SHORT ARTICLES AND REVIEWS

A DECADE OF STUDIES AT LOCH FLEET, GALLOWAY (SCOTLAND): A CATCHMENT LIMING PROJECT AND RESTORATION OF A BROWN TROUT FISHERY

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Introduction

Loch Fleet is a small upland lake in the hills of Galloway, in southwest Scotland (see photograph on the front cover of this issue, and Figs 1-3). The waters of the loch became more acidic in the 1970s and a brown trout fishery in the loch had failed. The following account, intended for the general reader, summarises an experimental project designed to reverse acidification of the loch by liming parts of the catchment, and we describe briefly the changes that have occurred in limed soils on the catchment, water chemistry in streams supplying the loch, the re-establishment of the trout fishery, and some associated changes in terrestrial and wetland ecosystems on the catchment.

The "Loch Fleet Project" was initiated early in 1984 as a pragmatic approach to reversing acidification and its associated fishery loss, with support and funding from the national coal and electricity industries. While the restoration of many acidified waters in Sweden had been achieved by direct addition of neutralising materials to lakes and streams, this was inappropriate in conditions found in the United Kingdom where acidified waters are usually found in western upland regions of heavy rainfall and rapid runoff. In such conditions, catchment liming would provide a longer-lasting neutralising reserve within soils. Moreover, catchment liming seemed to be a logical approach to counter the progressive acidification of base-poor soils resulting from 150 years of sulphur deposition. However, few attempts to lime catchments on any field scale had been made when the Loch Fleet Project was initiated.

For development of an effective and acceptable catchment liming practice it was necessary to approach the task in a scientific and objective way. The general aims, within which more specific objectives were to be achieved, were basically twofold: to demonstrate that water chemistry of a lake can be brought into a range suitable for trout by one or more of several treatments to the catchment or waters, including the addition of basic minerals to soils and/or waters, or the manipulation of the ion-exchange system of soils, e.g. by burning surface vegetation and soil, and to demonstrate the suitability of the water for a self-sustaining trout population when suitable chemical conditions had been achieved within the lake.

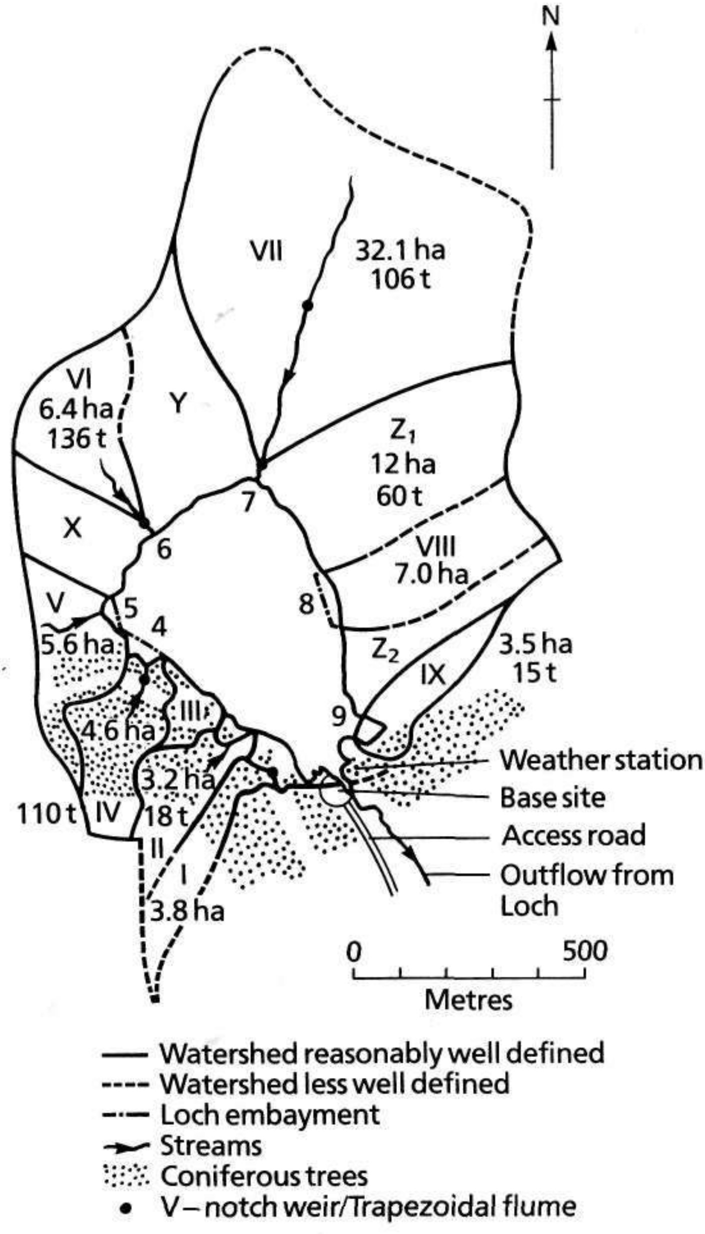
The initial 5-year programme of work was implemented through in-house and independent contracts. "Background" conditions were established before liming, a variety of preliminary tests were made, and equipment was installed. Sectoral treatments (Fig. 2) were planned within the catchment on the basis of laboratory and on-site field trials. Changes in water chemistry were followed from the start, with emphasis on major ionic constituents including aluminium. After liming in 1986, the loch was restocked with brown trout and their survival or success as a self-sustaining population was monitored. The outcome of much of this first phase of the project has been reported in detail by Howells & Dalziel (1992), which should be consulted for references to the original publications and reports, and methods used. Aspects of the work are also summarised by Howells et al. (1992).

While the first 5-year programme had met the specified objectives, a further 5-year surveillance period was undertaken, with revised objectives. These were to continue monitoring the post-liming water quality and the fate and health of the re-established trout population, and to study any possible adverse effects of liming on aquatic and terrestrial ecosystems.

The decade of investigation, now completed, of this small acid upland catchment in southwest Scotland has provided detailed insight into the characteristics of its terrestrial and aquatic components and its response to a variety of field interventions. Along with meeting the original aims, changes in non-target components of the ecosystem have been followed over time; as lime effectiveness inevitably declines, soil and water reacidification will occur. This unique and complex endeavour thus provides an opportunity to improve understanding both of acidification and its remediation.

FIG. 1. Loch Fleet and part of its catchment, with nearby Loch Grannoch beyond and Cairnsmore of Fleet (710 metres above sea level) in the background. The main inflow to Loch Fleet (the Altiwhat) is at the right of the picture and the outflow is on the left. The enclosures visible in the loch were used to study changes in water quality and biological communities independent of fish restrocking. Aerial photograph by Brian Acland, CEGB.

FIG. 2. *(Opposite, on page 7).* Loch Fleet, showing subcatchments (sectors) and total limestone applications made in 1986 and 1987. The stream draining sector VII, the Altiwhat, is the single natural nursery area for brown trout (also see picture on front cover of this issue).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IX
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3.2 ha
Weather station
Base site
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IV
18 t
Access road
II
Outflow from Loch
I
3.8 ha
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500
Metres
Watershed reasonably well defined
Watershed less well defined
Loch embayment
Streams
Coniferous trees
V – notch weir/Trapezoidal flume

The Loch Fleet environment

The catchment of Loch Fleet drains a granitic area of 111 hectares draining to the loch which lies at an altitude of 340 metres above sea-level. The loch, 1 7 ha in area and maximum depth 15 m, is the principal source of the Little Water of Fleet. This joins the Big Water of Fleet at Akiehill, about 12 km below the loch, eventually discharging into Wigtown Bay at Gatehouse of Fleet.

Loch Fleet lies within the Cairnsmore of Fleet granite intrusion. The peaty and granitic nature of the upper catchment is reflected in its acidic, low calcium runoff waters. In the lower catchment, below the Craigie Linn (a sill which marks the edge of the granite pluton) 7 km below the loch, soils are derived from fluvioglacial drift and river water quality improves. While the upper catchment is predominantly moorland, formerly used for rough grazing, the lower catchment is heavily afforested until, towards the coast, mixed farming prevails on the more alluvial soil. In these lower reaches there is a mixed but sparse fish population of salmon *(Salmo salar),* brown and sea trout *(Salmo trutta),* eel *(Anguilla anguilla)* and minnow *(Phoxinus phoxinus).*

The upper Loch Fleet catchment has a rigorous climate; it is classed as exposed, cool and wet. Rainfall is in excess of 200 centimetres a year, prevailing winds are westerly and strong, and air-temperatures in the region vary between only 550 to 1100 cumulated day-degrees Celsius. The acidity of rainfall has a mean pH of ca. 4.7 (i.e. a hydrogen concentration of 21 micro-equivalents per litre), and the chemical composition of rain is often influenced by the presence of sea-salts; indeed, sodium and chloride (major components of sea water) are respectively the major cation and anion in rain throughout the year.

In the adjacent area of Galloway there are eleven other acid lochs (pH below 4.8) draining granitic catchments; five have pH below 4.6 and are fishless. Thus the Loch Fleet Project has relevant implications for the region, and perhaps for other areas with similar geological, climatic and atmospheric conditions.

Acidification and the decline of brown trout

A fishery for brown trout *(Salmo trutta)* in Loch Fleet was managed by the Cally Estate (Gatehouse of Fleet). It provided sport for a small group of anglers who visited the site on foot to gain bags of up to 40 small trout in a single day, with an overall catch of about 150 trout a year (1940-1950). In the 1960s, however, the catch fell sharply, and in spite of efforts at restocking it had failed completely by 1970. Occasional summer pH measurements of the loch water in the 1960s are reported to have been about pH 6.0. The remains of diatoms in sediment cores taken from the loch were used to construct historical values for pH in the loch waters (Battarbee et al. 1992); the results suggest that, following afforestation in the area in the 1960s, there was a period of rapid soil erosion (attributed to pre-planting drainage) and severe acidification of the loch followed in about 1975. Afforestation (less than 10% of the catchment) may have enhanced the rate of acidification due to erosion associated with preparations for planting, or subsequent aerosol scavenging by the developing tree canopies, and may have resulted in more rapid acid drainage. Whether or not afforestation or a longer-term progressive acidification of soils was the principal cause, water quality by 1980 was inadequate for brown trout, with pH values in the range 4.0 to 4.5 and calcium concentrations below 0.5 milligrams per litre. When the Loch Fleet Project started in 1984, no fish were found in the loch and only a few eels were captured by electrofishing below the loch outflow.

Rain and water quality at Loch Fleet

Atmospheric deposition (i.e. rainfall and dry deposit) plays a large part in determining the quality of surface waters in upland areas, but the characteristics of the catchment soils and vegetation, and the intimate reactions that occur during soil permeation and drainage, are critical. Early measurements at Loch Fleet demonstrated the inability of the catchment to neutralise the deposited acid input, and there was a variable response from different sectors, with afforested sectors producing the most acid runoff. Indeed, the loch water itself was significantly more acid (pH 4.0 to 4.5) than the incoming rain (mean pH 4.7).

During the period 1985 to 1993, annual rainfall has averaged 2295 millimetres per year (Meteorological Office Solid State Event Recorder), nearly 10% higher than the Meteorological Office 30-year average of 2100 mm per year for the area, with a weighted mean hydrogen ion (H^+) concentration of 21.3 micrograms or microequivalents per litre (Table 1). Rainfall varies seasonally and year by year; it was less than average in 1989 and 1993, and exceeded it in other years, particularly in 1988 and 1992. Concentrations of acidity and sulphate in rain also vary but weighted mean concentrations varied little between 1985 and 1994. Estimated minimum (i.e. "bulk" deposition only) loads deposited annually were ca. 0.05 g hydrogen and 2.05 g non-marine sulphate per m^2 of catchment (Table 1), or ca. 0.5 kg and 20 kg per hectare respectively.

Thus, in the context of regional records for Scotland and for western European sites (Hornung et al. 1990), Loch Fleet receives only moderately acid rain but has an "acid loading" as high as acidified sites elsewhere in Europe and Scandinavia. In-catchment processes, including evapo-transpiration (estimated at ca. 30% for forested upland areas in Scotland),

FIG. 3. The wetland source area of the Altiwhat on Sector VII of the Loch Fleet catchment. This area was treated in 1986 with lime distributed in and around the pools and soakaways.

FIG. 4. Transporting bags of powdered lime by helicopter from a depot just outside the Fleet catchment.

raise most of the major ion concentrations in the loch water above those in rain (Table 1), but ammonia (as ammonium ions, NH_4^+) is seldom present in the loch outflow, and nitrogen (as nitrate ions, NO^-_3) is also low, especially during the summer months, suggesting that productivity in the loch may be limited by the amount of N available. Even in this base-poor catchment, however, concentrations of the base cations calcium and magnesium are almost doubled in the loch, compared with runoff concentrations, possibly due to a base-rich ground-water flow (2.3 milliequivalents of calcium + magnesium per litre each second) in the northeast corner of the loch.

Table 1. Mean concentrations and annual amounts of major ions in rainwater (bulk precipitation) at Loch Fleet for a 10-year period, 1984–1994.

Ions	Concentration (μequiv. l^{-1})	Annual fluxes (g m^{-2} $year^{-1}$)
H^+	21	0.05
NH_4^+	20	0.83
Na^+	113	5.85
K^+	1.9	0.16
$Ca+Mg^{2+}$	32	1.42
Cl^-	133	10.62
NO_3^-	20	2.85
SO_4^{2-}	57	6.13

Table 2. Mean concentrations (μequiv. l^{-1}) of major ions in runoff from sector V (1984–1994), and in the outflow of Loch Fleet before (1985–86) and after (1993–94) liming.

Ions	Runoff from sector V	Outflow pre-liming	Outflow post-liming
H^+	106	82	6
Na^+	231	179	187
K^+	0.4	0.8	3.3
$Ca+Mg^{2+}$	88	132	163
Cl^-	268	225	209
NO_3^-	8	15	14
SO_4^{2-}	162	101	100
Alk (HCO_3^-)	0	0	56

The maritime nature of the site is evident in the high input of sodium and chloride in rain, particularly enhanced in episodes of "sea-salt" rains during westerly storms in winter months. These raise the pH of rain towards circumneutral values, but paradoxically lead to acid episodes in storm runoff as the soil exchanges its stored hydrogen and aluminium ions for the readily available sodium ions deposited in the salty rain. Another maritime effect is the contribution of marine aerosol sulphate, which accounts for about 30% of the sulphate input in rain at Loch Fleet.

Before lime was applied in 1986, water quality in the loch was unsuitable for fish, but quickly responded to the liming treatments applied in 1986 or 1987 (Table 2, and next section). The adverse water quality, with low pH and calcium, continued in runoff from untreated sectors of the catchment, and this moderated the overall effectiveness of lime applied to about 30% of the total area. A "control" moorland sector V (see Fig. 2) was monitored over the decade of our study, and has maintained its adverse water quality throughout, with a current (1994) pH below 4.0.

Application of lime to sectors of catchment in 1986 and 1987

After preliminary investigations made through 1984 and 1985, lime was applied (as fine powder, or a slurry, or pellets of calcium carbonate) to selected sectors of the Loch Fleet catchment; these treatments and some others are summarised in Table 3. The treatments were undertaken early in April 1986, when three sectors were limed, and in April 1987 when some other sectors received smaller applications of lime; a mixed (NPK) general fertiliser was also spread on sector I (and sector II) in June 1987. Applications were made by hand from depots set up by helicopter (Fig. 4), except for sector IV where lime slurry was sprayed beneath the tree canopy, and sector IX where pellets were distributed from a helicopter.

Effects on water quality after large applications of lime to sectors IV, VI and VII in 1986

In April 1986, lime was applied at a nominal 20, 30 and 10 tonnes per hectare respectively on sectors IV, VI and part of VII (Table 3). The most evident change in runoff from these limed sectors was an immediate rise in pH and calcium concentrations, and a fall in aluminium (especially the toxic monomeric inorganic fraction); a slower and more moderated response was observed in the outflow of the loch (Fig. 5). Since liming, the runoff from these sectors has maintained water quality above the conservative target set to ensure survival of brown trout, i.e. pH above 6.0, calcium concentrations above 2 milligrams per litre (100 microequivalents or 50 micromoles of Ca^{2}+ per litre), and total aluminium concentrations below 100 micrograms per litre (Howells & Dalziel 1992).

The calcium concentrations and pH in runoff from sectors IV and VI still exceed those before lime was applied but, in the main spawning stream, the Altiwhat on sector VII, and in the loch itself, water quality is now

(1994) declining, with low pH and calcium concentrations (Fig. 5). However, although total aluminium concentrations increased in 1993/94, the toxic inorganic fraction remains low.

Effects on water quality after adding smaller amounts of lime and/or fertiliser to sectors I, II, Z1 and IX in 1987

The response of sectors receiving smaller amounts of lime and some other treatments in 1987 (Table 3) was less spectacular, but has interest in the context of practical land management. In sector Z1, where ca. 5 tonnes of lime per hectare was spread in 1987, and sector IX which received similar amounts of lime, mean pH in runoff samples was raised to 6.4 and 6.3 respectively, immediately after liming, and was reasonably maintained at 5.7 and 5.9 through to 1993/94. Calcium concentrations also rose immediately to 3.6 and 5.1 mg per litre respectively, and were maintained at 3.5 and 3.7 mg per litre. A slower and more sustained response observed on sector IX may be due, perhaps, to the application of lime in the form of pellets instead of fine powder.

On sector II, a mixed treatment consisting of adding both lime and general NPK fertiliser was used to test the theory that nitrogen in rainfall (as ammonium ions, NH_4^+) could have an acidifying effect on the rhizosphere, i.e. the upper soil layers where plant root activity occurs (Nilsson et al. 1982) and thus on runoff. Prior trials on individual trees seemed to be promising (Nisbet & Nisbet 1992). Sector I, treated with fertiliser but not limed, served as a control. Although calcium in runoff from sector II was raised from ca. 0.5 to 2.8 mg per litre, the concomitant rise in pH was not substantial; pH was only 4.5 after the application of lime and fertiliser, and in 1993/94 the mean pH was down to 4.0, close to that recorded in 1984. Some fertilising effect (represented by potassium and nitrate in runoff) was evident in the three years following treatment. In sector I, the application of fertiliser had no significant effect on the pH of runoff, although higher concentrations of potassium and nitrate were also present immediately after treatment and in the following two years. The greater effectiveness of the lime application to sectors Z1 and IX suggests that the base cation demand of forest exceeds that of moorland.

Effects on water quality after burning the moor on sector VIII in April 1987

Observations on runoff from a forested area in Norway, following a forest fire, showed a rise in pH (Rosenqvist 1985); the hypothesis was that uncultivated terrain becomes more acid over time due to acidifying processes in the rhizosphere and that acid soil conditions can be reversed by burning. "Muirburn" is a common upland management practice in

Table 3. Treatments applied in 1986 and 1987 to sectors I, II, IV-IX and Z1 on the catchment of Loch Fleet.

Sector	Area (ha)	Year	Treatment	Application rate (tonnes per ha)	Totals per sector (tonnes)
I (forest)	3.8	1987	Fertiliser	1, below the canopy	4 fertiliser
II (forest)	3.2	1987	Lime + fertiliser	5 1	18 lime + 4 fertiliser
IV (forest)	4.6	1986	Lime slurry	20, below canopy	110 lime
V (moor/ forest)	5.6	1986/7	None ("control")	None	None
VI (moor)	6.4	1986	Lime dust	30, spread over surface	135 lime
VII (moor)	32.1	1986	Lime dust	10, in wetland area (10 ha)	106 lime
ZI (moor)	12	1987	Lime dust	5, spread over surface	60 lime
VIII (moor)	7	1987	Muirburn	None	None
IX (moor)	3.5	1987	Lime pellets	7.5, spread on surface (2ha from the air)	15 lime

northern Britain, where dry moorland vegetation is burnt off in the spring, principally to encourage new growth of heather *{Calluna);* this was done on sector VIM in April 1987.

The consequences of the muirburn at Loch Fleet were not encouraging, however, as mean pH (4.2) and calcium (0.55 mg per litre) in runoff remained much as before, aluminium levels remained high, and even an expected short-term increase in nutrients was scarcely evident. One reason may have been the very wet conditions prevailing at the time of the burn, limiting the rise in soil temperature (maximum 75°C) although above-ground vegetation burned effectively.

Soil conditions before and after liming

The soils of the catchment are derived from the weathered granitic bedrock, with little glacial till underlying the substantial peaty deposits which cover more than 90% of the catchment. Waterlogging and

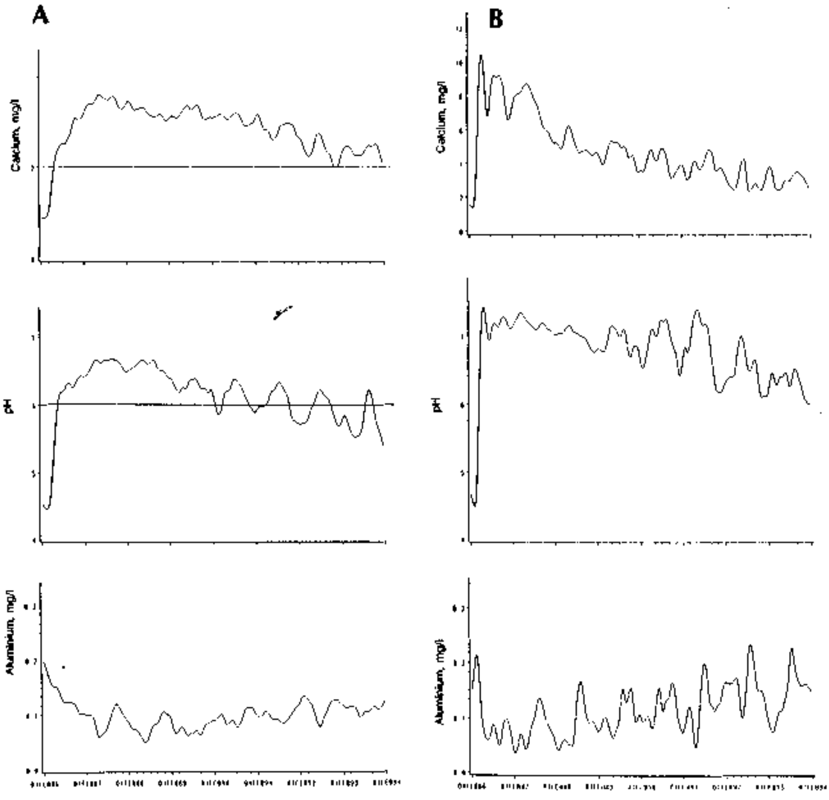


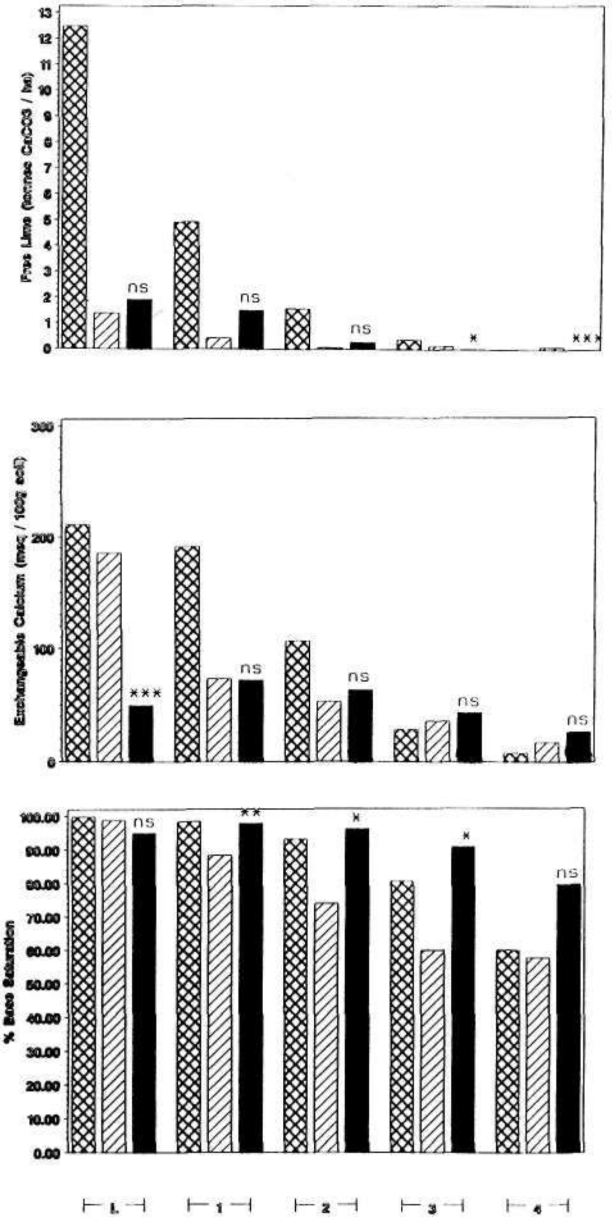
FIG. 5. Concentrations of calcium (mg per litre), pH, and aluminium (mg per litre) from February 1986 to February 1994; (A) in the Loch Fleet outlet, (B) in the Altiwhat, sector VII. Part of sector VII was limed in April 1986. Note the different scales used for calcium in (A) and (B); the horizontal line in (A) shows the "target" calcium concentration (2 milligrams or 100 microequivalents per litre) specified for a self-sustaining population of brown trout, coupled with a target pH of 6.0.

anaerobic conditions are found on gentler slopes. Some natural erosion of the peat on the exposed col (sector VII) draining to the Altiwhat has occurred in the past. The basal layers of the peat contain some mineral material but they are relatively impermeable and strongly acid (range pH 2.5 to 4.6), and low in calcium and magnesium. Prior to liming, such acid soils (mean pH 2.9 for more than 50 soil samples, suspended in calcium chloride), when exposed to high deposition of ions from rain, release aluminium first to the soil solution and then to runoff. In the high flow conditions associated with westerly storms, acid stream episodes occur, even though the westerly rain is only moderately acid.

Following applications of lime, as expected, there were immediate changes in the upper soils (Wilson & Bache 1995); base saturation increased to nearly 100% in the upper soil horizons within 6 months after application of lime (for example in sector IV, Fig. 6). Exchangeable calcium was replenished by dissolution of free lime, providing a long-term source of calcium to buffer acid inputs. Soil sampling in 1991 showed, however, that the free lime had already become reduced and runoff calcium was being supplied by the replenished pool of exchangeable calcium, now decreasing 5.5 years after liming (Fig. 6). Although some free lime in the upper soil layers is still present in places, it may have become unavailable, physically or chemically. Some of the lime has also seeped down to lower soil horizons and may be below the level of hydrological exchange. These processes could be important limitations of effective longevity of lime treatments.

Predictions from soil analysis (Wilson & Bache 1995) indicate that runoff from sectors IV and VI may fall to pre-liming values by the end of 1995, approximately 9 years after liming, although extrapolation from stream calcium concentrations (Dalziel 1995) indicates a longer period. For sector VII, drainage has reduced the soil base reserves in the 10-hectare limed area, and although some lime remains, water quality is now (1994) close to the limit of desired water quality. Smaller applications of lime in other sectors may have similar longevity but cannot be quantified in the same way, since stream/runoff flows were not measured directly. However, calculations based on calcium fluxes (Dalziel 1995) from sectors IV, VI and VII suggest that a large part of the applied lime remains in the catchment; to 1993 only about 20% of the applied lime had been discharged in runoff from sectors IV and VI, while about 40% had been released from sector VII. It is also evident that the loch is dependent on the volumes of flow from limed and unlimed sectors of the catchment. Since Sector VII provides the major flow of improved water quality, loch conditions cannot be better than that of the Altiwhat while acid deposition is unabated.

FIG. 6. *(Opposite, on page 17). (Upper)* Mean free lime (tonnes of $CaC0_3$ per hectare), *(middle)* mean exchangeable calcium (milliequivalents per 100 grams of soil) and *(lower)* mean percent base saturation, in 10 soil cores taken in 1987 (hatched bars), 1988 oblique bars) and 1991 (solid bars) from the forested area of sector IV on the Loch Fleet catchment. The five groups of bars in the text-figure represent (from left to right): (L), surface litter; (1), 0 to 2.5 cm depth; (2), 2.6 to 5.0 cm depth; (3), 5.1 to 10.0 cm depth; (4) 10.1 to 15.0 cm depth, ns = not significant; * significant at 5% level, ** significant at 1% level, *** significant at 0.1% level.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Consistent with our understanding of the mechanism of aluminium mobilisation in acid conditions, the higher pH of limed soils has resulted in lower aluminium concentrations in runoff, particularly the toxic inorganic fraction. This component remains low in section VII, in spite of pH below 5.0 in stream water at times; it may remain low until aluminium again saturates the soil exchanger.

Calculating the effectiveness of liming the catchment

Considerable attention has been given to predicting the effectiveness (or longevity) of the main liming treatments applied in 1986. Water quality improved rapidly to meet the needs of brown trout but for how long would the treatments continue to maintain water quality suitable for trout reproduction?

Early predictions made in 1989, based on 3.5 years of post-treatment hydrochemical flux data for calcium (Dalziel et al. 1991) suggested that water quality would be maintained through to the year 2000 by the high calcium concentrations in runoff from sectors IV and VI, even though for sector VII it would fall below the target threshold in 1992/3 (Fig. 7). These predictions proved to be broadly correct (Dalziel 1995), with the exception of sector VII, for which they were slightly pessimistic. However, recent water quality measurements from sector VII (October 1993 to March 1994) show that pH fell occasionally to 4.8, although calcium and inorganic aluminium remain satisfactory. The expectation is that water quality will soon decline further and will not meet the desired target. pHs in runoff water from sectors IV and VI remain as predicted, still considerably higher than those found before liming.

What, then, is the prognosis for the time period over which the loch water quality will remain satisfactory? How is effectiveness influenced by the "application dose" or the area treated? Does the way in which lime is applied change its effectiveness, i.e. delivery in runoff? Our records at Loch Fleet for the major (1986) and minor (1987) applications of lime provide the basis of the following analysis.

In the year before liming (mid-April 1985 to mid-April 1986), the amounts of calcium delivered in runoff from sectors IV, VI and VII were respectively 130.9 kg, 96.2 kg and 636.9 kg, or a total of 864 kg from 43.1 hectares, representing about 40% of the Loch Fleet catchment. This amount can be described as the "background" calcium contribution. Assuming, pro rata, uniform calcium export for the whole catchment excluding the loch (i.e. 111 ha), calcium export would be 2225 kg. This "background" would include the calcium in rain but not that of ground water (calcium 34.5 mg per litre; estimated flow 1 litre per second). Flow measurements made at the loch outlet for the preliming year, 1985-1986,

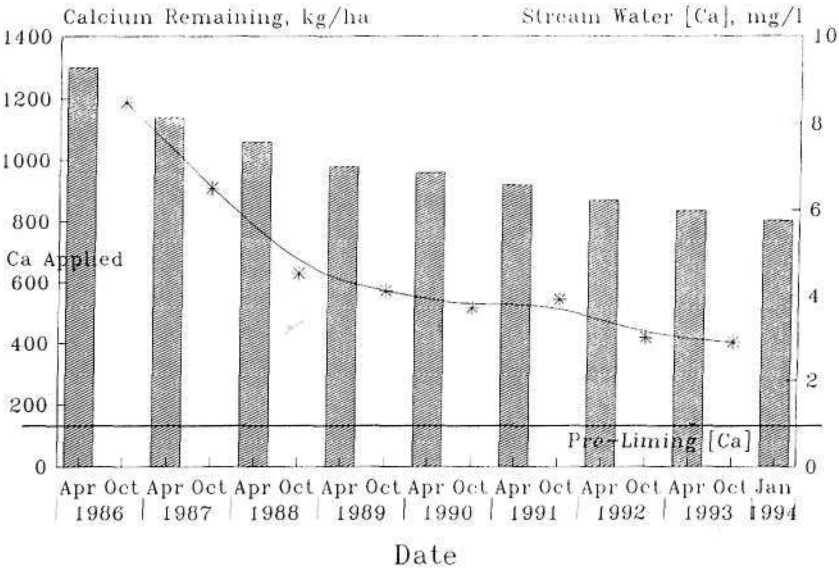


FIG. 7. Amounts (bars) of calcium (kg per ha) remaining each year (April) on the sector VII of the Loch Fleet catchment. The bar for April 1986 shows the total amount of lime applied per hectare on sector VII. Superimposed are the mean annual concentrations (*) of calcium (mg per litre) in the stream water (Altiwhat), April to April, following liming, with the trend drawn through these points. The preliming concentration in the Altiwhat was about 1 mg calcium per litre (horizontal line).

showed that 2.42×10^9 litres flowed from the loch, with a calculated calcium concentration of 0.91 mg per litre, close to the mean of 0.92 mg per litre measured during that year.

The target calcium concentration after liming was set at a minimum of 2 mg per litre. Over the period 1985 to 1991, during which time hydrochemical flux calculations were made, mean annual water loss from the loch outlet was 2.19×10^9 litres. To maintain a loch calcium concentration 1.1 mg per litre above the pre-liming level of 0.9 mg per litre, an additional 2149 kg of calcium is required, and this must come from the limed sectors IV, VI and VII, as well as their background contribution of 864 kg, i.e. a total of 3273 kg. The contribution from the smaller lime applications in 1987 has been ignored, while any rain or ground water contribution is considered unchanged, although both may indeed vary.

Using measured stream-water calcium concentrations (Dalziel et al. 1991), amounts of calcium contributed by each sector and related stream

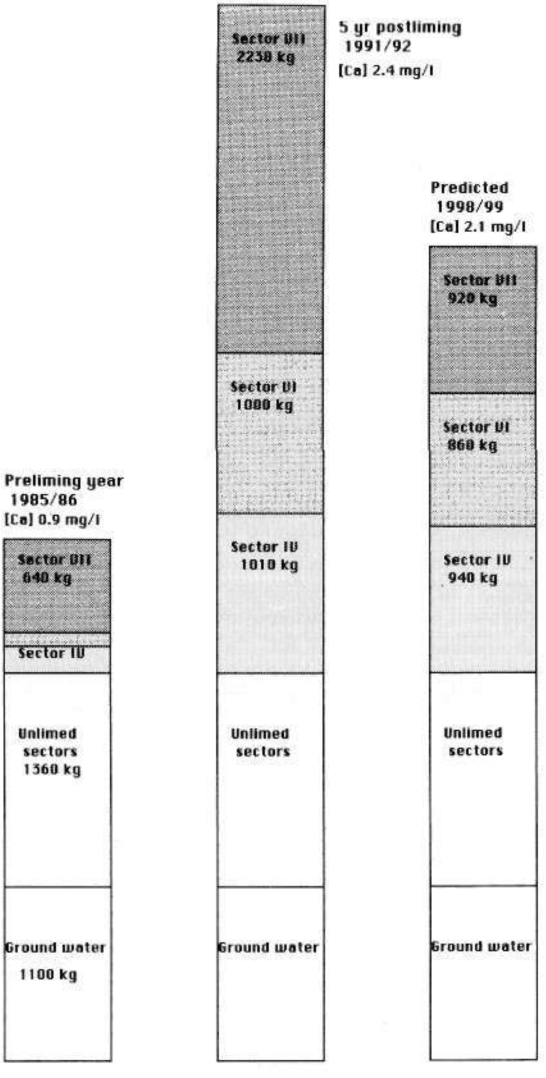


FIG. 8. Annual calcium flux from limed and unlimed sectors of the Loch Fleet catchment, for the pre-liming year 1985–86, five years after liming (1991–92), and that predicted for 1998–99. Estimated contributions from unlimed sectors and ground water are considered to be unchanging, and that from rain will have been included in the sectoral components. The measured mean and predicted calcium concentrations [Ca] in loch outflow are also included. The diagram is not drawn strictly to scale.

calcium concentrations can be predicted; for stream water coming from sectors IV and VI, calcium *concentrations* will remain well above pre-liming values until at least the end of the century (14 years after application). However, the *amounts* of calcium contributed by these two sectors will not be sufficient to maintain satisfactory loch water quality to this date. The contribution of sector VII, where the high and consistent volume of water discharged by the Altiwhat makes a greater contribution than the more alkaline but lower volume discharges from sectors IV and VI, is crucial. Earlier predictions, based on amounts of calcium contributed from all three sectors, suggested that the loch water calcium would fall below the 2 mg per litre target concentration sometime in 1993/4 (when the total calcium contributed from the three sectors would fall below 3273 kg) (Fig. 8). But this has not happened - the mean calcium concentration over the period October 1993 to March 1994 was 2.45 mg per litre. Thus, while the predictions for sectors IV and VI turned out to be broadly correct, that for sector VII was somewhat pessimistic. A small correction in the calcium concentration for the Altiwhat results in a proportionately greater change in the amount of calcium contributed from that sector.

These calculations serve to show the importance of considering total *amounts* of calcium contributed, rather than concentrations alone. They also emphasise the need, *inter alia,* to target catchment liming to areas that will provide sufficient export of applied calcium to the stream-flow and to the receiving water-body.

The brown trout fishery

Laboratory and field tests established that, before liming, the loch waters would not support survival of local strains of brown trout (Turnpenny 1992). A target water quality for the survival of eggs and fry was defined to ensure that a healthy population would develop. Following improvements in stream and loch water quality, three trout stocks were reintroduced to Loch Fleet, in 1987 and 1988, and their fate was monitored. Since then a self-sustaining population of brown trout has developed (Turnpenny et al. 1995); its future is dependent on the water quality but also depends on the limited spawning capacity of the Altiwhat. Over the last five years the population has continued to increase, although poor fry production (possibly due to adverse conditions in the Altiwhat during spring) has led to a current bias towards fish aged 3+ and 4+ years (Fig. 9). The stock of 1+ and older fish was estimated to be 2740 ± 841 from a catch, mark and recapture exercise in 1993. The median size (length) of fish older than age 1+ years is about 200 mm.

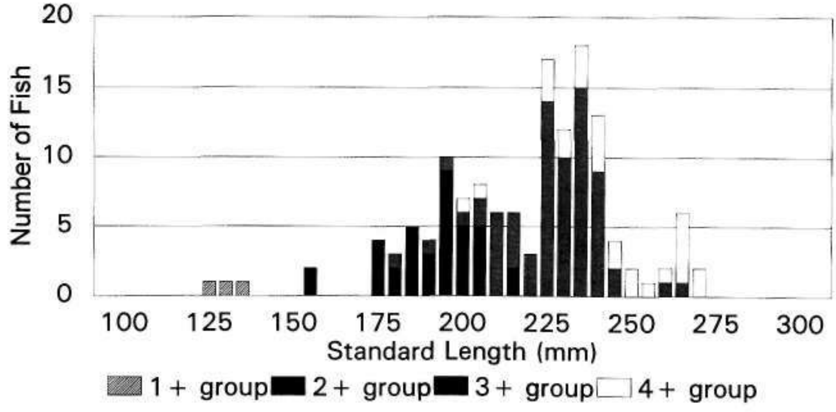


FIG. 9. The length-frequency distributions for four year-classes of brown trout caught in Loch Fleet in July 1993.

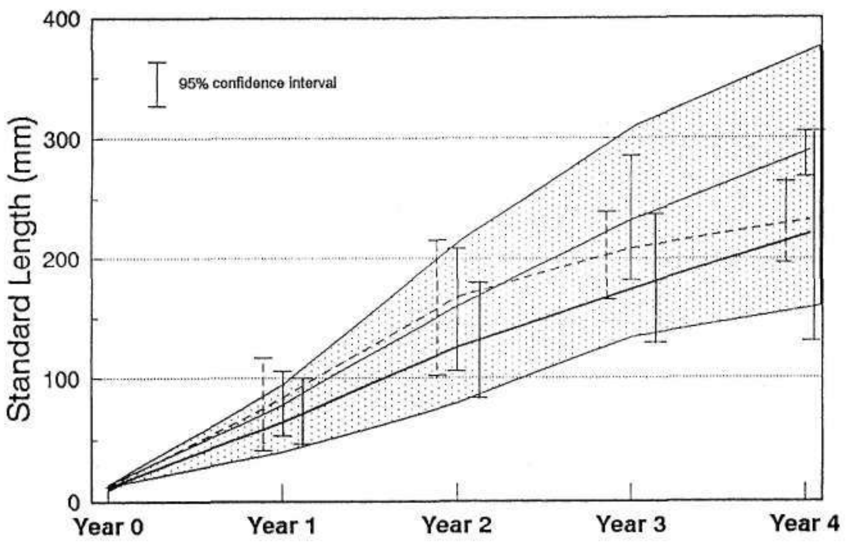


FIG. 10. Growth of brown trout in Loch Fleet, based on samples taken in 1988–1990 (upper solid line), 1992 (lower solid line) and 1993 (dashed line); vertical bars show 95% confidence intervals for mean standard body length (mm) in five year-classes. The extreme upper and lower lines enclose the 95% confidence intervals (dotted area) for mean growth in 18 upland Scottish lochs (Frost & Brown 1967).

Current growth rate is low compared with that seen initially (1988-1990), although in 1993 it improved over the 1992 rate (Fig. 10) and growth of the younger 1+ and 2+ age-groups is close to the growth rates measured in 1988 to 1990, suggesting that these, and the slower growth of older fish, reflect density dependent factors rather than declining water quality. The largest individual fish caught in 1993 was 300 mm in length, live weight 355 g; this can be compared with 315 mm and 367 g in 1992, and 263 mm and 254 g in 1991. The average condition factor (K), relating length with body weight, has not changed significantly ($p = 0.05$) since the fish were introduced.

Growth rates of fish in. Loch Fleet are not significantly different from those reported by Frost & Brown (1967) for 18 Scottish lochs (Fig. 10).

Densities of fry in the Altiwhat in June 1993 (1.61 per m^2) were greater than in 1992 (0.80 per m^2), but much less than those recorded in 1988 to 1991 (6 to 13 per m^2). In contrast to 1992, none were recorded in 1993 at the loch outlet where an artificial spawning bed has been constructed. The low fry densities may be attributed to high spring flows in 1991 and 1993, resulting in washout of fry from the nursery areas, but recruitment was worst in 1992. Starvation of fry due to overproduction, or overcutting of redds in the limited spawning area of the Altiwhat stream, are possible alternative explanations. Downstream trout populations in the Little Water of Fleet below the loch have shown no improvement; no fry were found in streams above the Craigie Linn waterfall, and few occur below. In these lower stream reaches, continuing poor water quality in runoff from the heavily forested catchment below the loch seems to be the main factor.

The calculated population structure of the stock shows some features of earlier predictions (Table 4; Turnpenny 1992), although the population may not have reached equilibrium. The 1993 standing stock is estimated at 423 kg, giving a stock density of 24.9 kg per hectare. This is at the lower end of the range reported for similar oligotrophic upland waters (24 to 67 kg per ha).

The diet of adult brown trout in Loch Fleet

Analysis of trout stomach contents was undertaken for summer-caught fish in 1988 (22 fish), 1989 (23 fish), 1991 (40 fish), 1992 (95 fish) and 1993 (105 fish) (Milner & Aston 1995). Identification of organisms/debris was pursued to generic level for the most part, but common invertebrates were identified to species, although for statistical analysis the data were combined as orders or families. The 1992 samples were sufficient to allow comparison between net and rod catch, and in 1993 between net, rod and spinner catches (Fig. 11).

Table 4. The observed population dynamics for the brown trout fishery at Loch Fleet compared with predictions made by Turnpenny (1992).

(A) Age/weight structure and totals for all year-classes of fish combined.

Variable	Year–class 0 (eggs)	1+	2+	3+	4+	5+	Totals
No. of fish							
predicted	63000	3750	1500	750	246	93	6339
observed	27231	75	713	1445	507	0	2740
Mean weight (g)							
predicted	–	10	60	350	1000	1300	2720
observed	–	34	102	170	202	0	508
Total weight of fish (kg)							
predicted	–	38	90	263	264	121	776
observed	–	3	73	245	102	0	423

(B) Replacement spawning stock, based on the numbers predicted and observed eggs shown in (A) above.

Variable	Predicted	Observed
Egg production per male and female (kg)	750	1187
Spawning efficiency (%)	90	60
First spawning age (years)	3+	2+
Weight of 2+ and 3+ spawners required (kg)	94	38

(C) Assuming the weight/age structure shown in (A), the spawning requirements could be met as shown below.

Age–class (Years)	Predicted: Numbers of fish	Predicted: Total wt (kg)	Observed: Numbers of fish	Observed: Total wt (kg)
2+	–	–	65	7
3+	100	35	130	22
4+	40	40	46	9
5+	15	20	–	–
Totals:-	155	95	241	38

(D) Fishery yield. After meeting the replacement spawning requirements shown above (C), the following numbers of fish aged 2+ years or more would be available for capture.

Age (years)	Number of fish		Total weight (kg)	
	Predicted	Observed	Predicted	Observed
2+	1500	648	90	66
3+	650	1315	228	224
4+	224	461	224	93
5+	77	-	100	-
Totals:-	2451	2424	642	383

Differences between years are substantial, possibly reflecting the conditions prevailing during the short sampling period each year. However, some common features were found throughout. Chironomid pupae dominate in numbers, but a great variety of other aquatic and terrestrial organisms are taken by the trout, including caddisflies (Trichoptera), mayflies (Ephemeroptera), terrestrial ants, bees and wasps (Hymenoptera), aphids (Homoptera) and flies (Diptera), as well as aquatic snails (Mollusca) and newts (Amphibia). The latter, along with trichopterans, form the bulk of the biomass consumed. Statistically significant differences were found in the numbers and weights of prey

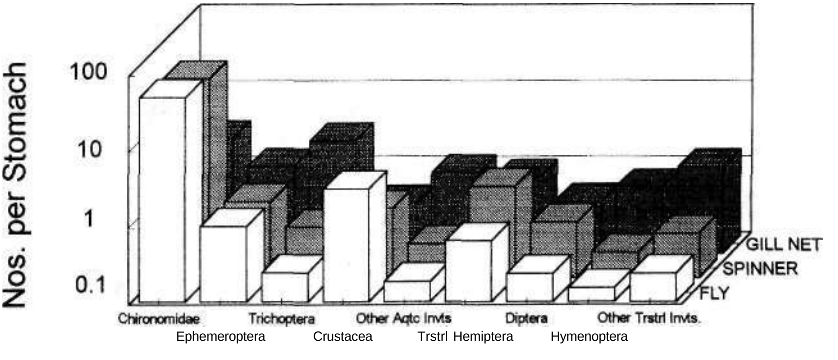


FIG. 11. Numbers (geometric means, logarithmic scale) of invertebrates found in the stomachs of 105 brown trout caught by fly, spinner and gill nets in Loch Fleet, July 1993. From left to right the taxa are: Chironomidae, Ephemeroptera, Trichoptera, Crustacea, other aquatic invertebrates and terrestrial Hemiptera, Diptera, Hymenoptera and others.

taken by trout caught by different methods, probably related to the depth at which fish were feeding. Terrestrial organisms also provide a significant contribution in summer-caught fish (Fig. 11). There is no evidence that diet is limiting for growth.

Freshwater invertebrates

During the first five years, 1984 to 1989, a regular seasonal sampling programme for littoral and benthic macro-invertebrates was undertaken (Battarbee et al. 1992). Samples were taken in spring, summer and autumn at 18 littoral (loch) and stream sites. Other studies during this period included the microbial community, diatoms, periphyton, macrophytes, primary productivity, and aquatic beetles (reported in Battarbee et al. 1992). Species diversity seems to have changed little at Loch Fleet after liming - about 100 species were recorded in 1984-1985 and 110 species in 1986-1989 (Milner & Aston 1995). About 30 "new" species were identified and 20 "acidophil" species were not recorded after liming. The infrequency of sampling, variable seasonal conditions during brief sampling visits, and the lack of any historical data for pre-liming conditions, makes detailed interpretation difficult.

In the loch itself, the numbers of invertebrates (mainly chironomids (midges), oligochaetes (worms), and arachnids (water-mites)) fell in the first few months after liming and before fish were restocked. A later recovery of the invertebrate community in deeper waters (mainly may-flies, caddisflies and chironomids) followed. After liming, the numbers of chironomids and mayfly larvae also increased in the Altiwhat. Mayfly larvae have also continued to increase in the loch, in spite of predation by trout. In the loch outlet, caddisfly larvae increased but larvae of filter-feeding simuliids (blackflies) increased and remained dominant, and possibly reflect increased productivity in the loch, supplying more suspended food materials to the outflow (Fig. 12).

At nearby Loch Dee, stream sampling since 1980 (Morrison & Collen 1992) shows that the greatest invertebrate diversity and abundance is found in the least acid Black Laggan stream, where the acid-sensitive mayfly *Baetis rhodani* is often abundant (up to 20% of the total). This species was found in the Altiwhat after liming although not in great numbers; it is also reported from trout stomachs. Some other species of macroinvertebrates (both "acidophil" and "calcophil" species) appeared after liming, perhaps because their occasional appearance was independent of liming, or because they tolerate the characteristic cool and nutrient-poor conditions at the site. A core of acid-tolerant species is found regularly in streams round Loch Dee, including larvae of several stoneflies *(Leuctra inermis, L. hippopus, Brachyptera risi, Chloroperia*

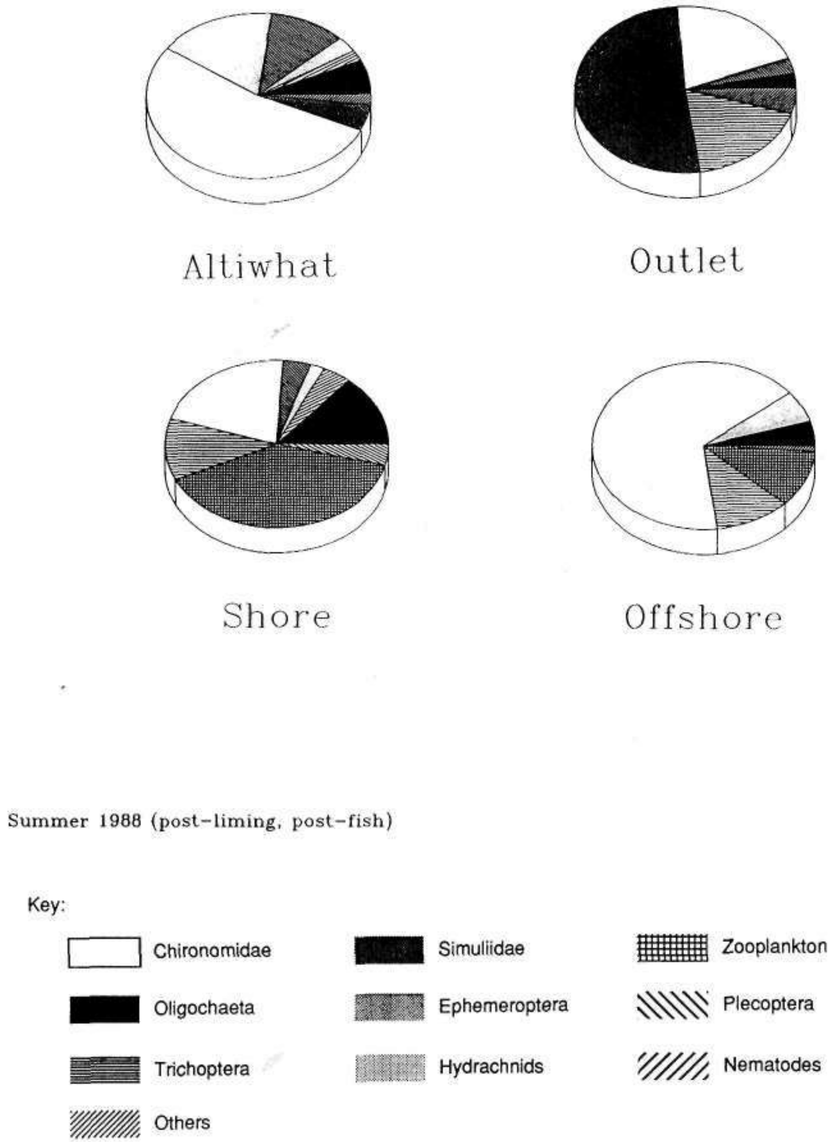


FIG. 12. The main invertebrate groups found in Loch Fleet (littoral and offshore samples), the main inflow stream (Altiwhat) and the outflow stream in summer 1988, after liming the catchment in 1986 and 1987, and restocking the loch with trout in 1987.

torrentium, Protonemura meyeri, Amphinemura sulcicollis), and species of Chironomidae. The same species occur in Loch Fleet samples, some before and some after liming. However, the molluscs *Ancylus fluviatilis* and *Lymnaea peregra,* which are locally abundant at Loch Dee, did not appear at Loch Fleet after liming, although the pea-mussel *Pisidium* (also found in Loch Dee benthos) was found in 1993 trout stomachs (and had been found in 1984 prior to liming). No major changes were reported after liming the White Laggan tributary of Loch Dee, although the appearance of the zooplankter *Daphnia hyalina* in the loch, in 1988, was linked with liming (Morrison & Collen 1992).

The aquatic beetle fauna of Loch Fleet and adjacent wetland areas was highly diverse (36 species) and abundant prior to liming and the reintroduction of trout. After liming, both diversity and abundance fell sharply, and the dominant species changed (Foster 1991). *Hydroporus palustris,* dominant in 1985, disappeared more quickly from open water than from impounded areas, suggesting that fish predation was more important than water quality. It was replaced by the smaller *Nebrioporus depressus,* another diving beetle better adapted to fish predation. Another species, *Agabus arcticus,* considered as acidophilic, has disappeared, while a small elmid beetle, *Oulimnius tuberculatus,* became abundant in 1992, a likely response to the higher pH (Foster 1994).

The findings at Loch Fleet can be compared with historic records for species of water-beetles found at sites in southwest Scotland, many based on multiple visits. Changes in the beetle faunas of several lochs can be traced since the 1900s; for three lochs on granite - Long Loch of the Dungeon, White Loch of Colvend, and Loch Dee - the same tendency emerges, where the larger species of *Ilybius* replace the smaller species of *Nebrioporus.* Until recently, Loch Doon showed an opposite trend (Fig. 13), now reversed. This has been associated with a decline in the fishery in Loch Doon with progressive acidification (Foster, pers. comm.). The beetle faunas of Llynau Gamallt, two limed Welsh lakes, also show parallel changes to those seen at Loch Fleet, with a pre-liming dominance of *H. palustris* and *A. arcticus,* which declined after liming.

The addition of lime direct to some fresh waters or to their catchments has been reported, in some cases, to increase their nutrient status, attributed to enhanced microbial activity in soils or sediments (Olem 1990; Kullberg & Petersen 1987). At Loch Fleet, the concentrations of both nitrate and total organic carbon increased in the short term after liming, and this could not be attributed simply to contamination of the lime by nutrients or to the minor fertiliser treatments applied in sectors I and II. Some increase in phytoplankton productivity was observed over the following three years after the 1986 liming, but some might be reasonably attributed to release of nutrients from decaying *Sphagnum*

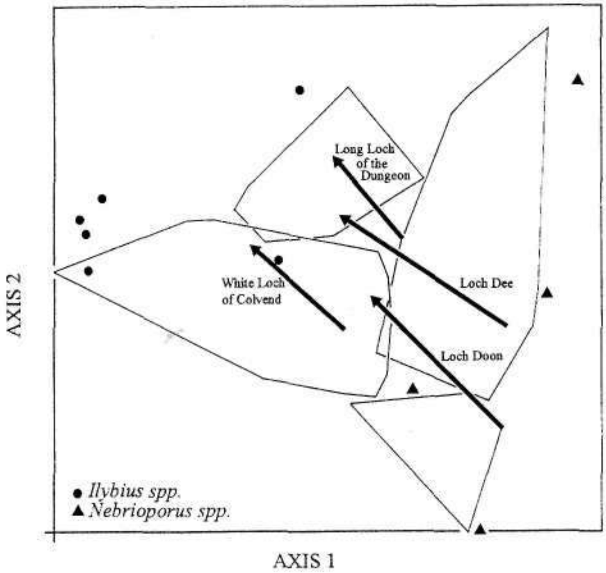


FIG. 13. DECORANA plot of scores for 85 lists of water-beetles (Coleptera) compiled for Galloway lochs during the 20th century. Four types of water-bodies are indicated for the polygons. The arrows connect scores over a 90-year period for four lochs draining granite catchments. A consistent change from a small species (▲, *Nebrioporus*) to a larger species (●, *Ilybius*) is associated with a decline in predation by fish in these four lochs. (Unpublished, courtesy of Dr G. N. Foster, SAC, Auchincruive, Ayr.)

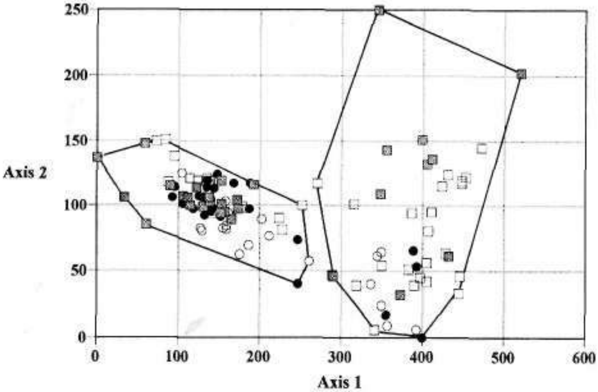


FIG. 14. DECORANA plots of assemblages of water-beetles (Coleptera), dragonflies (Odonata) and water-boatmen (Corixidae) in peat-pools on limed (shaded symbols) and unlimed (open symbols) areas of the Loch Fleet catchment, sampled in 1991 (○) and 1992 (□). Steep-sided pools are grouped on the left, shallow pools on the right.

moss in the loch, a consequence of liming (Battarbee et al. 1992). Although a more abundant and diverse aquatic plant community seems to be present after liming, any changes that may have occurred tend to be obscured by year-by-year variations, and grazing of vegetation by invertebrates may have been reduced following the reintroduction of predatory fish.

Effect of liming on invertebrates in bog pools

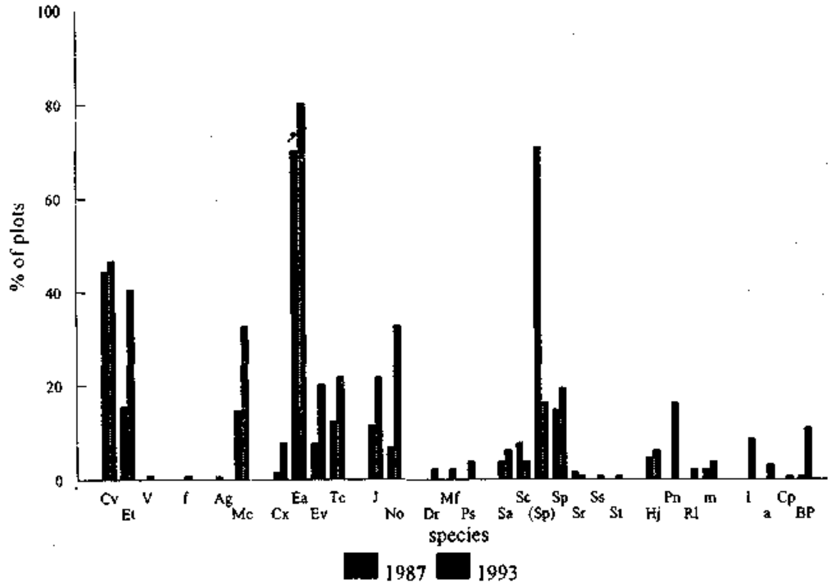
The impact of liming on the invertebrate fauna of relatively shallow moorland peat pools was studied in 1991 (48 pools) and 1992 (73 pools) (Foster 1995). Fifty-six taxa were identified. The abundance of immature stages indicated that many of the common taxa, generally considered acidophilic, appear to breed successfully in calcium-rich habitats. Although pools lying on limed areas had higher pH and calcium than those in untreated areas, the population densities of dragonfly larvae (Odonata), water-bugs (Hemiptera-Heteroptera) and water-beetles (Coleoptera) were unaffected. Two main assemblages of species were found (Fig. 14), one group characteristic of steep-sided pools (depths greater than 30 cm) which were dominated by dragonfly larvae, and a second group in much shallower pools (depth less than 5 cm) which were dominated by the coleopteran *Hydroporus* sp., a small diving beetle.

The localised vegetation and changes in substrata of the wetland area (see below) seem to have little or no effect on the invertebrate fauna of the bog pools, where colonisation by a few "invasive" species did not alter the main conclusions from multivariate analysis, shown in Fig. 14. As additional species typical of bogs are still being discovered in Sector VII, it could be argued that such additions are "not significant". However, among those found in 1993, some species are typical of man-made pools on silt, and a spider typical of sand dunes was also found. This raises the possibility that repeated limestone applications to the same area might encourage colonisation by such species.

Effect of liming on wetland vegetation

Within the upper part of sector VII, the small (ca. 4 ha) wetland area (see Fig. 3) which provides a maintained flow of water to the Altiwhat, was limed in 1986 by "spot" application of powdered limestone in and around pools and drainage areas. Overall, more than 100 tonnes was distributed over an area of about 6.5 ha. Substantial residues of lime are still to be found in this area. As expected in the higher pH and calcium conditions, liming resulted in the death of the acidophilic bog-moss *Sphagnum,* principally 5. *papillosum,* in soakaways and in an area (about 2000 m^2) of ombotrophic bog. To follow this change in the wetland vegetation a detailed spatial grid (128 points) was set up to record plant densities in 1987, and was repeated in 1993 (Clymo et al. 1992; Bragg & Clymo1995).

In 1987, 18 mosses and vascular plant species were reported, while in 1993 there were 27 (Fig. 15). Other than the loss of 5. *papillosum,*



KEY

Cv	*Calluna vulgaris*	Sa	*Sphagnum auriculatum*
Et	*Erica tetralix*	Sc	*Sphagnum capillifolium*
V	*Vaccinium* sp.	(Sp)	dead *Sphagnum papillosum*
f	unidentified fern	Sp	*Sphagnum papillosum*
Ag	*Agrostis* sp.	Sr	*Sphagnum recurvum*
Mc	*Molinia cerulea*	Ss	*Sphagnum subnitens*
Ev	*Eriophorum vaginatum*	St	*Sphagnum tenellum*
Tc	*Trichophorum cespitosum*	Hj	*Hypnum jutlandicum*
J	*Juncus* sp.	Pn	*Pohlia nutans*
No	*Narthecium ossifragum*	Rl	*Racomitrium lanuginosum*
Dr	*Drosera rotundifolia*	m	other mosses
Mf	*Montia fontana*	l	liverworts
Ps	*Polygala serpyllifolia*	a	algae
		Cp	*Cladonia portentosa*
		BP	bare peat

FIG. 15. Wetland plant species recorded in 128 plots on the limed source area in sector VII of the Loch Fleet catchment, in 1987 (solid bars) and 1993 (oblique hatching).

changes in other *Sphagnum* species were rather small, and for one, 5. *capillifolium,* some recovery is now evident in places, but *Sphagnum* species are still present in only 10% of sampled quadrats. Typical moorland plants, the cotton-grasses *Eriophorum angustifolium* and *E. vaginatum* increased, and purple moor-grass or flying bent *(Molinia caerulea)* expanded into some limed soakaways. The main new colonists were bulbous rush *(Juncus bulbosus)* and a moss *(Pohlia nutans),* and sometimes sedges *(Carex* spp.). On adjacent moorland areas, cross-leaved heath *(Erica tetralix)* and deer-sedge or deer-grass *(Trichophorum cespitosum = Scirpus caespitosus)* have increased.

Dead *Sphagnum* carpets and the underlying peat are thought to be susceptible to erosion where organic deposits are shallow. One such area lost peat between 1989 and 1993, and in some other places erosion has occurred over 4 years of observation. On deeper peat, dead *Sphagnum* has accumulated and compacted. Erosion in the limed areas was 2.1 to 3.0 cm in shallow peat and 1.2 to 2.6 cm in deeper peat, and did not resemble that occurring in an unlimed, naturally eroding area on the edge of the wetland, where mean peat loss was more than 19 cm.

Overall, changes in the limed wetland area seem to have been neither extensive nor very dramatic, and involve *Sphagnum* spp. rather than other flora; indeed, some increase in diversity of the wetland vegetation is evident, and recovery is indicated in marginal areas 7 years after liming. Erosion is slight, and possibly unchanged, and the invertebrate assemblages of peat pools and moorland have been maintained.

Effect of liming on moorland vegetation

Prior to liming, an extensive survey of the moorland vegetation was undertaken on a 50-m grid in 1984 and 1985, in total 452 quadrat sites (Clymo et al. 1992). A small sample was resurveyed in 1987 and the whole catchment again in 1992 (Still et al. 1992). The rather limited moorland vegetation is typical of the low nutrient status of the catchment soils, and the cool and exposed conditions. The vegetation is dominated by purple moor-grass or flying bent *(Molinia caerulea)* and heather or ling *(Calluna vulgaris),* although a total of 78 species has been recorded. Fifteen species-poor plant communities can be recognised, of which only five represent 80% of the catchment. The dominant environmental influence is that of flushing, which affects almost all of the catchment.

Differences in vegetation before liming and later, in 1992, are rather small, other than in the forested area where 51 quadrats were shaded out by conifer growth and have lost their original plant communities. Moist Atlantic heather moor is still the dominant community, followed by

Molinia grassland. Of the total of 78 species now present, only 16 occur in more than 10% of the quadrats sampled. Species recorded include 6 dwarf shrubs, 12 herbs, 7 grasses, 11 sedges and rushes, 4 ferns and 25 mosses. Thirteen species seen in 1992 were not recorded in the original survey, while six of the species recorded before liming were not found, although three were seen elsewhere in the catchment (i.e. not within the quadrats). Most of the "new" species (including two orchids) are common plants of bog and moorland, and are of widespread but scattered occurrence. Only one or two species indicative of more base-rich conditions were recorded in the limed catchments, and only in one or two quadrats; overall the plant communities of limed and unlimed areas are unchanged.

Effect of liming on moorland invertebrates

A study of beetles and spiders in limed and untreated areas of Loch Fleet was made in 1988, 1991 and 1993 (Foster et al. 1995). A total of 76 spider species, 28 species of ground beetles (Carabidae) and 64 species of non-carabid beetles were identified. Multivariate analysis identified two

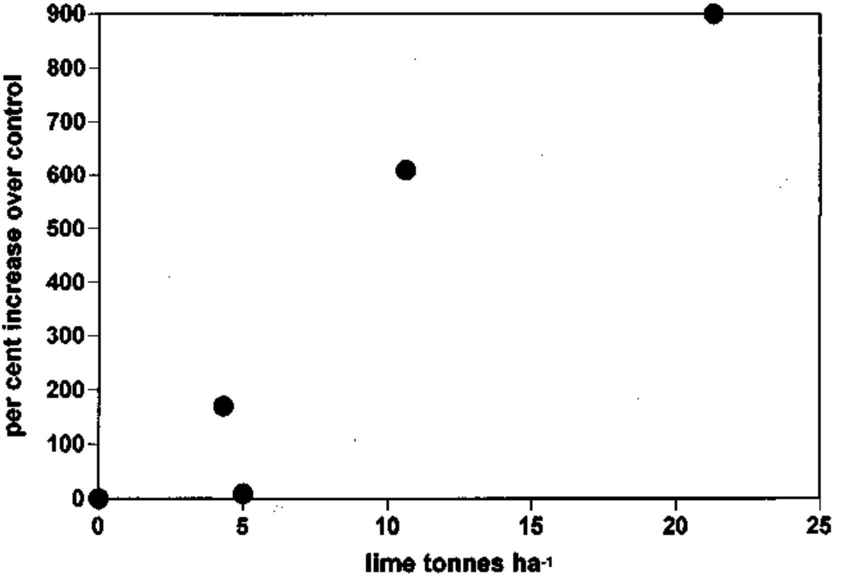


FIG. 16. Percentage increase in numbers of adult *Trechus obtusis* (Coleoptera) caught in pitfall traps on limed moorland areas of the Loch Fleet catchment, in relation to the amount of lime added (tonnes per hectare).

groups of species associated, respectively, with areas of open moorland and afforestation. The burnt sector VIII had the lowest catch of spiders, a reflection of abundance rather than diversity, while both diversity and abundance were generally high for beetles (also in limed sector VII). Differences between years of sampling were substantial, regardless of the treatments applied. No species declined as a result of liming, but a rise in the numbers of one beetle, *Trechus obtusis,* was attributed to liming, and significantly related to the rate of lime application (7.5 to 10 tonnes per ha) (Fig. 16).

Attempts made in 1990 and 1991 to sample other invertebrates associated with vegetation (Hemiptera, Diptera and Collembola (springtails)) failed to provide sufficient samples for analysis, mainly because of their sparse populations, and prevailing windy conditions.

Terrestrial mammals

A study of small mammals at Loch Fleet was undertaken as part of a wider investigation on small experimentally-limed plots at Llyn Conwy, North Wales, and on larger plots at Llyn Brianne, South Wales. In the Welsh studies, liming had short-term effects on common shrews *{Sorex aranaeus),* reducing their activity for 2 to 3 months. However, it had no effect in the longer term on activity, numbers, population dynamics or nutritional status. Liming decreased the activity of pygmy shrews (5. *minutus)* for at least 6 months and possibly for up to 2 years (Shore 1991). At Loch Fleet, the only effect observed was a smaller catch of female pygmy shrews on plots on limed areas. At Conwy this had been attributed, in part, to a reduced abundance of invertebrate prey, but this was not the case at Loch Fleet; indeed, prey may have even increased (see previous sections). It is puzzling that males are not affected similarly. There was no evidence of a decline in the numbers of field voles *(Microtus agrestis)* at any site.

Summary and conclusions

Water quality at Loch Fleet prior to liming was incompatible with a trout fishery. Liming about 40% of the catchment in 1986 and 1987 raised the pH and calcium levels, and reduced toxic aluminium concentrations. The improved conditions have been maintained up to 1994, but water in the loch, and its principal inflow stream, is now falling close to the desired threshold of quality. Liming may have led to a short-term increase in nutrients, with some evidence of increased productivity.

Brown trout were present in Loch Fleet from the 1940s to 1960s, but were lost by the 1970s. After liming, restocking with local strains of trout in

1987 was successful, and a self-recruiting population became established within 2 years. Growth rates of individual fish are typical of those found in other softwater oligotrophic upland lakes in Scotland. Recruitment is highly variable, however, and was attributed to severe spring conditions and the limited spawning capacity of the nursery stream, rather than to current or declining water quality. Diet is varied and sufficient for the current population of ca. 3000 fish aged 1+ years or older.

Invertebrates in the loch and its tributaries are reasonably diverse for an oligotrophic upland lake, dominated numerically by chironomids, and larvae of mayflies and caddisflies. After liming and fish restocking, the diverse assemblage of aquatic beetles was reduced, and larger visible species were replaced by smaller cryptic species. Other invertebrate taxa changed little, although the acid-sensitive mayfly *Baetis rhodani* was found after liming. Lower abundances in the lake immediately following liming were not consistent with concurrent increases observed in the tributary streams.

The invertebrate fauna of peat pools in the catchment was not affected by liming.

The effectiveness of liming was estimated from calcium fluxes. It is predicted that conditions in the main inflow stream and the loch will begin to decline from 1994 onwards, and will possibly affect the fish population from that time. Runoff from other limed sectors will maintain high pH and calcium levels, but flow from these will be insufficient to maintain target water quality in the loch.

Other effects due to liming. During a decade of study, an exhaustive effort has been made to quantify significant effects of liming on sensitive components of both aquatic and terrestrial ecosystems. The loss of *Sphagnum* spp. from a limited area of wetland in sector VII appears to be the only effect of concern. This seems likely to be temporary (unless liming is repeated at this site); however, 7 years after liming in 1986 there is, within the limed area, a wider diversity of wetland species. Erosion is less than at adjacent exposed and untreated areas.

Ecological interactions on a catchment. The Loch Fleet Project has provided an opportunity to explore a series of interactions, from atmospheric deposition, through chemical and biological processes within the catchment, and thence to discharge downstream. The importance of canopy processes, hydrological pathways, soil conditions, water quality, composition of the aquatic community, and their interactions, and changes after liming and fish restocking, have become evident. Responses in the terrestrial ecosystem surrounding the loch have been minimal, however, suggesting that it is a stable system, relatively unperturbed by the substantial intervention of liming. Burning of vegetation in part of the catchment failed to improve runoff quality, although vegetation changes persist.

Recommended liming practice. Direct liming of lakes in conditions typical of upland areas in the UK (high rainfall, maritime influences, high lake turnover, base-poor soils) cannot be successful unless repeated frequently. Liming a catchment (or part) provides for a sustained release of alkalinity and calcium, and will also reduce leached aluminium to non-toxic levels. Limited application of powdered or pelleted lime to water-source areas at doses of about 10 tonnes per ha at 10-year intervals seems appropriate in the conditions typified by Loch Fleet, given current levels of acid deposition.

Addition of lime is not a simple alternative to reducing emissions of acidic and potentially acidic substances into the atmosphere, although the impoverished fauna of most acid waters is limited as much by low calcium concentrations as by the acidity itself (i.e. pH). Moreover, calcium concentrations are likely to fall as a result of reduced emissions and deposition of acid materials on to catchments. Liming should be regarded as an essential tool for remediation if the aim is to re-establish a diverse aquatic community, including fish, in calcium-poor upland water-bodies. The question of how high to set overall target values for water quality, in relation to expectations for producing a modest or more substantial trout fishery, or even to restore water-bodies to "pristine" conditions, is still to be incorporated into future debates about sustainability in aquatic environments.

Acknowledgements

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References

Bragg, O. M. & Clymo, R. S. (1995). Seven years of vegetation change following liming of *Sphagnum* communities in sector VII of the Loch Fleet catchment. *Chemistry & Ecology,* 9, 237-251.

Battarbee, R. W., Logan, N. S., Murphy, K. J., Raven, P., Aston, R. J. & Foster, G. N. (1992). Other aquatic biology: flora and fauna. In *Restoring Acid Waters: Loch Fleet 1984-1990* (eds G. Howells & T. R. K. Dalziel), pp. 289-330. Elsevier, London.

Clymo, R. S., Foster, G. N., MacKay, J., Robertson, J., Shore, R. & Skidmore, D. I. (1992). Terrestrial biology in limed catchments. In *Restoring Acid Waters: Loch Fleet 1984-1990* (eds G. Howells & T. R. K. Dalziel), pp. 331-359. Elsevier, London.

Dalziel, T. R. K. (1995). Deposition inputs, water quality and liming effectiveness. *Chemistry and Ecology, 9,* 145-161.

Dalziel, T. R. K., Dickson, A. & Proctor, M. V. (1991). Calcium flux calculations and predictions of catchment liming effectiveness at Loch Fleet, Galloway, Scotland. In *International Lake and Watershed Liming Practices* (eds H. Olem et al.), pp. 223-242. Terrene Institute, Washington.

Foster, G. N. (1991). Aquatic beetle population changes associated with recreating a trout fishery by liming a lake catchment. *Archiv fur Hydrobiology,* 122, 313-322.

Foster, G. N. (1995). Evidence for insensitivity in some insects inhabiting peat pools. *Chemistry and Ecology,* 9, 223-235.

Foster, G. N., Eyre, M. D., Luff, M. L. & Rushton, S. P. (1995). Responses of some terrestrial invertebrates to catchment treatments applied at Loch Fleet. *Chemistry and Ecology,* 9, 213-221.

Frost, W. E. & Brown, M. E. (1967). *The Trout.* (New Naturalist Special Volume). Collins, London.

Hornung, M., Roda, F. & Langan, S. J. (1990). A review of small catchment studies in western Europe producing hydrochemical budgets. Air Pollution Research Report No. 28, CEC, Brussels. 186 pp.

Howells, G. & Dalziel, T. R. K. (Editors) (1992). *Restoring Acid Waters: Loch Fleet 1984-1990.* Elsevier, London. 421 pp.

Howells, G., Dalziel, T. R. K. & Turnpenny, A. W. H. (1992). Loch Fleet: liming to restore a brown trout fishery. *Environmental Pollution,* 78, 131-139.

Kullberg, A. & Petersen, O. (1987). Dissolved organic carbon, seston and macroinvertebrate drift in an acidified and humic stream. *Freshwater Biology,* 17, 553-564.

Milner, A. G. P. & Aston, R. J. (1995). Pre-and post-liming aquatic communities and trout diets. *Chemistry and Ecology,* 9, 199-211.

Morrison, B. R. S. & Collen, P. (1992). The trout {*Salmo trutta* L.) and invertebrate populations of Loch Dee and its inflowing streams. In *Acidification, Forestry and Fisheries Management in Upland Galloway,* pp. 107-122. Foundation for Water Research, FR/SC0003, Marlow, England.

Niisson, S. I., Miller, H. G. & Miller, J. G. (1982). Forest growth as a possible cause of soil and water acidification — an examination of concepts. *Oikos,* 39, 40-49.

Olem, H. (1990). *Liming Acidic Surface Waters.* Lewis Publishers, Chelsea, Michigan. 331 pp.

Shore, R. F. (1991). The effects on small mammals of liming moorland. Institute of Terrestrial Ecology, Report LC/5/003, 51pp.

Still, M. J., Henderson, D. J., Hudson, G., Madden, S. & Hawker. D. (1992). Survey of the Vegetation of Loch Fleet Catchment. Macaulay Land Use Research Institute Report, 25 pp.

Rosenqvist, I. Th. (1985). Acid precipitation and acid soil in freshwater lake chemistry. *Land Use Policy,* **January 1985,** 70-73.

Turnpenny, A. W. H. (1992). The history of the Loch Fleet fishery and fresh water quality for fish and other aquatic fauna. In *Restoring Acid Waters: Loch Fleet 1984-1990* (eds G. Howells & T. R. K. Dalziel), pp. 39-73. Elsevier, London.

Turnpenny, A. W. H., Fleming, J. M. & Wood, R. (1995). The brown trout population at Loch Fleet eight years after liming. *Chemistry and Ecology,* 9, 185-197.

Wilson, E. J. & Bache, B. W. (1995). The effects of liming on soil chemistry at Loch Fleet, Scotland; changes in soil chemistry with time following liming. *Chemistry and Ecology,* 9, 163-183.