Chapter (non-refereed)

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The status of fish populations in waters likely to have been affected by acid deposition in Scotland

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1 Introduction

Although known to be a problem since the 1920s, it is only over the last 15 years or so that ecologists in the northern hemisphere have become increasingly concerned about the impact of acid deposition on freshwater ecosystems and other parts of the environment (Almer 1974; Beamish *et al.* 1975; Harvey 1975; Haines 1981). In Scandinavia (especially southern Sweden and Norway), and more recently in North America (both in Canada and the USA), numerous scientific studies related to the problem have been initiated and there has been a massive growth in the literature over the last few years. Many other countries are now involved in work on acid deposition, but in Great Britain the input in the field of freshwater ecology has been relatively small until recently (United Kingdom Acid Waters Review Group 1986).

Considerable general agreement appears to be developing from the research data (involving field survey, monitoring and experimental work) produced in Scandinavia and North America (Drablos & Tollan 1980; Haines 1981; Johnson 1982). Rain in many parts of the world—including the British Isles (United Kingdom Review Group on Acid Rain 1983; Mathews *et al.* 1984)—is acid and has probably become more so during this century. This rain and associated dry deposition appear to have acidified some fresh waters—especially those in areas of base-poor geology whose buffering capacity is low.

Organisms at each major trophic level are affected by this acidification. The diversity of phytoplankton decreases with acidification but the production of some algae and mosses increases (Battarbee 1984). The diversity and production of most macrophyte communities decrease with decreasing pH, and the same appears to be true of zooplankton and zoobenthos, though the situation is more complex with invertebrates (Engblom & Lingdell 1983). If the acidification is sufficiently great to exclude fish, then their absence as the normal top predators can lead to an unusual abundance of some prey species. Amphibians (Tome & Pough 1982) and birds (Eriksson 1984) can also be affected.

One of the earliest indicators of acid pollution and one of its most important effects was the disappearance of many fish—especially salmonids (Atlantic salmon *Salmo salar*, brown trout *Salmo trutta* and arctic charr *Salvelinus alpinus*)—from rivers and lakes in which they were previously abundant (Wright & Snekvic 1978; Muniz & Leivestad 1980; Harvey & Lee 1982; Schofield 1982). For example, Atlantic salmon have disappeared from many rivers in southern Scandinavia and the number of lakes in these areas without populations of brown trout and arctic charr has increased dramatically, especially over the last 15 years (Overrein *et al.* 1980; Johnson 1982). Massive kills of salmon and trout have been observed during snowmelt and after heavy rain (Henriksen *et al.* 1984).

Only recently has any significant interest been taken in the effect of acid deposition on fresh waters in Great Britain (Watt Committee on Energy 1984; United Kingdom Acid Waters Review Group 1986), although the Scandinavians have long felt that Britain is one of the important sources of the excess atmospheric acidity affecting their fresh waters. Moreover, the approach to research has been complicated by the fact that (i) there are few background data of sufficient antiquity from appropriate waters with which the current situation can be compared, (ii) there is a complex interaction between the atmosphere, coniferous forests (whose area in Great Britain, especially Scotland, has increased enormously over the last few decades) and acid input to adjacent streams, and (iii) many upland waters are brown and organically stained.

Thus, there is no doubt that acid deposition is having a significant and increasing impact on fresh waters in extensive areas of Scandinavia, North America and elsewhere (Wright *et al.* 1980). It is highly likely that similar changes are taking place in some fresh waters in Great Britain where the rain is acid (Cape *et al.* 1984) and the underlying rocks have a low buffering capacity (Harriman & Wells 1985). However, until very recently, most research in Britain had been peripheral to the problem, and little of it directly answered the question of whether fresh waters in Great Britain have been extensively affected by acid deposition.

The most relevant work at the start of the present project was that carried out in Galloway and the Loch Ard area of Scotland by Harriman and Morrison (1980, 1981, 1982). Some work has also been carried out in Wales (Stoner *et al.* 1984). Recently, many other relevant projects have started in different parts of the United Kingdom with a variety of objectives. The most relevant study of all to the present work was the background survey of water chemistry carried out in 1979 in south-west Scotland (from Norway) by Wright and Henriksen (1980).

The present project is primarily a study of the fish populations of selected waters in adjacent granite and non-granite areas likely to be affected by acid precipitation. The main objective has been to reveal how many waters are fishless and to compare existing with previous data for these waters. The latter are mainly angling records which, though never quantitative and sometimes anecdotal, are adequate as far as presence/absence comparisons are concerned.

The objectives of the present project were as follows.

i. To select, by means of a desk study of topographical, geological and atmospheric deposition maps, suitable sets of study lochs in adjacent granite and non-granite areas of Scotland. The catchments of these lochs were subsequently classified according to land use.

ii. Where possible, to gather information on the historical status of the fish populations of these waters from the published literature, estate records, anglers and others.

iii. To sample the fish populations in the lochs, their inflows and outflows using conventional fishery methods and to ascertain background water chemistry, bathymetry and hydrology.

2 Desk study: lochs on granite

The total number of lochs in Scotland, in various size, and other, categories, has been determined by Smith and Lyle (1979). The assumption in the present study is that those lochs lying on granite bedrock are among the most vulnerable to acid deposition; a necessary preliminary to any field work was to determine the numbers and distribution of such lochs. From this information it would then be possible to select suitable sets of waters, including controls, for study.

2.1 Map survey

The main objectives of the desk study, therefore, were to transfer the boundaries of the granite areas of Scotland from geological survey maps to 1:50000 scale Ordnance Survey (OS) topographical maps, and to determine the number of lochs of various size classes within these areas.

The granite areas of Scotland were traced from the British Geological Survey collection of geological maps at either 1:63360 or 1:50000 scales, with the exception of 5 maps which were unavailable. The collection of geological maps consisted of solid, solid and drift and drift editions. The granite areas on any given geological map were traced on to one sheet of tracing paper, together with grid line reference marks. Intrusions of non-granitic rock within the granite blocks were also marked.

The transfer of information at the 1:50000 scale was a simple matter but where the geological maps were at a scale of 1:63360, other methods were used. (1) The appropriate 1:63360 scale OS map was overlaid with the tracing and the information transferred to the 1:50000 scale OS maps by eye, using grid lines and cartographic features for reference. (2) The tracings were photographically enlarged to a 1:50000 scale. Grid lines enabled identification of any distortion, but with care this was negligible. The latter method enabled a more rapid and accurate transfer of the solid geology to the OS maps. In some cases, the tracings had to be taken from hand-painted geological maps where the absence of grid lines meant that distortion could only be detected by reference to the appropriate 1:63360 and 1:625000 geological maps.

In 3 cases, the outlines of the granite areas bore little resemblance to the 1:625000 geological map. The areas covered by these sheets were, therefore, tranferred by grid overlay from the 1:625000 geological map. Similarly, those areas not covered by geological maps at either 1:63360 or 1:50000 scale were drawn in from the 1:625000 scale map using a grid overlay.

Having transferred the granite areas to the 1:50000 scale maps, a method of identifying the granite blocks within the 5 major geological areas of Scotland was devised by modification of the block nomenclature system of Anderson (1939). Thus, within the 5 regions of Scotland (viz north-west Highlands, northern Highlands, Grampian Highlands, midland valley and southern uplands), each granite block was given a number and name (see Figure 1 & Table 1). The only exceptions to this system were the Shetlands and Outer Hebrides, which were treated separately.

2.2 Loch counts

Using the system of granite block nomenclature outlined above, a count was made of all lochs whose basins were located entirely within areas of granite. The lochs were allocated to 8 size classes (<1, 1-4, 4-12.5, 12.5-25, 25-50, 50-100, 100-200 and >200 ha) by using grid overlays to determine the surface area, and any named lochs were noted. This procedure was followed for each granite block and the data were recorded on regional data sheets. A master sheet, which incorporated the data from all the regions, was then constructed (Table 2). Details of lochs whose basins occurred partially within granite blocks were recorded as footnotes on the regional data sheets.

Because the study was concerned with the status of fish in areas likely to have been affected by acid deposition, and as lochs whose basins are within granite may have catchments predominantly outwith granite areas, it was decided to make a further count of 'pure granite' lochs. Thus, all lochs >1 ha in surface area whose catchments were located entirely within the granite blocks were counted using the same procedure as above. A new master sheet was then produced from these data (Table 3). The effect of imposing this new standard was to shift the location of potential sites for field sampling towards the centres of the granite blocks. In many instances, the younger, more acidic granites are located near the middle of the

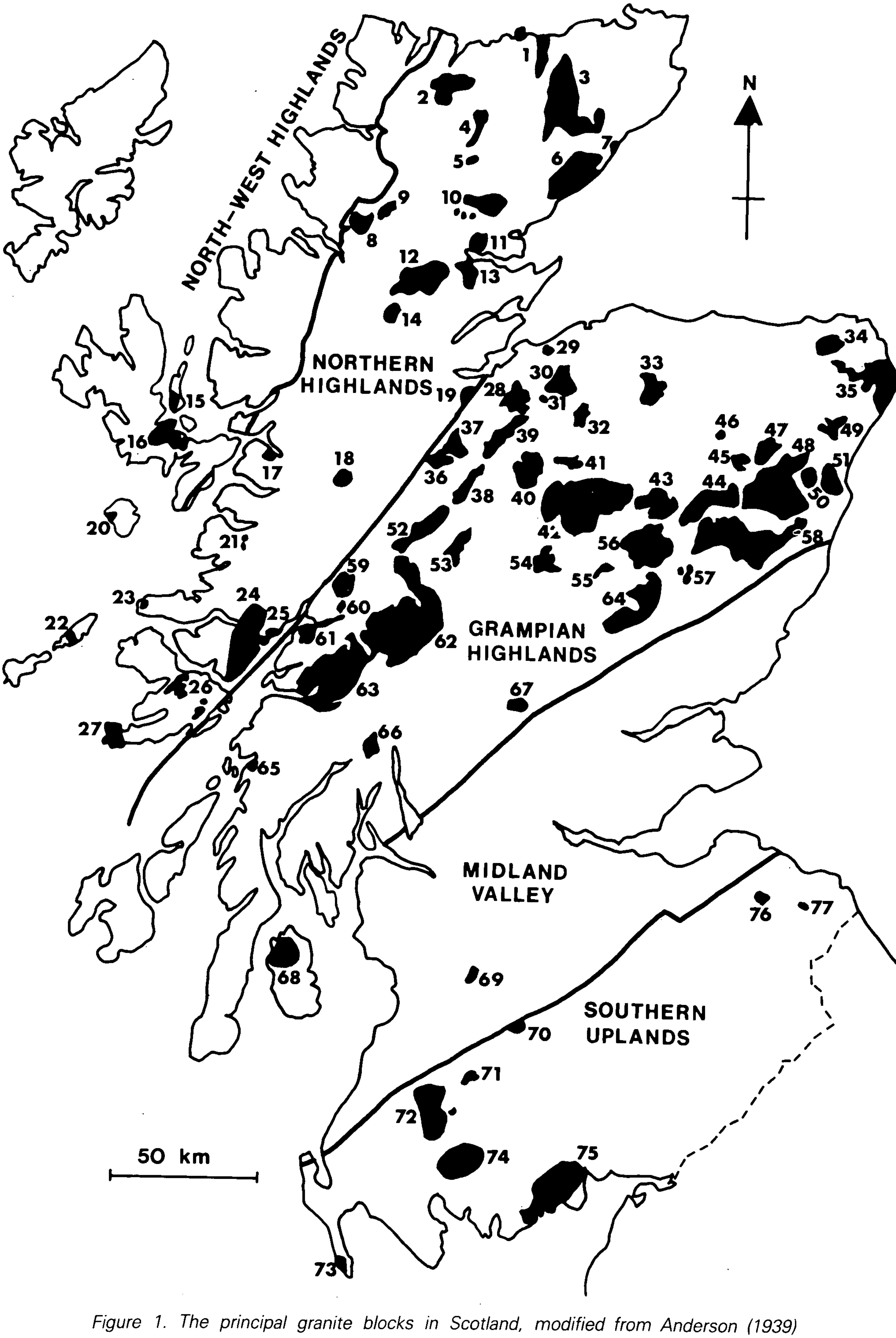

Figure 1. The principal granite blocks in Scotland, modified from Anderson (1939)

Table 1. The system of naming the granite blocks of Scotland

Number	Name	Number	Name
1	Strathy & Strath Halladale	40	Monadhliath
2	Loch Loyal	41	Boat of Garten
3	Caithness	42	Cairngorm
4	Strathnaver	43	Glen Cairn
5	Loch Gaineamhach	44	Ballater
6	Helmsdale	45	Alford
7	Newport	46	Cairn More
8	Loch Borralan	47	Bennachie
9	Ben More	48	Hill of Fare
10	Lairg (& satellite blocks)	49	Pitmedden
11	Migdale	50	Kinellar
12	Kildermorie Forest	51	Aberdeen
13	Fearn	52	Corrieyairack
14	Strath Rannoch	53	Dalwhinnie
15	Raasay	54	Beinn Dearg
16	Skye	55	Carn Mor
17	Loch Duich	56	Lochnagar
18	Cluanie	57	Ben Tirran Group
19	Loch Ness (north)	58	Mount Battock
20	Rhum	59	Ben Nevis
21	South Morar	60	Mullach Nan Coirean
22	Coll	61	Ballachullish
23	Ardnamurchan	62	Moor of Rannoch
24	Morvern-Strontian	63	Etive complex
25	Loch Linnhe	64	Caenlochan
26	Mull	65	Loch Melfort
27	Ross of Mull	66	Glen Fyne
28	Moy	67	Glen Lednock
29	Nairn	68	Arran
30	Ardclach	69	Distinkhorn
31	Loch Winter	70	Lowther Hills
32	Grantown on Spey	71	Cairnsmore/Carsphairn
33	Benn Rinnes	72	Loch Doon
34	Strichen	73	Mull of Galloway
35	Peterhead	74	Cairnsmore/Fleet
36	Knockie Lodge	75	Criffel
37	Foyers	76	Lammermuirs (N)
38	Sherramore Forest	77	Lammermuirs (S)
39	Tomatin		

blocks (Anderson 1939), a factor which is relevant to the objectives of the study. However, for logistic reasons, the shift had serious implications for gaining access to many sites. Furthermore, because catchment size tends to increase with loch size, very few large (>100 ha) 'pure' lochs were available for study. For this reason, a small number of lochs whose catchments were predominantly (>75%) granitic in nature were noted separately and termed 'fringe' lochs.

From the data now available, it was possible to prepare a list of potential sites for study in the field. For all 'pure' lochs >1 ha within the granite blocks under consideration, various catchment details, such as size class, altitude, number of inflows, presence of outflows, degree of catchment afforestation, method and ease of access, were recorded. During site selection, lochs with neither an inflow nor an outflow were not normally considered, as it was felt that these lochs would be unlikely to be able to support natural trout populations anyway, given their requirement for running water at spawning time. The names given on the 1:50000 OS maps were those used for the lochs. Where no name was given to a loch, a 'name' was allocated from the nearest named cartographic feature—usually a topographical one.

'Control' lochs were also selected from the 1:50000 OS maps. They were chosen for their proximity to granite blocks but their catchments were entirely outwith granite. Where possible, the control sites were of a similar size and had catchment characteristics resembling those of the study sites. At least one appropriate control loch was chosen for each granite block containing one or more study sites.

A master list of potential study sites was prepared, initially to be issued to sports fishermen. In order to avoid biased reports from anglers, study sites and control sites were not identified and it was stressed in an accompanying questionnaire that the list included lochs of varying susceptibility to acidification. About 500 of these lists and questionnaires, asking for details of past catches from any of the lochs concerned, were issued to anglers all over Scotland.

Background information on each loch was collected from Murray and Pullar (1910) and other sources. Finally, lochs to be sampled in the field were selected. This selection was in some ways a progressive process, and ultimately the choice of lochs visited depended on various factors such as access, permission, weather, geographic distribution, features of apparent special interest, etc. A full list of all those visited is given in Table 4.

Table 2. The number of lochs in different size classes whose basins occur entirely within granite blocks

	Size class (ha)								
Region	<1	1-4	4-12.5	12.5-25	25-50	50-100	100-200	>200	Total
Southern uplands	30	14	10	2	3	5	2	0	66
Midland valley	47	2	2	0	1	0	0	0	52
Grampian Highlands	514	84	31	5	6	5	2	4	651
Northern Highlands	284	79	24	10	6	1	0	1	405
North-west Highlands	21	6	1	0	0	0	0	0	28
Western Isles	17	7	4	1	0	0	0	0	29
Shetland & Orkney	246	40	13	4	1	1	0	0	309
Total	1159	232	85	22	17	12	4	5	1536

Table 3. The number of lochs of >1 ha in different size classes whose catchments occur entirely within granite blocks

Region	Size class (ha) <1	1-4	4-12.5	12.5-25	25-50	50-100	100-200	>200	Total
Southern uplands	—	8	7	2	1	1	1	0	20
Midland valley	—	2	2	0	1	0	0	0	5
Grampian Highlands	—	69	24	2	4	1	0	0	100
Northern Highlands	—	67	21	8	4	0	0	0	100
North-west Highlands	—	6	0	0	0	0	0	0	6
Western Isles	—	0	0	0	0	0	0	0	0
Shetland & Orkney	—	35	10	2	1	0	0	0	48
Total	—	187	64	14	11	2	1	0	279

3 Loch catchments

Once lochs had been selected for study in the field, special attention was given to the nature of the catchment of each in order to help in the understanding of its ecology, and eventually as an aid to identifying the factors most involved in the acidification process (Henriksen 1982; Bobee & Lachance 1984).

3.1 Catchment areas

The topographical catchment area of each site was identified from, and drawn on to, either 1:50000, 1:25000 or 1:10000 scale OS maps, depending on its size and difficulty of delineation. The area was then measured by planimetry. Transparent overlays of each catchment watershed were produced photographical-

Table 4. Checklist of lochs visited during the survey

Number	Loch name	NGR	Status
1	Grannoch	25542700	G
2	Fleet	25560699	G
3	Lochenbreck	25643656	C
4	am Fhaing	17687488	G
5	nan Craobh	17775484	G
6	Tearnait	17748469	G
7	Dubha 'Morvern'	17704529	C
8	Caol	17817482	G
9	Uisge	17805550	G
10	Mhic Pheadair Ruadh	27282475	C
11	Dubh 'Kingshouse W'	27273538	G
12	Dubh 'Kingshouse N'	27279541	G
13	Dubh 'Kingshouse E'	27281535	G
14	Mathair Eite	27289543	G
15	Gaineamhach	27303535	G
16	Gaineamhach 'NE'	27308538	G
17	Gaineamhach 'SE'	27311534	G
18	Einich	27913990	G*
19	Beanaidh	28911027	G
20	Mhic Ghille-chaoil	28922025	G
21	Pityoulish	28920135	C
22	na Seilge	29922587	C
23	Talaheel	29955488	G
24	nan Clach Geala	29935495	G
25	Dubh Cul Na Beinne	29984544	G
26	Tuim Ghlais	29978525	G
27	Long L of the Dungeon	25468842	G
28	Round L of the Dungeon	25467847	G
29	Enoch	25446851	G*
30	Arron	25443838	G
31	Neldricken	25445829	G*
32	Dungeon	25525845	C
33	Narroch	25452815	G
34	Round L of Glenhead	25450804	G
35	Long L of Glenhead	25446808	G
36	Valley	25445817	G
37	Harrow	25528867	C
38	Dow	25457808	G
39	Dalbeattie Plantain	25425602	G
40	Fern	25645625	G
41	White	25655547	G*
42	Barean	25615556	G
43	Clonyard	25575555	G
44	Fellcroft	25585506	C
45	Bengairn	25885522	G
46	Duff's	25425602	G
47	Kernsary	18882802	C
48	Ghiuragarstidh	18890812	C
49	Policies	38755075	G
50	Waterton	38758087	G
51	of Skene	38785075	G*
52	Brandy	38340754	C
53	Corby	38924144	C
54	Muick	38290830	G*
55	Dubh 'Muick'	37239827	G
56	Buidhe	37253827	G
57	Lochnagar	37253860	G
58	nan Eun	37230854	G
59	Sandy	37227865	G
60	Bharradail	16393634	C
61	Beinn Uraraidh	16401534	C
62	nam Breac	16408558	C
63	nam Manaichean	16398557	C
64	Laoim	16376489	C
65	Sholum	16400491	C
66	Sholum 'W'	16393489	C
67	Leorin 'W'	16368484	C
68	Leorin 'E'	16373486	C
69	na Beinne Brice	16383483	C
70	'Moine na Surdaig'	16383493	C
71	Coirre Fhionn	16901459	G
72	Iorsa	16915380	G
73	Garbad	16019238	C
74	Cnoc an Loch	16935286	G
75	a'Mhuillin	16940496	G
76	Kirkaldy	28963417	G
77	a'Chaoruinn	28755375	G
78	an t'Sidhein	28973323	C
79	nan Stuirteag	38002320	G
80	a'Mhill Bhig	27225132	C
81	a'Mhill Bhig 'Lower'	27226134	C
82	Maol Meadhonach 'Upper'	27239153	G
83	Maol Meadhonach 'Lower'	27238150	G

G = granite (G* = fringe group)
C = control

Table 5. Percentage occurrence in the catchment of major components relevant to acidification

Number	Loch name	Bedrock granite	Granite-derived drift	Soils peat	Land use conifers
1	Grannoch	100	85	28	60
2	Fleet	100	84	16	11
3	Lochenbreck	0	100	25	81
4	am Fhaing	100	100	32	0
5	nan Craobh	100	100	33	0
6	Tearnait	100	100	30	1
7	Dubha 'Morvern'	0	0	33	0
8	Caol	100	100	33	0
9	Uisge	100	82	19	0
10	Mhic Pheadair Ruadh	0	85	31	0
11	Dubh 'Kingshouse W'	100	98	31	0
12	Dubh 'Kingshouse N'	100	100	33	0
13	Dubh 'Kingshouse E'	100	100	33	0
14	Mathair Eite	100	100	33	0
15	Gaineamhach	100	100	32	0
16	Gaineamhach 'NE'	100	100	31	0
17	Gaineamhach 'SE'	100	100	33	0
18	Einich	>75	87	13	0
19	Beanaidh	100	60	20	2
20	Mhic Ghille-chaoil	100	0	50	0
21	Pityoulish	0	0	0	37
22	na Seilge	0	0	95	0
23	Talaheel	100	0	100	0
24	nan Clach Geala	100	0	100	0
25	Dubh Cul Na Beinne	100	0	100	0
26	Tuim Ghlais	100	0	100	0
27	Long L of the Dungeon	100	0	0	0
28	Round L of the Dungeon	100	67	33	10
29	Enoch	>75	90	0	0
30	Arron	100	100	0	0
31	Neldricken	>75	100	0	0
32	Dungeon	100	0	19	7
33	Narroch	100	83	17	0
34	Round L of Glenhead	100	100	0	0
35	Long L of Glenhead	100	100	0	0
36	Valley	100	96	4	0
37	Harrow	0	25	21	14
38	Dow	100	100	0	0
39	Dalbeattie Plantain	100	67	20	97
40	Fern	100	69	31	27
41	White	>75	100	0	25
42	Barean	100	100	0	66
43	Clonyard	100	100	0	7
44	Fellcroft	0	0	23	0
45	Bengairn	100	100	0	25
46	Duff's	100	100	0	64
47	Kernsary	0	0	24	5
48	Ghiuragarstidh	0	0	25	2
49	Policies	100	100	0	37
50	Waterton	100	91	12	18
51	of Skene	>75	88	8	17
52	Brandy	0	0	13	0
53	Corby	0	0	40	13
54	Muick	>75	69	34	1
55	Dubh 'Muick'	100	100	11	0
56	Buidhe	100	100	3	0
57	Lochnagar	100	100	0	0
58	nan Eun	100	100	0	0
59	Sandy	100	100	0	0
60	Bharradail	0	0	15	0
61	Beinn Uraraidh	0	0	26	0
62	nam Breac	0	0	30	0
63	nam Manaichean	0	0	25	0
64	Laoim	0	0	25	0
65	Sholum	0	0	25	0
66	Sholum 'W'	0	0	25	0
67	Leorin 'W'	0	0	25	0
68	Leorin 'E'	0	0	25	0

69	na Beinne Brice	0	0	25	0
70	'Moine na Surdaig'	0	0	25	0
71	Coirre Fhionn	100	100	15	0
72	Iorsa	100	100	25	0
73	Garbad	0	0	100	0
74	Cnoc an Loch	100	0	25	0
75	a'Mhuillin	100	31	7	0
76	Kirkaldy	100	0	63	10
77	a'Chaoruinn	100	42	67	8
78	an t'Sidhein	0	0	0	0
79	nan Stuirteag	100	0	25	0
80	a'Mhill Bhig	0	0	0	0
81	a'Mhill Bhig 'Lower'	0	0	23	0
82	Maol Meadhonach 'Upper'	100	100	0	0
83	Maol Meadhonach 'Lower'	100	100	23	0

ly, at scales to suit the soil and land use maps mentioned below.

3.2 Catchment soils

Soil maps (available at a scale of 1:250000) were used to determine the soil types present in each catchment area (Macaulay Institute 1982).In order to calculate the percentage of the catchment area covered by a particular soil type, a grid overlay was used. Square counts of each soil type within this overlay were then made to calculate the percentages for the catchment as a whole. The major soil categories involved were lithosols, alluvial soils, rankers, brown earths, podzols, surface water gleys, groundwater gleys and peats.

3.3 Catchment surface rocks

Very little quantitative information was available on the extent of exposed surface rocks in each catchment. Eventually, it was decided to make use of the information in the data books accompanying the soil maps (Macaulay Institute 1982) and to place each loch catchment area in one of the following 4 broad categories: non-rocky, moderately rocky, rocky and very rocky. This information was available from the descriptions of the drift geology of each catchment, the details of which had already been worked out as described above.

3.4 Catchment vegetation

As with rock presence, vegetation was assessed using the descriptive information supplied with the maps. The number of different categories of vegetation present was divided into the percentage of the catchment covered. The following major vegetation categories were used: moor, heath, grassland, rush pasture, bog, deciduous woodland, coniferous woodland and arable crops.

A separate analysis of land use within each catchment was made using the 1:50000 OS series. The quadrat square count method was again used and the percentage presence of each of the following categories was obtained: rough pasture, arable farmland, forest, open water and urban areas.

Data concerning some of the major relevant components from this analysis are given in Table 5.

4 Field research programme

4.1 General

The majority of the lochs concerned are in mountainous areas, often at some distance from the nearest vehicle access. This fact led to a number of logistic problems and forced a choice of equipment which was as light and portable as possible (Plate 1). Normally, a team of 4 people was required for each field trip and site visits involved walks of up to 20 km each day. Each site was visited at least twice during each trip.

4.2 Bathymetry and echo sounding surveys

Although the main focus of investigation was the fish population, it was also considered relevant to have background physical (and chemical) information for each site. At most sites, therefore, brief bathymetric surveys were made if such data were not already available (eg from Murray & Pullar 1910). It was thereafter possible to calculate loch volumes and to produce estimates of theoretical water retention times from catchment and climatic data. Water retention time is an important hydrological parameter and its potential value in the acidification context is that it allows a differentiation among sites concerning the impact of periodic inputs, from a purely hydrological aspect, which may be helpful in identifying sites at risk.

The echo surveys were made from small boats (either fibreglass or inflatable) which were dragged or carried to the lochs. A compact, portable echo sounder and battery pack were fitted to a rucksack frame and also carried to the sites. A full description of the methods and results of the bathymetric surveys is given in Appendix 1. In total, bathymetric information was obtained from surveys of 49 lochs, and equivalent data were available from 15 additional sites, mostly from Murray and Pullar (1910), making a total of 64 sites.

An additional purpose of the echo surveys was to supplement the fish catch data, with further information on fish numbers and distribution from echo traces. Overall, however, this proved unsuccessful for 2 reasons. First, many of the lochs were too shallow (<3 m) for the practical detection of fish, partly due to the narrow area sounded at these depths and partly to probable fish avoidance of the boat. Second, at a number of sites regarded as fishless or having very low stocks, dense echoes were recorded in mid-water from sources as yet unidentified. This caused uncertainty as it was not possible, with the equipment used, to make a positive distinction between echoes from fish and these other echoes. Consequently, systematic attempts to detect fish were abandoned.

4.3 Water chemistry

Sub-surface water samples were taken routinely from the major inflow to each loch and from its outflow. Where there were no inflows, or these were not running, substitute samples were taken from the loch near the point deemed most likely to have an inflow during wet weather or at the part furthest from the outflow.

Two sets of samples were always taken: one during the first visit and another during the second (usually one, 2 or 3 days later). The samples were kept in cool, dark containers until they were analysed. The range of analyses carried out included Hazen clour, pH, conductivity, calcium, magnesium, total aluminium, PO_4 phosphorus, NO_3 nitrogen, NH_4 nitrogen, chloride and SO_4 sulphur; foremost among the determinands measured were pH and calcium (Brown 1982).

4.4 Benthic invertebrates

During 1984, collections of leeches (Hirudinea) and snails (Mollusca: Gastropoda) were made from the littoral zone of each loch visited, by collecting all the specimens found on a sample of 100 stones. These stones were lifted randomly between the edge and 50 cm depth of water. The stones usually ranged in size from 10 cm to 20 cm in diameter. All specimens collected were placed in labelled tubes and brought back to the laboratory for identification. The information (Table 6) was subsequently assessed in relation to granite and 'control' sites (Rooke 1984).

Table 6. The occurrence of leeches (Hirudinea) and molluscs (Mollusca) at the lochs sampled during 1984. The numbers are counts per 100 littoral stones

Lochs	Hirudinea	Mollusca
Granite:		
% occurrence	32	16
minimum number	0	0
maximum number	21	24
mean	2.3	1.5
Control:		
% occurrence	83	50
minimum number	0	0
maximum number	6	12
mean	3.2	5.3

4.5 Loch fish

Each loch visited was gill netted if permission had been given, and full details of the methods used are given in Appendix 3. The fish caught were identified and measured for length and weight. They were subsequently sexed and samples of scales (for ageing) and flesh (for metal analysis) were taken. The stomach contents of a sub-sample of each catch were examined.

The aims of the gill netting were as follows.

i. To give information on the status of fish in the lochs and the size/age structure of the population, as acidification causes recruitment failures which distort both age structure and growth rates (Frenette & Dodson 1984).

ii. To provide stomach contents for analysis of the diet, because reduced fish predation (eg where acidification has lowered fish numbers) allows an increase in the numbers of invertebrate biota and their significance in fish diet increases correspondingly.

iii. To provide flesh samples for chemical analysis, because the long-range transportation of heavy metals or their local release through the acidification process may show up by their accumulation in fish tissues.

iv. To allow examination of fish for any pollution-induced deformities.

4.6 Stream fish

Establishing whether or not inflow and outflow streams are suitable for young salmonids, later to be recruited to the loch, was regarded as an important part of the study. The population structure of the nursery stream populations was also felt to be of considerable significance, as (at least for salmonids) it is these nursery streams which are most vulnerable to acid 'events' (Bjarnborg 1983), reflected years later by missing year classes in the loch.

At each loch, standard electro-fishing procedures, using portable battery-powered equipment, were carried out in both the major inflow and the outflow. Fishing was continued for a known period of time and the length and width of streams fished were noted. All fish caught were identified, measured for length and returned to the stream alive.

5 Principal results

The principal objective of this study was a relatively straightforward one: to what extent do fish populations in fresh waters in Scotland appear to have been affected by acid deposition? The approach adopted was to examine a large sample of a type of water known to be vulnerable to acidification—lochs with granite basins and catchments—and to study the status of fish in these lochs and their associated streams as well as in nearby 'control' systems, whose catchments were not on granite.

The detailed results of the project are considered in the individual scientific papers presented as Appendices to this report. Here, only the major conclusions relative to the initial objective are considered.

The main results are summarized in Table 7 and in Figure 2, where the values for pH and calcium are cross-plotted. Superimposed on these plots is the acidification curve proposed by Henriksen (1979) which assumes that, in acidified waters, bicarbonates are used up as acidity increases, leaving the calcium at a disproportionately higher level than normal. The curve indicates the normal relationship expected between the 2; any waters whose values are significantly above this curve are assumed to be acidified. In this way, 'acidified' waters can be distinguished from those which are naturally 'acid'.

According to the Scandinavian information, the more acidified a loch, the more likely it is to be fishless; it is evident from Figure 2 that most of the present data agree with this view. Of all the 52 granite sites examined, 14 (27%) were found to be fishless, whereas, of the 17 control lochs (excluding those on Islay), none were fishless. Similar results were obtained for fish populations in the inflow and outflow streams of these lochs. Though information is not available for all of them, it is known that the majority of these fishless lochs formerly had trout populations (Plate 2). The conclusion is that these lochs have become more acid in recent years and that this has caused the extinction of the fish.

There has been considerable controversy over the origin of the pollutants concerned and the actual nature of the acidification process (Brown & Sadler 1981; Howells 1983), but the present results certainly agree with the historical data presented by Flower and Battarbee (1983), Battarbee (1984) and others, for some of the sites which are now fishless.

How serious is the problem in Scotland? It is known from map counts that there are some 31460 lochs in Scotland as a whole but only 1536 (4.88%) have basins within granite. However, the majority (1159) are small lochs (less than 1 ha). This class was not examined. Only 279 lochs larger than one ha have basins and catchments lying entirely on granite; this number represents 0.89% of the Scottish total. These figures could be interpreted as indicating that, even if all these lochs are affected, acidification is not having a serious overall effect on fish and fresh waters.

The real situation is not so straightforward, however, for 2 principal reasons. First, there are notable differences in the way in which lochs on granite appear to be affected in different geographic areas (Figure 3). Thus, a very high proportion of the waters on granite in Galloway have become acidified and fishless over the last few decades, but practically none on granite in, say, the Criffel area (Plate 3), Rannoch Moor (Plates 4 & 5), Morvern (Plate 6) or Caithness (Plate 7). It must also be remembered that some waters may be

Table 7. Percentage of loch and stream sites at which the fish species recorded during this study were caught. The data refer only to the results from gill netting (lochs) and electro-fishing (streams)

Fish species	Lochs	Streams
Atlantic salmon (*Salmo salar*)	0	2
Brown trout (*Salmo trutta*)	68	65
Arctic charr (*Salvelinus alpinus*)	2	0
Pike (*Esox lucius*)	3	2
Minnow (*Phoxinus phoxinus*)	3	5
Roach (*Rutilus rutilus*)	2	0
Eel (*Anguilla anguilla*)	3	23
Three-spined stickleback (*Gasterosteus aculeatus*)	0	13
Nine-spined stickleback (*Pungitius pungitius*)	0	2
Perch (*Perca fluviatilis*)	3	0
Total number of species	7	7

fishless for reasons other than acidification (Plate 8). Second, although they may still contain fish, a number of waters appear to be partially acidified, and presumably the process is continuing. In many of these systems (eg Loch Grannoch, shown in Plates 9 & 10), the fish populations are already showing signs of disappearing and therefore an uncertain number of waters will be added to the fishless total, unless acidification is reversed by calcium applications or other measures of the kind already in progress at Loch Dee (Burns *et al.* 1984) and Loch Fleet (Central Electricity Generating Board 1985). Third, there are other types of base-poor rocks (eg schists); lochs with catchments on these are also vulnerable to acidification. Fourth, the extensive deposits of peat in many Scottish catchments and the consequent increase in the organic content of their waters must reduce the risk from aluminium toxicity, regardless of solid geology.

6 Conclusions

In summary, in only one part of Scotland—Galloway—do significant numbers of lochs appear to have been substantially affected by acidification. Here, 2 major blocks of granite (Doon and Cairnsmore) are involved. In total, there are 38 lochs on these blocks, 23 of which are more than one ha in area.

During this study, 11 of these 23 larger lochs were examined. It was concluded, from chemical data, that all of them were acidified (Henriksen 1979) and 6 were found to be fishless. Fish in the other 5 lochs showed signs of acid stress (tail deformities, fewer young fish, etc). It is assumed that the 12 lochs not examined are similarly affected by acidification, and, indeed, this

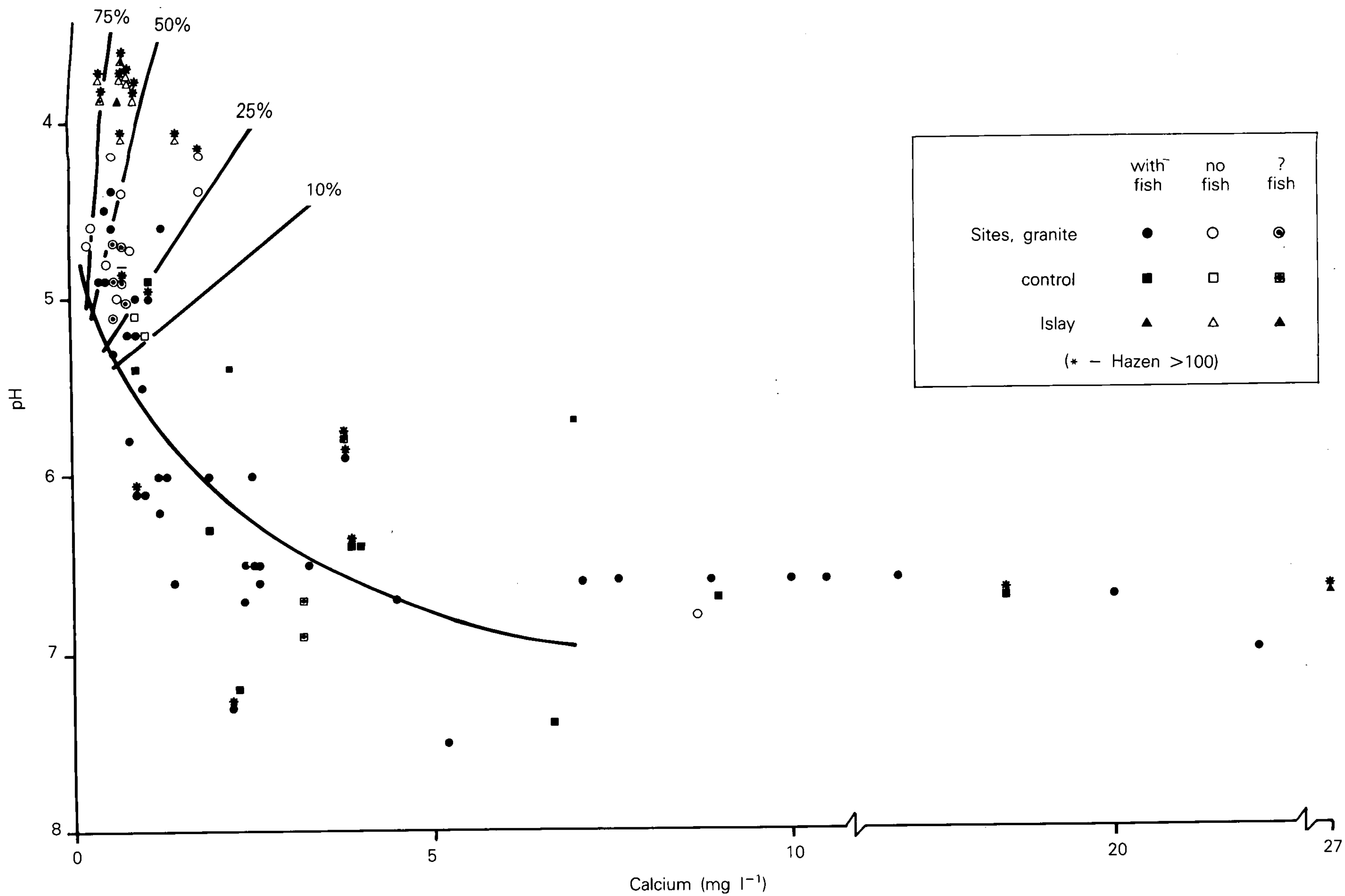

Figure 2. pH and calcium plots of lochs fished during this study, superimposed on the acidification curve of Henriksen (1979) and the proportions suggested likely to be fishless by Brown (1982), recalculated from Wright and Snekvic (1978). It should be noted that not all the sites shown are applicable to this curve because of their high organic content (*).

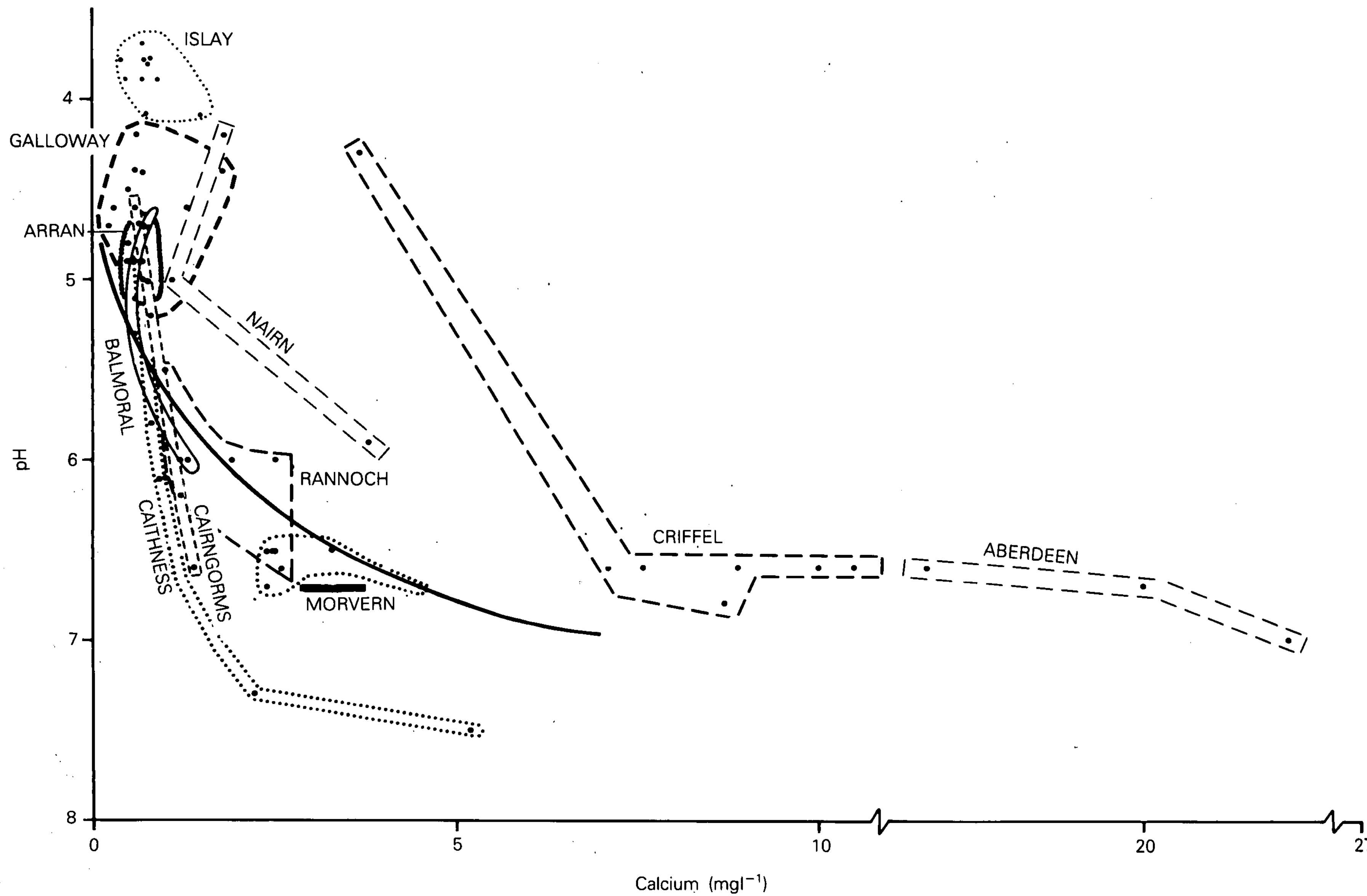

Figure 3. Geographic relationships of pH and calcium plots of all lochs on granite sampled during the project. Also shown is the Henriksen (1979) acidification curve, though it should be noted that not all the sites shown are applicable to this curve because of their high organic content.

appears to be the case from the data of other workers. Virtually all of them are acidified chemically (Wright & Henriksen 1980) and in several of them the fish populations are exhibiting acidification symptoms (Burns *et al.* 1984; Hay 1984).

Over the rest of Scotland there was very much less evidence of lochs on granite being significantly affected by acidification (Figure 4). In total, there are 354 lochs more than one ha in area on granites other than Doon and Cairnsmore. This study examined 38 of these lochs in 7 different areas—Morvern, Criffel, Rannoch, Caithness, Cairngorm, Balmoral and Aberdeen. The great majority of these appeared to show no signs of acidification, and only 4 were fishless. A similar situation appears to be likely for those lochs not examined.

The situation, however, is by no means a simple one. In addition to the lochs on granite, 11 'control' lochs were examined, and, although all of these lochs were found to contain fish, some of these (in Galloway at least) appeared to be acidified chemically. Thus, waters in areas of hard rock (slates and schists) other than granite are being affected, as has been found with streams in the Loch Ard area (Harriman & Morrison 1981).

Extensive areas of peat in the catchment also modify the situation. Though these peats are in themselves fairly acid, they may control the effect of aluminium to a substantial extent so that fish are little affected. Some extremely acid, very stained, waters were found on Islay. Some were fishless but there was no evidence that they had ever had self-sustaining trout populations. One of the lochs, however, definitely did have fish in the past and has lost its population within the last century. Whether this loss was due to increased acidity from the surrounding peat or from atmospheric deposition is difficult to say in the present state of knowledge of the chemistry of humic waters as related to the acidification process (see also Appendix 5).

The main conclusion drawn from these results appears to be quite simple—some lochs on granite in Scotland have been acidified and become fishless over recent years, but these represent a small percentage of the Scottish total. The effect is localized and predominantly in south-west Scotland. In addition, some other

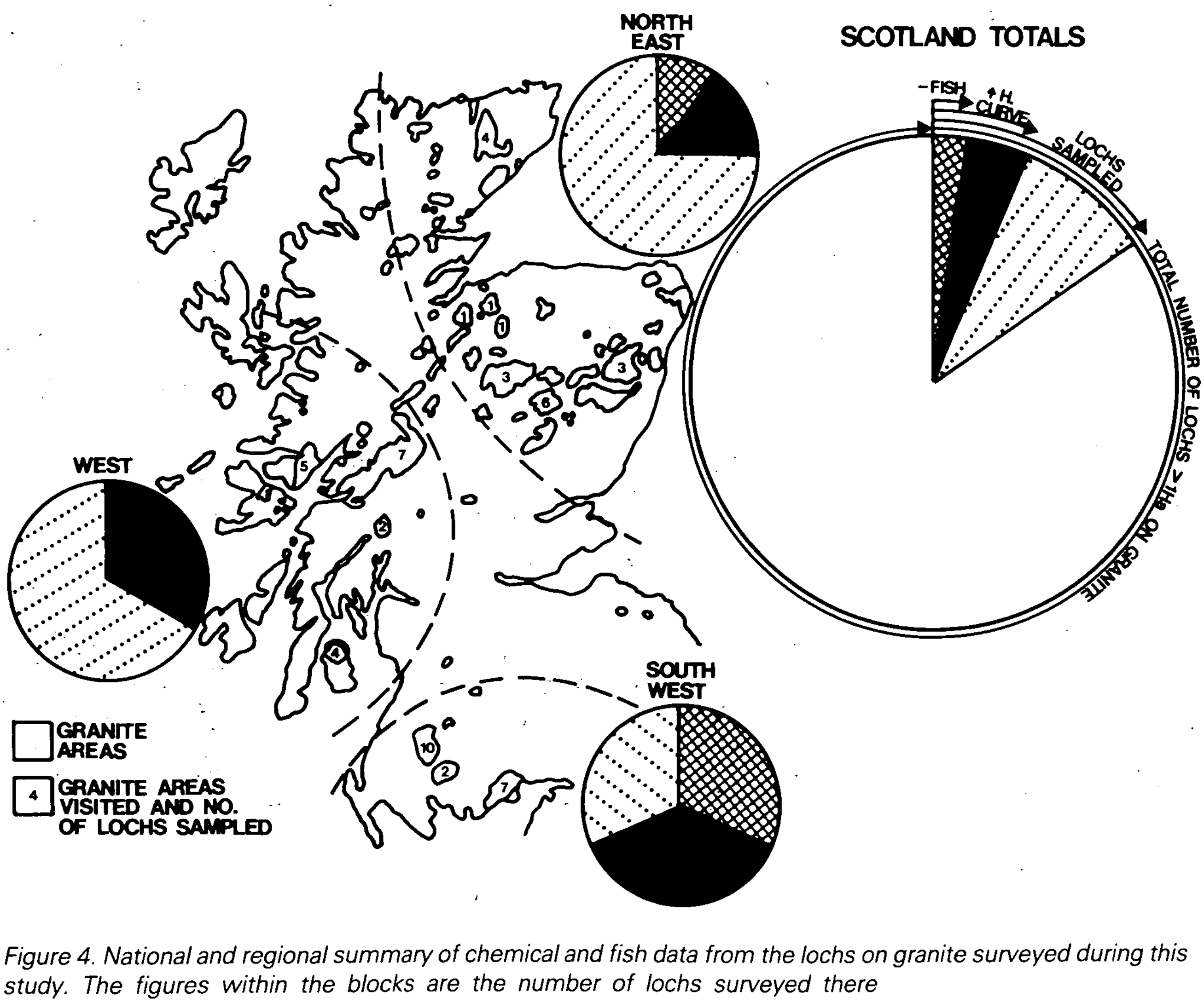

Figure 4. National and regional summary of chemical and fish data from the lochs on granite surveyed during this study. The figures within the blocks are the number of lochs surveyed there

Plate 1. Transporting sampling equipment to hill lochs in Galloway. Loch Enoch, lying at a height of 493 m, is 4 km away over the ridge on the horizon, and 3 other lochs there will be visited the same day (Photograph R N B Campbell)

Plate 2. Loch Valley in Galloway, previously a good loch for brown trout, is now fishless. The last 2 trout recorded from this loch were taken by the photographer in 1970. Beyond it can just be seen Loch Neldricken, which is also fishless now, but formerly held brown trout and pike (Photograph P S Maitland)

Plate 3. Duff's Loch in Galloway. Though lying entirely within the Criffel granite block, this loch, like most of the others in the block, appears to have sufficient buffering material in the catchment drift to counter acidification, for it supports a good population of brown trout and nine-spined sticklebacks (Photograph P S Maitland)

Plate 4. Dubh Loch ('Kingshouse N') on the Moor of Rannoch. One of the many peat-stained lochs on granite in this area, its waters, though brown and moderately acid, still manage to support a good population of brown trout (Photograph K H Morris)

Plate 5. Loch Mhic Pheadair Ruadh is one of the 'control' lochs in the study and lies entirely outside the neighbouring granites of the Moor of Rannoch. It supports a substantial population of brown trout and minnows (Photograph K H Morris)

Plate 6. Loch Tearnait in Morvern, Argyll. Though lying entirely on granite and with relatively clear water, it appears to be sufficiently buffered to maintain a good population of brown trout and three-spined sticklebacks (Photograph P S Maitland)

Plate 7. Loch Dubh Cul Na Beinne in Caithness is one of several brown-stained lochs on the granites in this area. Like most of them, it supports an excellent population of brown trout (Photograph P S Maitland)

Plate 8. Loch nan Eun on the Balmoral Estate in Grampian is a clear water loch lying entirely on granite and is apparently fishless. It is not known whether it has always been so or whether it at one time held brown trout (Photograph R N B Campbell)

Plate 9. Loch Grannoch in Galloway, which formerly supported an excellent fishery for brown trout and contained one of the few populations of arctic charr in south-west Scotland. The trout population has declined dramatically in the last 2 decades and the charr appear to have been extinct for some years (Photograph P S Maitland)

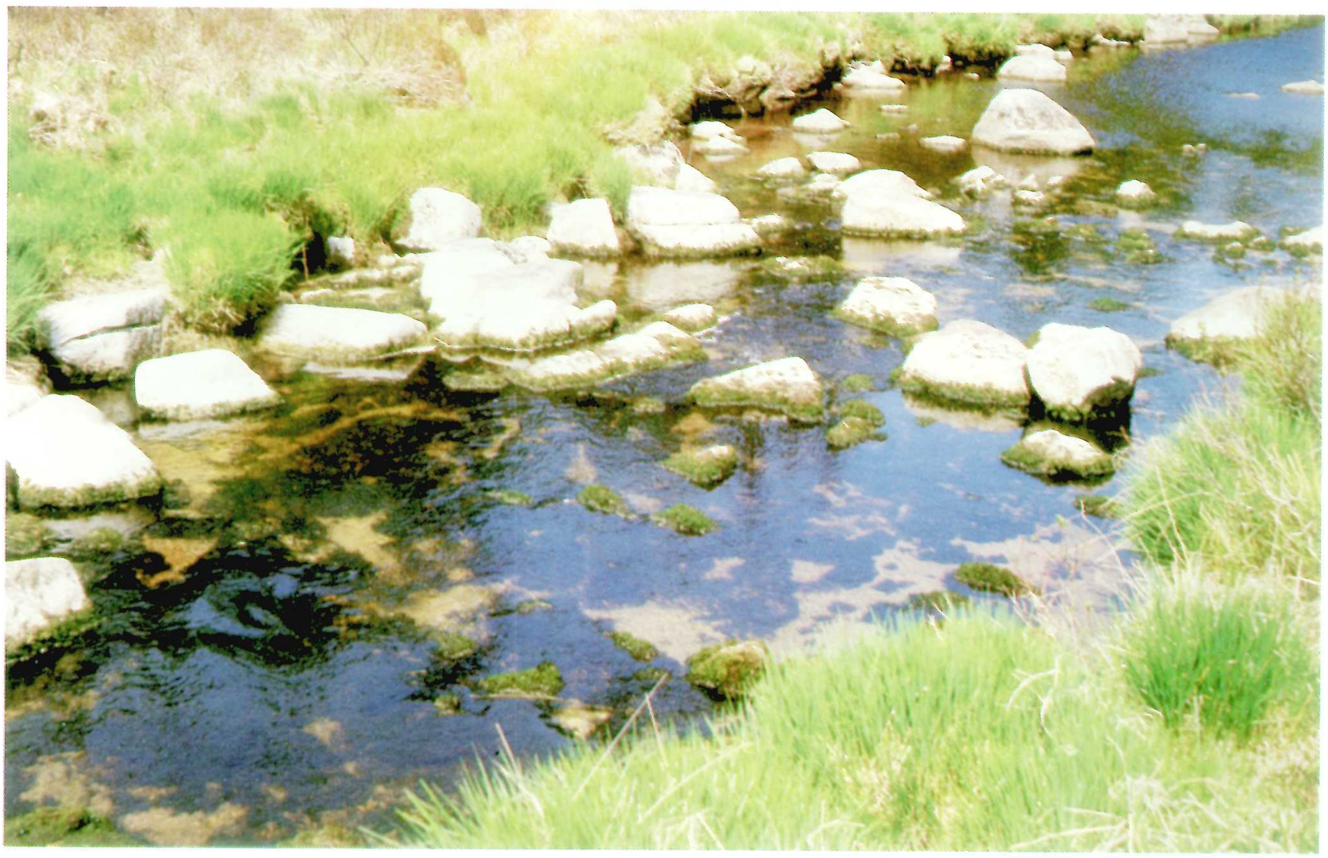

Plate 10. The outflow from Loch Grannoch in Galloway. Though this burn looks attractive with clear water, clean gravels and an exuberant growth of moss, it is no longer able to support any fish in its highly acid waters (Photograph P S Maitland)

Plate 11. Loch Enoch in Galloway was reported to have brown trout with deformed tails in 1882. The loch is now fishless—as are Loch nam Manaichean on Islay and Loch Fleet in Galloway, both of which once possessed trout with similar deformities (reported in 1872 and 1948 respectively) (Photograph P S Maitland)

Plate 12. The Round Loch of Glenhead in Galloway is one of several lochs in this area apparently still undergoing changes due to acidification. The brown trout population is sparse and many have deformed tails; only eels occur in the outflow burn (Photograph A A Lyle)

lochs are acidifying and are likely to lose their fish over the next one or 2 decades. Again, the number involved appears to be small.

A number of questions remains to be answered, however, and future research should be directed at these. What are the precise characteristics of the acidified (and acidifying) lochs (especially, say, in Galloway) which make them particularly vulnerable? What is the rate of acidification in those which are continuing to change, and what is the most appropriate way of monitoring this rate?

Other interesting areas of future research have also been revealed. What is producing the scattering effect on echo soundings from fishless lochs, and could a monitoring system be developed which is based on this phenomenon? Fish tail deformities may well be one of the earliest warnings that acidification is affecting fish; perhaps the value of this factor too could be assessed for future monitoring purposes. These topics are discussed further in Section 7.

7 Future research

During the relatively short 2-year study period of this project, it became apparent that certain chemical and biological features found in some of the sample lochs required further research, if their association with the acidification process was to be understood. Three of the most important of these features are discussed below.

During the echo sounding surveys for bathymetry, large numbers of echoes were recorded from the open water of those lochs which were thought to be acidified (from their chemistry) and fishless (from the netting). Due to a shortage of time and suitable equipment, it was not possible to identify the source of these echoes during the surveys. However, because of their high densities, their spatial distribution and some casual investigation, it is suggested that they are caused by invertebrates of some kind—possibly corixids, beetles or chironomid pupae.

A possible explanation is that, as fish decrease in number during the process of acidification and eventually disappear, their prey species often increase in number and spread into the formerly more vulnerable, open water, where the larger species can be detected by echo sounding. This feature was recorded in many of the acidified Galloway lochs, in Islay (where the lochs appear to be very acid from natural causes) and in some lochs in the Grampian Region.

A second interesting feature arising within the project came initially from the historic evidence of deformity in the tails of trout from acidified waters, possibly caused by acid episodes in spawning streams during embryological development. Past examples have been recorded from lochs in Galloway (1882, 1927 and 1940), one of these, for example, being Loch Enoch (plate 11), and on Islay (1872). All the lochs concerned are now very acid and fishless; they are also among the highest in altitude in their area. In 1985, deformed trout were caught in acidified lochs in the same areas—for example, the Round Loch of Glenhead (Plate 12)—but at lower altitudes, suggesting a progression of acidification with decreasing altitude.

Both the Galloway and Islay lochs that produce or produced these similarly deformed trout are highly acid. They almost certainly differ, however, in the amount of the toxic inorganic aluminium which is present in their waters. Its level was probably high in the clear Galloway lochs but likely to be very low in the heavily organically stained Islay lochs. A common cause of these deformities would be the acidity itself—in Galloway from acid deposition but in Islay from either organic acids alone or combined with acid deposition—rather than anything associated with aluminium, or possibly other metal, toxicity. The physiological mechanism responsible is probably a distortion of the calcium metabolism, which has been associated with deformed non-salmonid fish in acidified lakes in North America. Studies of the features of this process and its incidence in various waters may establish them as valuable indicators of the start of the acidification of some systems.

Finally, an important area for future research is the whole question of the levels of aluminium and other elements in the chemical processes taking place, in clear acidified waters on the one hand and the many naturally acid, highly organically stained, waters on the other. A feature in which the fresh waters of Scotland seem to differ from those subject to acidification in both Scandinavia and North America is the high proportion of very organic waters in Scotland. This factor has important consequences for aluminium toxicity, because, of all the forms aluminium can take in solution, it is only the inorganic forms that are toxic to fish (Driscoll *et al.* 1980). However, the most toxic of these aluminium ions react strongly with organic molecules to form harmless organo-metallic compounds.

The level of toxicity of the other inorganic forms is unclear, as is their interaction, if any, with organic molecules, but Driscoll *et al.* (1980) have shown that, in waters with high dissolved organic content, organically bound aluminium is the predominant fraction of total aluminium. Because the formation of these organo-metallic complexes clears water of peat staining, presumably any water stained brown is free of the most toxic form of dissolved aluminium, and there are a great many such brown waters in the base-poor uplands of Scotland. The possibility is, therefore, that most of upland Scotland is protected, to some degree, from the effects of acidification by its peaty soils, whereas the mineral soils of parts of Scandinavia and North America offer no such protection to their waters. Thus, Scotland as a whole may be much less susceptible to loss of fish populations through acidification, even though the amount of acid deposited may be as great as elsewhere.

The lack of information about this process, particularly in relation to the valuable Henriksen (1979) acidification criteria for lochs, means that some of the lochs were not really suitable for the analyses described in this report. Further study of this aspect is required if peat-stained waters, of which there are many in Scotland, are not to be excluded from any overall appraisal of the impact of acidification. In addition, there are a number of important lochs which lie only partly on granite, but where this factor combines with others, in particular extensive afforestation, to lead to significant acidification. Loch Doon, which has the only remaining population of arctic charr in south-west Scotland, is such a loch, and as such merits further investigation.

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