecology of streams draining forested and non-forested catchments in an area of central Scotland subject to acid precipitation

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Abstract

A study of 12 streams draining forested and non-forested catchments was made in an area of central Scotland where slow-weathering bedrock was predominantly quartzite, schists and slates. Sitka spruce (*Picea sitchensis* Carriere) was the most common tree species. Precipitation in the area had an annual mean pH in the range 4.3–4.5. Streams within the planted zone were always more acid than those outside and had higher concentrations of aluminium and manganese. With one exception, trout were absent from streams within long-established forests and planted salmon eggs (*Salmo salar* L.) died within a few weeks. A high proportion of such eggs survived in streams outside the forest. *Siphlonurus lacustris* Eaton was the only mayfly nymph found in the most acid streams in summer collections. In winter samples, mayfly nymphs, *Heptagenia lateralis* (Curtis) were found in only one forest stream but several species were present in the non-forested catchments. It is suggested that spruce forests can effectively collect acid pollutants which are subsequently washed out, thus accelerating the acidification of the soil. Streams therefore become increasingly acid as the neutralisation capacities of their catchments decrease.

Introduction

Recent studies of precipitation and surface water chemistry have shown that rain falling over central and southern Scotland is often very acidic (mean $\mathrm{pH} < 4.5$) and some of the surface waters in these areas exhibit similar acidity. Such waters are associated with bedrock which is highly resistant to chemical weathering, e.g. granite, schists and slates, and as a result they have low buffering capacity.

Other investigations, particularly in Scandinavia and North America, have revealed a similar pattern and have shown that acidification may produce many changes in freshwater ecology (Almer *et al.* 1974; Beamish 1974; Leivestad *et al.* 1976; Schofield 1976). The most serious problems associated with acidification have been the decline and loss of fish populations, reduction in species diversity of benthic communities and mobilisation of certain toxic metal ions. Although acid precipitation has been cited as a major cause of this acidification phenomenon, other sources of acidification, including changes in forestry and agricultural practices, may be important (Rosenquist 1978; Seip & Tollan 1978).

Many studies of the cycling of nutrients and other ions in forest ecosystems have been reported (e.g. Likens *et al.* 1977; Henderson *et al.* 1977) and some investigations have revealed differences between deciduous and coniferous forests, in particular, the inability of spruce and pine species to neutralise incoming acid precipitation. (Nihlgard 1970, 1972; Cronan *et al.* 1980).

In Scotland the Forestry Commission and private forestry groups follow a policy of intensive cultivation of coniferous trees, predominantly sitka spruce (*Picea sitchensis* Carriere), and these plantations now cover large areas of the western half of

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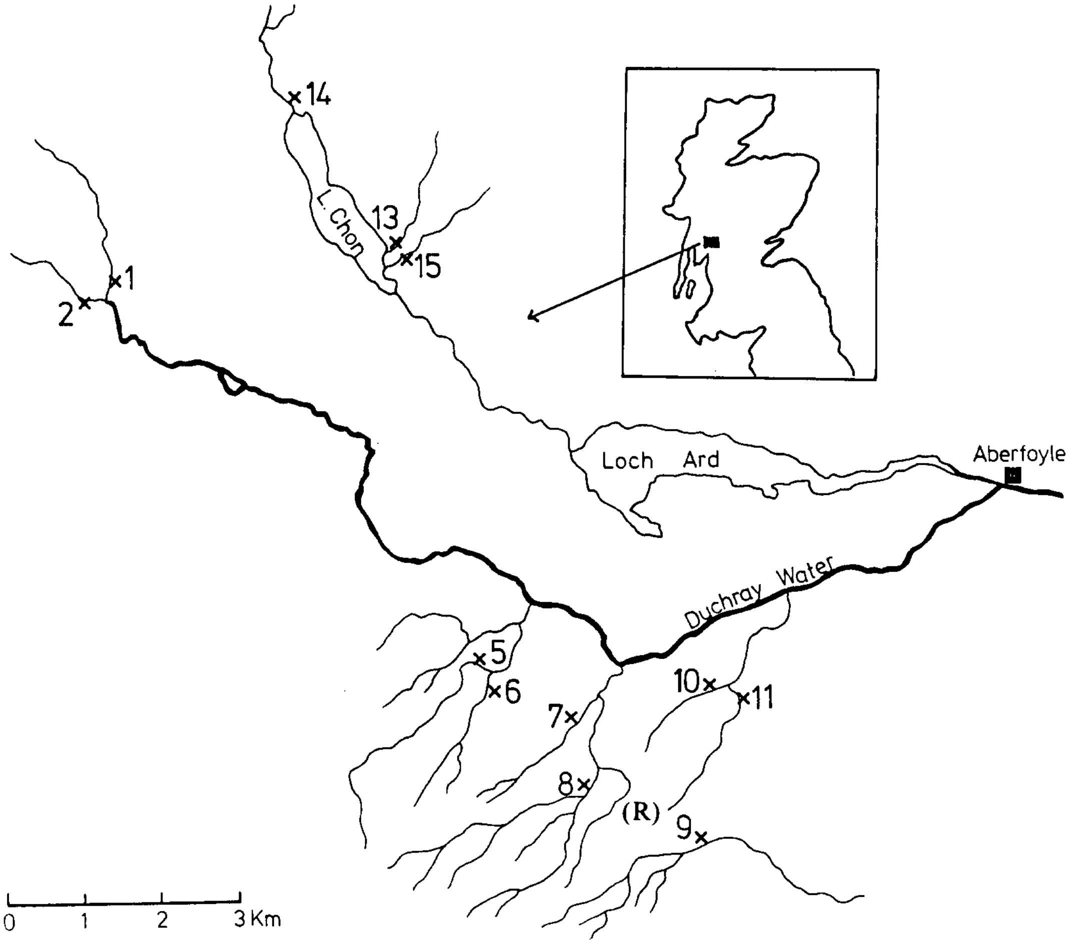

Fig. 1. Maps of Duchray and Loch Chon areas showing stream numbers, sampling sites (X), and precipitation collection site (R). The inset shows the location of the study site in Scotland.

Scotland where acid, peaty soils predominate. Streams draining this type of mature coniferous forest catchment were found to be more acid than streams draining adjacent moorland catchments (Harriman 1978) and were apparently fishless.

This paper describes a detailed study of the combined and individual effects of acid precipitation and coniferous afforestation on stream ecology and suggests possible reasons for the differences found.

Site description

The study site lies to the west of Aberfoyle (National Grid Reference NN 525.010) and is in two parts referred to as the Duchray area and the Loch Chon area respectively (Fig. 1). In the Duchray area streams 1, 2 and 6 drain non-forested catchments, streams 7, 8, 9, 10 and 11 drain old forested catchments (about 25 years old) and stream 5 drains a young forested catchment about 5 years old. In the Loch Chon area streams 13 and 15 were not forested and stream 14 drained a 25 yr old forested catchment. The precipitation collector was sited within the Duchray area. Sitka spruce was the dominant species in both areas although small stands of Scots Pine (*Pinus sylvestris* Linnaeus), Lodgepole pine (*Pinus contorta* Louden) and Norway spruce (*Picea abies* Karsten) were also present. In the unforested area the streams drain typical moorland catchments with a few scattered deciduous trees along the banks. Land use has been unchanged in these catchments for many decades. In the Duchray area acid peat of varying depth overlies a basement complex of sedimentary rocks composed of a mixture of schistose grits, graywackes, slate and phyllite. A gradual merging into mica schists and various undifferentiated schists occurs in the catchments of the head water streams 1 and 2. The Loch Chon area is of similar geology although peat formations are less evident in the catchments of streams 13 and 15. In the old forested catchments a well defined layer of undecomposed spruce needles covers the soil surface to a depth of about 5 cm.

All the streams have a stony bed and their mean width varies between 2 and 4 metres. *Nardia scalaris* (Schrad.) and *Scapania* spp. are the most common bryophytes to be found in the streams and *Mougeotia* and *Tabellaria* are the most common algae

Methods and materials

The sampling and most of the analytical methods used for studying bulk precipitation and stream water were described by Harriman (1978). Ammonia was determined using an Orion Ionalyser 901 with gas sensing ammonia electrode. Sulphate and chloride were determined by the ion-exchange methods of Mackereth *et al.* (1978). Manganese, copper and zinc were determined by atomic absorption spectrometry using solvent extraction when appropriate. Aluminium was determined by the absorptiometric method of Dougan & Wilson (1974) using catechol violet as the chromogenic reagent. Stream and rainwater samples were collected every two weeks when weather conditions allowed. Weak acid concentrations were determined using the method of Gran (1952).

Samples of invertebrate fauna in the streams were collected using a handnet with pore size *ca* 950 μm. The bed of the stream was disturbed by kicking for a period of two minutes and the dislodged animals were carried by the current into the net which was held immediately downstream of the disturbed area (Standing Committee of Analysts 1978). This method has the advantage that a wide range of stream habitats can be sampled in a short time. In addition quantitative samples of invertebrates froms streams 6, 7, 10, 13 and 14 were taken in March 1977 using a Surber-type sampler with a 0.1 m^2 frame. Statistical analysis of the results was done using the Kruskal-Wallis test (Elliott 1971).

The distribution of fish in the streams was determined using electro-fishing apparatus.

Experiments were conducted to investigate the survival of fish fry in the streams. For these studies, about 3000 unfed salmon and brown trout fry, reared from hatchery stock in water of pH range 6.5 to 7.5, were introduced into short stretches of streams 7, 8, 9, 10 and 11 in April 1976 at a density of around 5 fish m^{-2}. For the egg survival experiments, 2 mm mesh plastic Netlon boxes (Harris 1973), each containing 50 salmon eggs together with some 5–20 mm diameter gravel, were buried in the stream bed to a depth of about 10 cm. When inspecting the eggs it was assumed that those which were opaque and white were dead and that the live eggs were translucent and yellow or pale orange in colour.

It has been shown (Mills 1967; Smith 1980) that where light penetration to the stream is prevented by overhanging vegetation, the biomass in that section is less than in sections where there is no obstruction. Accordingly, all experiments and invertebrate sampling described here were done in open areas of stream to eliminate differences caused by light and cover.

Results

Chemical characteristics

The chemistry of bulk precipitation, collected in the Duchray area (1973–79), was dominated by sulphate, hydrogen and marine salts (Table 1). Sulphate from marine sources was calculated using the Mg/SO_4 ratio in sea water assuming all magnesium in precipitation was of marine origin. Excess sulphate (total less marine sulphate) was significantly correlated with H^+ in all years ($P < 0.01$ 1973–77 and 1979, $P < 0.05$ 1978) and the deposition of acid pollutants was invariably associated with air masses crossing Scotland from a southerly or easterly direction. Most of the major emissions of sulphur dioxide and other acid gases are located along this general trajectory. Air masses from the north and west give less acid rain ($pH > 4.8$) with

Table 1. Mean and range (in parentheses) of concentrations of major ions in bulk precipitation collected at the Duchray site (μeq l^{-1}).

	pH	H^+	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+	Cl^-	Total SO_4^{2-}	'Excess' $*SO_4^{2-}$	NO_3^-
1973	4.3	50	87	8	32	26	n/a	107	84	71	6
		(10–126)	(21–208)	(2–15)	(4–75)	(7–60)		(4–268)	(47–203)	(12–190)	(1–17)
1974	4.3	50	102	9	29	32	n/a	117	75	59	10
		(5–126)	(26–227)	(5–17)	(6–98)	(8–69		(20–280)	(29–261)	(14–250)	(1–49)
1975	4.3	50	84	7	19	28	n/a	101	76	62	5
		(9–186)	(31–147)	(3–15)	(5–72)	(7–49)		(4–204)	(30–343)	(15–332)	(1–27)
1976	4.4	40	109	8	15	30	n/a	104	103	88	8
		(1–158)	(21–848)	(3–22)	(1–91)	(4–198		(4–876)	(54–218)	(41–206)	(1–35)
1977	4.4	40	84	7	10	20	12	87	72	62	6
		(2–100)	(10–487)	(7–31)	(1–77)	(4–34)	(4–34)	(12–560)	(16–161)	(16–151)	(1–21)
1978	4.5	32	83	3	5	17	17	76	88	80	6
		(1–127)	(38–378)	(1–23)	(1–91)	(5–48)	(2–124)	(4–160)	(47–296)	(34–280)	(1–32)
1979	4.4	40	99	5	6	17	20	112	83	72	6
		(1–100)	(20–452)	(2–10)	(1–25)	(1–92)	(2–68)	(12–508)	(44–183)	(35–180)	(1–42)

* Calculated using marine Mg^{2+}/SO_4^{2-} ratio assuming all Mg^{2+} is from marine sources. n/a not analysed.

Table 2. Mean concentration of ions in precipitation and selected streams in the Duchray and Loch Chon areas (1979). All results as μeq l^{-1} except pH. Standard Error (±) is given in parentheses.

		pH	H^+	Na^+	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	Cl^-	SO_4^{2-}	NO_3^-
Duchray area	Precipitation	4.43	37	99	5	6	17	1	112	83	6
	+Stream 2	4.90	13 (4)	133 (19)	9 (1)	59 (3)	54 (6)	9 (1)	150 (31)	115 (5)	10 (2)
	*Stream 5	4.83	15 (4)	130 (13)	7 (1)	80 (5)	53 (5)	13 (0.9)	160 (22)	133 (5)	9 (2)
	*Stream 6	5.25	5 (2)	129 (11)	7 (1)	81 (4)	64 (5)	9 (1.2)	150 (21)	136 (4)	11 (2)
	**Stream 7	4.39	41 (6)	151 (8)	6 (11)	49 (2)	63 (4)	28 (1.6)	176 (16)	152 (4)	9 (1)
	**Stream 9	4.16	68 (10)	147 (12)	6 (1)	37 (3)	57 (4)	18 (0.8)	172 (22)	147 (5)	11 (1)
Loch Chon area	**Stream 14	4.75	18 (5)	199 (11)	7 (1)	92 (5)	60 (3)	18 (2.0)	235 (18)	146 (5)	10 (1)
	+Stream 15	5.80	2 (0.6)	139 (12)	10 (2)	100 (4)	61 (4)	4 (0.8)	171 (21)	125 (5)	9 (1)

+ Moorland stream; * Young forest; ** Mature forest.

higher marine salt content. About 15–20% of the total sulphate input was from marine sources although lower values were obtained when the marine influence was small.

During 1979 a detailed study was also made of the chemistry of selected streams in the study area (Table 2). On any given sampling day the forest streams were always more acid than adjacent moorland streams and acidity increased with increasing stream flow.

The ability of coniferous forests to collect pollutants can be demonstrated by comparing the concentrations of the conservative chloride anion in rain, with the concentration in forest and moorland streams (Fig. 2). The concentration of chloride (and sodium) increased with increasing forest age and percentage of forest cover in the catchment.

Sulphate concentrations were also higher in forest streams but not to the same extent as chloride. Average hydrogen ion concentrations (Table 2) were many times higher in the forest streams although in the Loch Chon area streams were generally less acid than their counterparts in the Duchray area.

A comparison of relative acidity and forest age (Fig. 3) implies a 'forest' effect resulting in a higher output of hydrogen ions from mature forest catchments.

Associated with increasing stream acidity was the

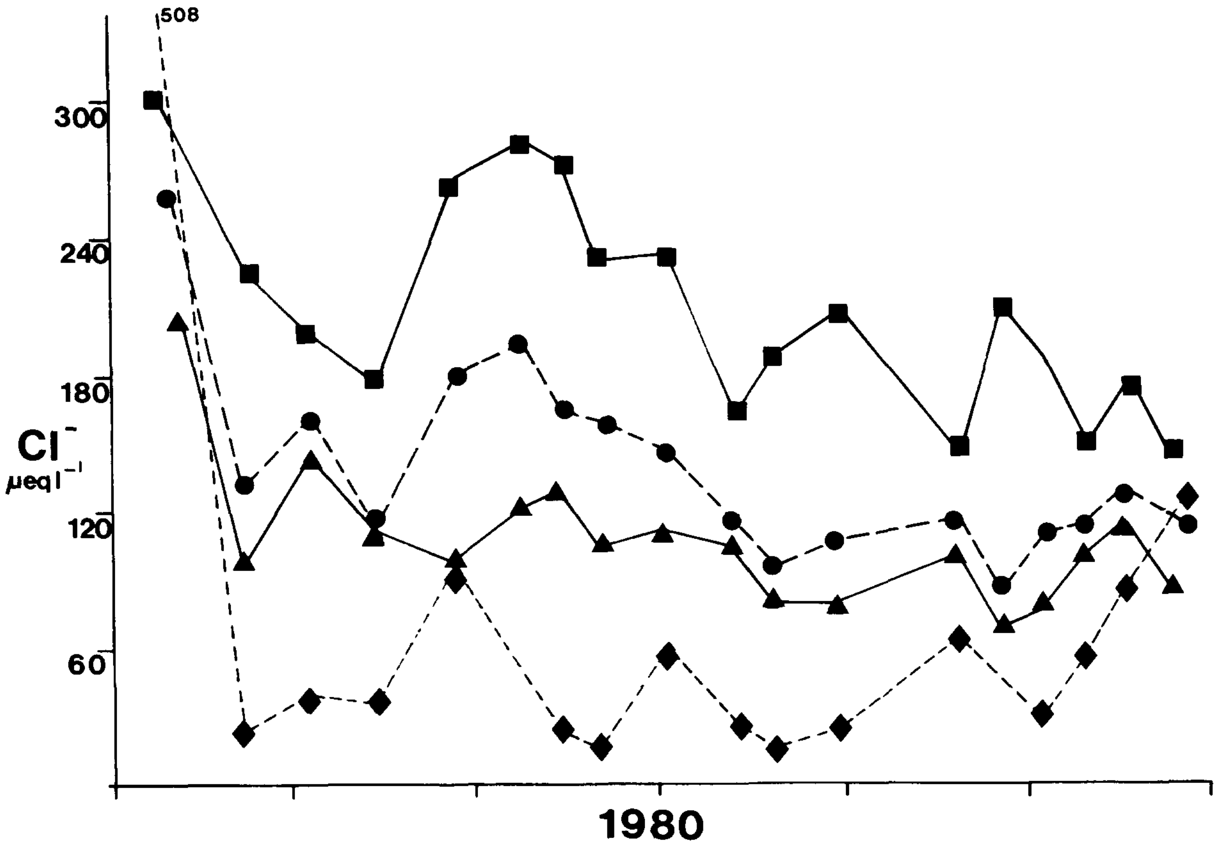

Fig. 2. Comparison of chloride concentration in precipitation (♦. . .♦), with moorland stream 2 (▲——▲), stream 9 (●---●), with ~60% mature forest cover, and stream 14 (■——■), with ~90% mature forest cover.

mobilisation of pH-dependent metal ions, notably aluminium and manganese. The aluminium content of streams 7, 8, 9, 10, 11 and 14 ranged from about 100 μg l^{-1} to 350 μg l^{-1} whereas the content of streams 1, 2, 6, 13 and 15 rarely exceed 100 μg l^{-1}. The managanese concentration followed a similar pattern with values for streams with forested catchments averaging about 90 μg l^{-1} and for non-forested ones about 30 μg l^{-1}. Copper concentrations were fairly uniform in all the streams with a mean of about 1.5 μg l^{-1}. Zinc levels averaged 14 μg l^{-1}, the highest concentrations being recorded in the most acid streams (L. A. Caines, pers. comm). A more detailed report of the heavy metal distribution will be published elsewhere.

The weak acid content varied from about 80 μeq

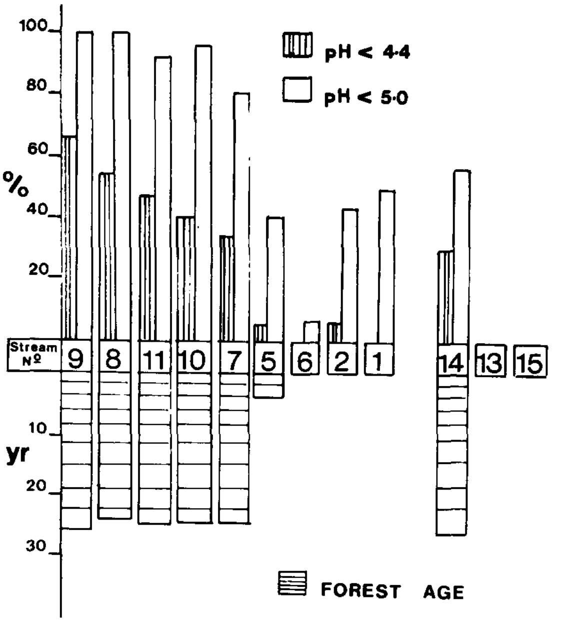

Fig. 3. Comparison of forest age with pH distribution for streams in the Duchray and Loch Chon areas.

Table 3. Distribution of invertebrate fauna in streams of the Duchray and Loch Chon areas based on samples collected in March and July 1977 and March 1978. (No July samples from streams 5 and 15). For each area, streams are arranged in order of decreasing acidity.

	Duchray area							L. Chon area		
	9	10	7	5	2	1	6	14	15	13
OLIGOCHAETA										
Tubificidae										+
Enchytridae			+		+	+	+	+	+	+
Lumbriculidae	+	+	+		+	+	+			+
Lumbricidae										+
Naididae	+		+			++	+	+	+	+
CRUSTACEA										
Gammarus pulex (L)										+
INSECTA										
EPHEMEROPTERA										
Rhithrogena sp.					+	+	+		+	+
Heptagenia lateralis (Curt.)					+		+		+	+
Ecdyonurus spp.							+			+
Ephemerella ignita (Poda)										+
Paraleptophlebia submarginata (Steph.)					+	+				
Siphonurus lacustris Eaton	+	++	+							
Baetis rhodani (Pict.)							+		+	+
B. muticus L.										+
PLECOPTERA										
Leuctra nigra (Olivier)	+	+	+							
L. hippopus (Kemny)	+	+	+	+	+	+	+	+		
L. inermis Kemny	+	+	+	+	+	+	+	+	+	++
L. fusca (L.)	+	+	++		+	+	+	++		+
Leuctra spp. (small nymphs)	+		+		+	+		+		
Capnia vidua Klap.	+		+							
C. atra Morton			+							
Nemoura spp.			+			+	+	+	+	+
Amphinemoura sulcicollis (Steph.)	++	++	++	++	++	++	++	++	+	++
Protonemoura meyeri (Pict.)		+		+	+	+	+	+	+	+
P. praecox (Morton)										+
Brachyptera risi (Morton)		+	++	+	+	+	+	+	+	+
Chloroperla torrentium (Pict.)	+	+	+	+	+	+	+	+	+	+
C. tripunctata (Scop.)							+			+
Isoperla grammatica (Poda)							+		+	+
Diura bicaudata (L.)		+					+			
Perlodes microcephala (Pict.)							+	+		
Perla bipunctata Pict.										+
Dinocras cephalotes (Curt.)										+
TRICHOPTERA										
Rhyacophila dorsalis (Curt.)	+	+		+	+		+	+	+	+
Plectrocnemia conspersa (Curt.)	+	+	+	+				+	+	+
P. geniculata McLachan			+							+
Polycentropus flavomaculatus (Pict.)		+				+	+	+		
Wormaldia occipitalis (Pict.)							+			
Hydropsyche sp.										+
Limnephilidae	+		+	+		+	+		+	+
MEGALOPTERA										
Sialis fulignosa Pict.	+	+	+					+		

Table 3. (continued).

	Duchray area							L. Chon area		
	9	10	7	5	2	1	6	14	15	13
DIPTERA										
Simuliidae	+	+	++	+	+	+	+	+	+	+
Chironomidae	+	+	+	+	++	+	++	+	+	++
Other Diptera (mainly Tipulidae)	+	+	+		+	+	+	+	+	+
COLEOPTERA										
Platambus maculatus L.	+		+		+	+		+		
Agabus sp.		+								
Oreodytes rivalis Gyll.	+		+		+	+	+	+		
Limnius volkmari (Panz.)					+			+		
Oulimius tuberculatus (Müll.)					+		+	+		
Elmis aenea (Müll.)							+			+
Hydraena gracilis Germar							+			+
Helodidae						+	+		+	+
HYDRACARINA		+						+		

+ Present; ++ More than 30% of animals in any one of the samples taken from that stream.

l^{-1} in the more acid streams to about 25 μeq l^{-1} in the less acid streams. Using the first ionisation constant for weak acids of about 10^{-6} (Glover & Webb 1979), the contribution of such acids to the free acidity is unlikely to be significant, particularly in the more acid, forest streams.

Invertebrates

A list of the species found in the spring collections (kick samples) in 1977 and 1978 and the summer collection in 1977 is given in Table 3. In spring samples the most abundant animals were stoneflies, in particular *Amphinemoura sulcicollis, Brachyptera risi* and *Leuctra* spp. Mayfly nymphs were not found in the more acid streams (nos. 7, 9, 10 and 14) and were most abundant in samples from streams 6 and 13. In summer, Oligochaeta, Chironomidae larvae, and nymphs of the stonefly *Leuctra fusca* predominated, but *Ecdyonurus* spp. and *Baetis rhodani* were found in stream 6 and *Ephemerella ignita, Heptagenia lateralis* and *Ecdyonurus* sp. in stream 13. *Siphlonurus lacustris* was the only mayfly found in the more acid streams. There were no summer collections from streams 5 and 15. Although the stonefly *Chloroperla torrentium* was common in all the streams sampled, the closely related *C. tripunctata* was found only in streams 6 and 13.

In the analysis of Surber samples collected in March 1977 from streams 6, 7, 9, 10, 13 and 14 the animals were grouped into 36 taxa. On comparing numbers of individuals from each stream, no significant difference ($P > 0.05$) was found in 25 of the taxa represented. Significant differences in numbers of the stoneflies *L. hippopus, L. inermis, B. risi, A. sulcicollis, C. torrentium* and *C. tripunctata* were found, but only *C. tripunctata,* present in samples from streams 6 and 13, showed any clear association with streams of a particular pH range. Similarly, the mayfly nymphs *H. lateralis* and *B. rhodani* were present in significantly greater numbers ($P < 0.05$) in streams 6 and 13 than elsewhere, and *Rhithrogena* sp. and *B. muticus* were more abundant in streams 6 and 13 respectively. Only *H. lateralis* (stream 14) and *S. lacustris* (streams 9 and 10) were found in the more acid waters.

When the invertebrates collected in the Surber

Table 4. Biomass (in g^{-1} wet weight) of invertebrate fauna in streams of the Duchray and L. Chon catchments. Figures based on Surber samples taken in March 1977.

	Stream					
	9	10	7	14	6	13
Mean pH	4.1	4.2	4.3	4.7	5.4	6.5
Biomass	0.55	0.77	1.36	1.37	1.32	0.85

Table 5. Survival of eyed salmon eggs (50 eggs per box) planted in three streams in the experimental area on 3 February 1977.

	Dates of inspection and number of live eggs or alevins per box					
	23.3.77	15.4.77				
Stream 9	45	0	1	1	1	
Stream 7	38	5	6	7		
Stream 13	none inspected	40	43	44	46	46

One of the boxes in stream 7 was lost.

Table 6. Survival of newly-fertilised salmon eggs (50 per box) planted in Duchray and Loch Chon streams on 22 and 23 November 1977.

	Number of live eggs per box				
	Forested catchments		Non-forested catchments		
Date of inspection	7	9	2	6	15
9.1.78	4 ± 4	0	43 ± 5	23 ± 6	29 ± 5
2.3.78	0 ± 1	0	39 ± 3	18 ± 6	26 + 2
23.3.78	0	0	not sampled	18 + 3	25 ± 4
[a]20.4.78	0	0	27 ± 7	[b]4 + 6	15 ± 1

[a]Figures for this date include hatched eggs.
[b]Four of the five boxes partly out of water.

samples were weighed no relationship was found between biomass and pH (Table 4).

Fish

An electro-fishing survey failed to reveal any trout in the majority of streams draining the forested catchments (nos. 7, 8, 9, 10, 11). Juvenile trout were found in stream 14, which flows directly into L. Chon, and streams 1, 2, 6, 13 and 15.

Table 5 gives the results of an experiment to determine whether eyed salmon ova would survive in streams 7, 9 and 13.

On 22 and 23 November 1977 sufficient newly-fertilised salmon eggs were planted in five streams to allow for the removal of five boxes per stream at intervals during the period prior to hatching to determine the survival rate of eggs in each stream. The results (Table 6) showed that eggs in the most acid stream (9) died within two months of planting but some eggs in a slightly less acid stream (7) remained alive for three months after planting.

In September 1976, streams which had been stocked with fry in April that year were electrofished but no fry were recovered. Because of the long dry summer it was thought that low water conditions might account for the absence of fish. This was certainly the case in stream 10 which dried up completely. Flowing water between pools was observed in other streams, however, and fish were found in stream 13 even although most of the flow was within the stream bed rather than over it.

Discussion

The ability of vegetation, particularly mature forests, to collect wet and dry deposition ('filtering' effect) has been demonstrated by many workers, e.g. Miller & Miller (1980) and Nihlgard (1970). The extent to which each element is collected depends on the transfer mechanism from the atmosphere to the vegetation surface (Fowler 1980). The collection of marine salts appears to be a simple process whereas that of sulphur and nitrogen gases (and aerosols) is much more complex. The concentration of most elements increases through the forest canopy to the forest floor although throughfall and stemflow water is consistently more acid for coniferous forests than deciduous forests (Nihlgard 1970; Cronan *et al.* 1980). Other concentrating processes such as increasing interception of rain by forests (Calder & Newson 1979) and crown leaching could be important.

If marine salts are excluded from the stream chemistry then sulphate remains as the major anion component. During high flow conditions if excess sulphate is not balanced by calcium and magnesium ions then aluminium and hydrogen ions make up the deficit. Streams draining mature forest catchments have higher sulphate and lower calcium and magnesium concentrations than adjacent moorland streams and consequently have higher aluminium and hydrogen concentrations.

Increased cation leaching and uptake by trees could reduce the base saturation of forest soils (McFee 1977; Nihlgard 1972), and the effects of the elimination of ground vegetation, due to canopy closure, should be investigated further.

The retention time of drainage water is dramatically reduced by the modern ploughing techniques used prior to planting. Later, as the forest matures, the rooting systems become established and

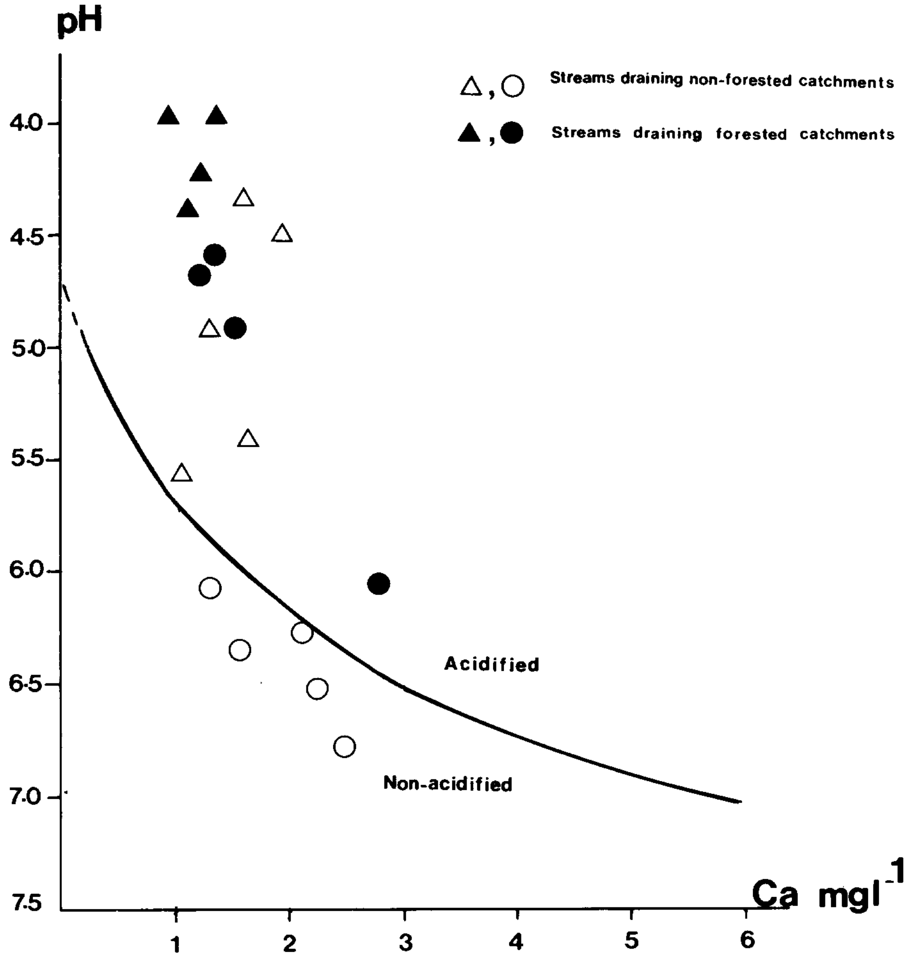

Fig. 4. Comparison of pH and calcium content of forested and non-forested streams during high (▲, △) and low (●, ○) flow conditions. The empirical curve divides acidified from non-acidified waters. (after Henriksen 1979).

channelling of subsurface water could be considerable thus reducing the degree of mixing between incoming precipitation and the neutralising solutions in contact with soil and mineral surfaces (Voigt 1980). Although there are apparent differences between forest and moorland streams, all the streams studied are acidified by acid precipitation. The concept of acidification and the various methods of estimating the extent of acidification are discussed in detail by Henriksen (1979, 1980). In low flow conditions the moorland streams achieve non-acidified status, according to Henriksen's pH/calcium empirical curve, whereas forest streams are permanently acidified (Fig. 4).

The relative production and release of organic acids in forest and moorland soils was not investigated in this study. However, it is most unlikely that, in these relatively clear-water streams, the contribution of dissociated organic acids to the total acidity would be significant, especially when stream pH falls below pH 4.5. Aluminium appears to be an important factor in explaining the variance of weak acid concentrations in surface waters (Henriksen & Seip 1980). Differences in the concentration and speciation of this element in surface waters depends on acidity, the complexing agent and the distribution of aluminium compounds in the soil (Cronan *et al.* 1978; Johnson 1979). It is probable that the high aluminium (and possibly manganese) content of the more acid streams is an important factor in regulating the distribution of fish in these streams (Cronan & Schofield 1979;

Dickson 1978; Driscoll *et al.* 1980).

The harmful effects of acid water on fish have been known for many years (Dahl 1927). Surface waters in the pH range 4.0–4.5 are likely to be harmful to adult salmonids which have not been acclimatised to low pH values, but resistence to this pH range increases with size and age. The range 4.5–5.0 is likely to be harmful to the eggs and fry of salmonids (Alabaster & Lloyd 1980). The survival of the different stages of the life cycle can be influenced by the concentration of other ions: In low conductivity water mortalities have been reported in the pH range 5.0–5.5 (Bua & Snekvik 1972). Freshwater fish, in an unstressed environment, successfully regulate the ion concentrations in their body fluids (Black 1957; Evans 1975), but as water acidity increases towards the lethal limit the uptake of Na^+ ions is strongly inhibited (Packer & Dunson 1970). The transepithelial potential across the gill membrane changes from positive to negative thus allowing preferential absorption of hydrogen ions (McWilliams & Potts 1978). A reduction in the permeability of the gill membrane to Na^+ and H^+ ions can be effected by increasing the calcium content of the water (Cuthbert & Maetz 1972; Eddy 1975). In natural waters where the pH is consistently below pH 4.5, it is likely that increasing mortality among eggs and fry will result in the reduction and eventual elimination of salmonid populations (Jensen 1971; Carrick 1979).

In the more acid streams flowing into the River Duchray, newly fertilised eggs died within a few weeks of planting and few of the planted eyed eggs survived to hatch. Several eggs in these experiments survived for longer than others indicating that there is some variation in the tolerance of salmon eggs to these conditions. This variation may partly explain the differences in survival rate in the other streams. The increased mortality observed in April may well have been due to deaths on hatching since it is known that this is a particularly critical time for fish reared in acid waters (Daye & Garside 1979). Rain during the weeks prior to hatching could also have lowered the pH of the water to a level that was lethal for some of the eggs. Harris (1973) reported considerable variations in the survival of salmon eggs in artificial redds (65.3–99.4%) and experimental egg boxes of the type used here (69.0–99.0%).

There are many reports of laboratory studies to determine the effects of acidity on the various stages of the life cycle of salmonid species. Some species appear to be more resistant than others and differences within species have also been suggested (Carrick 1979; Johansson *et al.* 1977; Daye & Garside 1979; Leivestad *et al.* 1976). Even the reported physiological effects of acidity on fish are sometimes at variance (Westfall 1945; Kuhn & Koecke 1956; Lloyd & Jordan 1964), although such findings are not unexpected when experimental design, test media, genetic differences and other factors (Carrick 1979) are considered. One stress factor encountered in the field, but not usually in laboratory experiments, is the continually changing chemical environment. Large variations in acidity and other ion concentrations can occur regularly in poorly buffered waters and such changes can seriously influence the survival of fish. We found many dead brown trout in an acid loch (pH *ca* 5.0) in south-west Scotland. These fish, stocked 4 days previously, had been reared in hatchery water at about pH 7. The loch still had a population of natural brown trout which had presumably become acclimatised to the changing chemical environment. This reaction to sudden change in pH might account for the disappearance of salmon and trout fry introduced to the Duchray streams during 1976.

The most common feature of the invertebrate samples was the scarcity of mayfly nymphs in the more acid streams. Similar observations have been made by other workers (Jones 1948; Sutcliffe & Carrick 1973). The stonefly *C. tripunctata* was likewise limited in its distribution, being confined to streams 6 and 13 in contrast to the widely distributed and closely related *C. torrentium*. In other respects the fauna in the more acid streams was not atypical, and although the range of species was generally less extensive, representation of the main groups of animals, e.g. insect families, was similar to that found in less acid streams in the area and in other parts of the country (Morgan & Egglishaw 1965). Egglishaw (1964) showed that distribution of *L. inermis, A. sulcicollis, Rhithrogena* sp. and *B. rhodani* in a stream could be correlated with the distribution of plant detritus. Although there was little plant detritus in streams 7, 8, 9, 10 and 11, *A. sulcicollis* was the most abundant animal in samples from streams, 7, 9 and 10, suggesting that in these streams scarcity of detritus may not be the main factor limiting the spread of *B. rhodani* and *Rhithrogena* sp. The absence of these insects from the more acid streams is probably due to unsuccessful attempts at colonisation since the species in question are present in nearby waters. This failure may be a direct consequence of high acidity, but the effects of the high concentration of aluminium and manganese have yet to be studied. The importance of factors other than acidity is suggested by the abundance of the mayfly *S. lacustris* in stream 7, 9 and 10. Outwardly at least this insect is similar to members of the family Baetidae which have not been found in these waters. *S. lacustris* is not confined to acid waters but it has a sporadic distribution, certain aspects of which have still to be explained (Macan 1961).

The figures for invertebrate biomass given in Table 4 indicate that the absence of fish from many of the streams in the area is unlikely to be related to a scarcity of food.

Conclusions

Streams draining forested catchments appear to be more acid and have higher concentrations of the major anions SO_4^{2-} and Cl^- than streams draining adjacent non-forested catchments. The concentrations of aluminium and manganese are highest in the more acid streams.

The distribution of fish and invertebrates in the streams appear to be directly related to stream chemistry, especially acidity and aluminium content. If, as suggested, the intensive cultivation of spruce trees, and associated management practices, reduces the neutralising capacity of the soil then any comparable area subject to acid precipitation would be expected to show the same effects. Preliminary investigations in the Galloway area of south-west Scotland indicates that a similar situation exists in that region.In north-west Scotland, where the mean pH of precipitation is close to pH 5.0, the effects of planting spruce trees might not be as serious although further studies in such areas are required to support this comment.

Summary

1. In Scotland the Forestry Commission follows a policy of intensive cultivation of conifers, predominantly sitka spruce, for the production of wood-pulp. These forests are often in areas where the bedrock is slow-weathering (quartzite, schist or slate) and the geochemical influence on the environment is small.
2. A study of the ecology of 12 streams draining forested and non-forested catchments was made in an area subject to acid precipitation ($pH < 4 \cdot 5$), about 30 km to the north of Glasgow.
3. The streams draining forested catchments are always more acid than the streams draining non-forested catchments and have higher concentration of aluminium and manganese.
4. Brown trout (*Salmo trutta* L.) are present in all streams draining non-forested catchments but in only one of the streams draining old forested catchments.
5. Salmonid eggs were planted in selected streams draining forested and nonforested catchments and their survival was monitored. Results suggest that the absence of trout is probably due to mortality in the early stage of the life cycle.
6. Invertebrate studies indicated similar numbers of animals in all the streams, although in streams draining forested catchments mayfly nymphs were absent from spring collections and in summer the only mayfly nymph present was *Siphlonurus lacustris.*
7. The differences found in the fish and invertebrate fauna appear to be closely related to the content of hydrogen and aluminium in the streams.
8. Spruce forests appear to be effective collectors of acid pollutants and might also denude the soil of base elements thus increasing soil acidity, particularly in the surface horizon. These factors probably combine to reduce the neutralising capacity of the soil which results in higher acidity in streams draining forested catchments.

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References

Alabaster, J. S. & Lloyd, R., 1980. Water Quality Criteria for Freshwater Fish. Butterworth, London.

Almer, B., 1974. Effect of acidification on Swedish Lakes. Ambio 3: 30–36.

Beamish, R. J., 1974. Loss of fish populations from unexploited remote lakes in Ontario, Canada as a consequence of atmospheric fallout of acid. Wat. Res. 8: 85-95.

Black, U. S., 1957. Excretion and osmoregulation. In: Brown, M. E. (ed.) The Physiology of Fishes. Academic Press, New York.

Bua, B. & Snekvik, E., 1972. Kelleforsøk med rogn av laksefisk 1966–1971. Virkning av surhet og saltinnhold i klekkevannet. Vann 7: 86–93.

Calder, I. R. & Newson, M. D., 1979. Land use and upland water resources in Britain – a strategic look. Wat. Resour. Bull. 15: 1628–1639.

Carrick, T. R., 1979. The effect of acid water on the hatching of salmonid eggs. J. Fish. Biol. 14: 165–172.

Cronan, C. S., Reiners, W. A., Reynolds, R. C. Jr. & Long, G. E., 1978. Forest floor leaching. Contributions of mineral, organic and carbonic acids in New Hampshire subalpine forests. Science 200: 309–311.

Cronan, C. S. & Schofield, C. L., 1979. Aluminium leaching response to acid precipitation. Effects on high elevation watersheds in the north west. Science 204: 304–306.

Cronan, C. S., Reiners, W. A. & Reynolds, R. C. Jr., 1980. The impact of acid precipitation on forest canopies and soils in the northeastern U.S. In: Proc. Internat. Conf. Ecological Impact of Acid precipitation, Sandefjord, Norway, pp. 158-159.

Cuthbert, A. W. & Maetz, J., 1972. Effect of Ca^{++} and Mg^{++} on sodium fluxes through the gills of Carassius auratus. J. Physiol. 221: 633-643.

Dahl, K., 1927. The effects of acid water on trout fry. Salm. Trout Mag. 46: 35–43.

Daye, P. G. & Garside, E. T., 1979. Development and survival of embryos and alevins of the Atlantic salmon, Salmo salar L., continuously exposed to acid levels of pH from fertilisation. Can. J.Zool. 57: 1713-1718.

Dickson, W., 1978. Some effects of the acidification of Swedish Lakes. Verh. int. Verein Limnol. 20: 851-856.

Dougan, W. K. & Wilson, A. L., 1974. The absorptiometric determination of aluminium in water. A comparison of some chromogenic reagents and the development of an improved method. Analyst 99: 413–430.

Driscoll, C. T. Jr., Baker, J. P., Bisogni, J. J. Jr. & Schofield, C. L., 1980. Effect of aluminium speciation on fish in dilute acidified waters. Nature 284: 161-164.

Eddy, F. B., 1975. The effect of calcium on gill potentials and on sodium and chloride fluxes in the goldfish Carassius auratus. J. comp. Physiol. 96: 131–142.

Egglishaw, H. J., 1964. The distributional relationship between the bottom fauna and plant detritus in streams. J. anim. Ecol. 33: 463-476.

Elliot, J. M., 1971. Some Methods for the Statistical Analysis of Samples of Benthic Invertebrates. Freshwater Biological Association, Scientific Publ. No. 25, Wilson & Son, Kendal, Cumbria, England.

Evans, D. H., 1975. Ion exchange mechanisms in fish gills. Comp. Biochem. Physiol. 51A: 491-495.

Fowler, D., 1980. Removal of sulphur and nitrogen compounds from the atmosphere in rain and by dry deposition. In: Proc. Internat. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, pp. 22–32.

Glover, G. M. & Webb, A. H., 1979. Weak and strong acids in the surface waters of the Tovdal region in S. Norway. Wat. Res. 13: 781-783.

Gran, G., 1952. Determination of the equivalence point on potentiometric titrations: Part II. The Analyst 77: 661–671.

Harriman, R., 1978. Nutrient leaching from fertilised forest watersheds in Scotland. J. appl. Ecol. 15: 933-942.

Harris, G. S., 1973. A simple egg box planting technique for estimating the survival of eggs deposited in stream gravel. J. Fish Biol. 5: 85–88.

Henderson, G. S., Harris, W. F., Todd, D. E. Jr. & Grizzard, T., 1977. Quantity and chemistry of throughfall as influenced by forest type and season. J. Ecol. 65: 365–374.

Henriksen, A., 1979. A simple approach for identifying and measuring acidification of freshwater. Nature 278: 542-545.

Henriksen, A., 1980. Acidification of freshwaters - a large scale titration. In: Proc. Internat. Symp. Ecological Effects of Acid Precipitation, S.N.S.F. Project Ås - Norway (in press).

Jenson, K. W. & Snekvik, E., 1972. Low pH levels wipe out salmon and trout populations in southernmost Norway. Ambio 1: 223–225.

Johansson, N., Runn, P. & Milbrink, G., 1977. Early development of three salmonid species in acidified water. Zoon 5: 127–132.

Johnson, N. M., 1979. Acid rain: neutralisation within the Hubbard Brook ecosystem and regional implications. Science 204: 497–499.

Jones, J. R. E., 1948. The fauna of four streams in the 'Black Mountain' district of South Wales. J. anim. Ecol. 17: 51-65.

Kuhn, O. & Koecke, H. U., 1956. Histologische und cytologische Veränderungen der Fischkieme nach Einwirkung in Wasser enthaltener schädigender Substanzen. Z. Zellforsch. mikrosk. Anat. 43: 611-643.

Leivestad, H., Henry, C., Munz, I. P. & Snekvik, E., 1976. Effect of acid precipitation on freshwater organisms. In: S.N.S.F. Project Research Report 6. Impact of acid precipitation on forest and freshwater ecosystems in Norway 86–111.

Likens, G. E., Bormann, F. H., Pierce, R. S., Eaton, J. S. & Johnson, N. W., 1977. Biogeochemistry of a Forested Ecosystem. Springer-Verlag, New York.

Lloyd, R. & Jordan, D. H. M., 1964. Some factors affecting the resistance of rainbow trout (Salmo gairdnerii) to acid waters. Int. J. Air Wat. Pollut. 8: 393-403.

Macan, T. T., 1961. A Key to Nymphs of the British Species of Ephemeroptera. Freshwater Biological Association, Scientific Publication No. 20.

Mackereth, F. J. H., Heron, J. & Talling, J. F., 1978. Water Analysis: Some Revised Methods for Limnologists. F.B.A. Scientific Publication No. 36.

McFee, W. W., Kelly, J. M. & Beck, R. H., 1977. Acid precipitation effects on soil pH and base saturation of exchange sites. Wat. Air Soil Pollut. 7: 401-408.

McWilliams, P. & Potts, W., 1978. The effects of pH and calcium concentrations on gill potential in the Brown Trout. J. comp. Physiol. 126: 277–286.

Miller, H. G. & Miller, J. D., 1980. Collection and retention of atmospheric pollutants by vegetation. In: Proc. Int. Conf. Ecological Impact of Acid Precipitation Sandefjord, Norway 33-40.

Mills, D. H., 1967. A study of trout and young salmon populations on forest streams with a view to management. Forestry 40 Suppl.: 85-90.

Morgan, N. G. & Egglishaw, H. J., 1965. A stream survey of the bottom fauna of streams in the Scottish Highlands. Part I. Composition of the fauna. Hydrobiologia 25: 181-211.

Nihlgard, B., 1970. Precipitation, its chemical composition and effect on soil water in a beech and spruce forest in south Sweden. Oikos 21: 208-217.

Nihlgard, B., 1972. Plant biomass, primary production and distribution of chemical elements in a beech and planted spruce forest in south Sweden. Oikos 23: 69–81.

Packer, R. K. & Dunson, W. A., 1970. Effects of low environmental pH on blood and sodium balance of Brook Trout. J. exp. Zool. 174: 65-72.

Rosenqvist, I. Th., 1978. Alternative sources for acidification of river water in Norway. The Science of the Total Environment 10: 39-49.

Schofield, C. L., 1976. Acid precipitation: effects on fish. Ambio 5: 228-230.

Seip, H. M. & Tollan, A., 1978. Acid precipitation and other possible sources for acidification of rivers and lakes. The Science of the Total Environment 10: 253-270.

Smith, B. D., 1980. The effects of afforestation on the trout of a small stream in southern Scotland. Fish. Mgnt. 11: 39–58.

Standing Committee of Analysts, 1978. Methods of Biological Sampling, Handnet Sampling of Aquatic Benthic Macroinvertebrates. Department of the Environment/National Water Council. HMSO London.

Sutcliffe, D. W. & Carrick, T. R., 1973. Studies on mountain streams in the English Lake District 1. pH, calcium and the distribution of invertebrates in the River Duddon. Freshwat. Biol. 3: 437–62.

Voigt, G. K., 1980. Acid precipitation and soil buffer capacity. In: Proc. Internat. Conf. Ecological Impact of Acid Precipitation, Sandefjord, Norway, pp. 53-57.

Westfall, B. A., 1945. Coagulation anoxia in fishes. Ecology 26: 283–287.

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