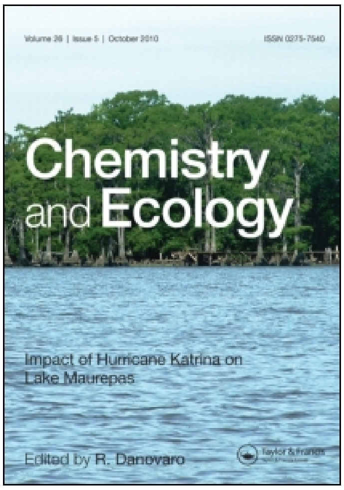

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THE LOCH FLEET PROJECT IN THE CONTEXT OF ACIDIFICATION REDUCTION MEASURES

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At Loch Fleet, and in other liming studies in similar environments, catchment liming is successful if an adequate amount of lime is added to hydrological source areas. Geochemical modelling demonstrates that the relatively late acidification of L. Fleet is consistent with the ameliorating effect of an alkaline groundwater input: the presence of this input implies that had the Loch not been limed in 1985 it would have recovered to conditions suitable for fish in about 20 years, given current commitments to sulphur emission reductions. Lakes without similar alkaline groundwater are not likely to recover as quickly. The different consequences of liming and emission reduction as methods of restoring acid waters are reviewed and contrasted. Restoration of waters by liming may result in some undesirable effects on the terrestrial catchment: these are discussed but it is concluded that catchment liming, used with discrimination, can be an acceptable management tool.

KEY WORDS: S emissions, acid soils/waters, liming

INTRODUCTION

The Loch Fleet Project was set up in 1984 to demonstrate that the chemistry of an acidified lake could be brought into a state suitable for trout by catchment manipulation treatments, and that a self-sustaining trout population could be supported (Howells and Dalziel, 1992). It has succeeded in those aims. Since the experiment was started, however, international agreements to reduce sulphur and NO_x emissions in Europe to a very significant extent have been made. This paper discusses several issues related to the declining level of acid deposition. What would have happened to Loch Fleet if it had not been limed? Would it have recovered unassisted, by now or in the future? Are the results from Loch Fleet compatible with other catchment manipulations in similar habitats, and what else can be learned from those studies? And finally, the improvement in water quality of Loch Fleet was achieved, but the ecology of the terrestrial environment was altered subtly. Are such alterations acceptable or inevitable?

LIMING EXPERIENCE AT OTHER SITES

Liming for the purpose of mitigation of acidification has been extensively reviewed over the last few years (Sverdrup and Warfvinge, 1988; Olem, 1990; Howells and Dalziel, 1992). Lake liming is established technology with effects that are now fairly predictable (Olem, 1990) even though the results of early Swedish attempts ranged "from illustrious to disastrous" (Sverdrup and Warfvinge, 1988). Catchment liming, as at Loch Fleet, is less well established and the Project has made a major contribution to advancing the science behind the technique. The results from two other major liming studies in the UK are outlined here for comparison with Loch Fleet (Table I).

The oldest of the studies which involve liming is the Loch Dee Project, situated 10 km NW of Loch Fleet. Most of the liming treatments have been applied to the White Laggan Burn (Welsh and Burns, 1987). Here catchment liming had no measurable effect. The successful treatments involved application of large quantities of powdered limestone directly into the burn. Though the other treatments were not successful in measurably improving water quality, the calcium applied did dissolve and thus presumably contributed to undetected small water quality improvements. The conclusion appears to be that large quantities of finely-divided, and thus rapidly dissolving, limestone are needed for a significant effect.

More catchment treatments were attempted at Llyn Brianne. The final report from the Project is as yet unpublished, and this information was obtained from Dr. N. S. Weatherley, UK National Rivers Authority. Liming whole moorland catchments was effective, as at Loch Fleet (Table I). Liming of hydrological source areas was also effective, and more economical with limestone. This was also true of source areas within coniferous forest, though in this case peaks of aluminium in the runoff were not eliminated entirely by treatment. In contrast, use of pelletized limestone (necessary for penetrating the forest canopy) to lime forest source areas was not very effective. Agricultural improvement, which included a liming component, was somewhat surprisingly not effective, nor was clearing the stream banks of trees. The project seems to have demonstrated that an adequate amount of lime of high dissolution rate applied to hydrological source areas is the pre-requisite for successful liming. Liming hydrological sink areas has little or no effect. As source areas comprise typically 5–10% of these

Table I Success of liming treatments at Loch Dee and Llyn Brianne. "Success" is defined as a measurable effect on water quality.

Treatment	*Rate*	*Success?*
LOCH DEE		
Stream–shells (1980)	5 t	No
Stream–shells (1980)	5 t	No
Stream–powdered limestone (1981)	10 t	No
Catchment–powdered limestone (1981/2)	80 t	No
Stream–limestone chips (1981/2)	80 t	No
Stream–powdered limestone (1983)	75 t	Yes
Stream–powdered limestone (1985)	100 t	Yes
LLYN BRIANNE		
Entire moorland catchment	$9\,t\,ha^{-1}$ on 34 ha	Yes
Moorland source area	$15\,t\,ha^{-1}$ on 7%	Yes
Pelletized limestone–forest source area	$9\,t\,ha^{-1}$ on 12 ha	Slight
Powdered limestone–forest source area	$30\,t\,ha^{-1}$ on 4 ha	Yes
Agricultural improvement–magnesian limestone	$10\,t\,ha^{-1}$	Slight
Bankside forest clearance	–	No

upland catchments, selective liming of these areas is very cost-effective, but may conflict with conservation interests (see below).

The results discussed here and elsewhere (Olem, 1990) seem to lead to a recipe for catchment liming as a surface water mitigation measure, which is "apply an adequate amount of rapidly-dissolving limestone to the hydrological source areas". This begs some questions, such as how to decide how much is adequate, and from what point of view (cost, longevity), and how to identify the hydrological source areas. The use of soil liming models, such as SLiM (Warfvinge and Sverdrup, 1989) needs to be explored further. A model which had been validated against observed responses would be useful, for instance in predicting treatment longevity, exploring whether nature conservation interests can be accommodated by partial liming, or devising a whole catchment management programme.

LOCH FLEET WITHOUT LIMING: DIAGNOSIS AND PROGNOSIS

Why did Loch Fleet acidify?

When considering Loch Fleet in the context of acidification reduction measures, it is useful to consider what would have happened to Loch water quality and fishery status if the lake had not been limed. Predicting this requires an understanding of why the lake acidified in the first place. This is readily understood in general terms–the magnitude of acidification processes, principally acid deposition, exceeds that of de-acidification processes, principally mineral weathering (Skeffington, 1992). Table II shows some estimates of the important fluxes which, *on the assumption that the catchment is in steady state*, can be used to explore the possibilities. The top section of Table II shows positive alkalinity fluxes: first non-marine base cation fluxes in precipitation (magnesium and sodium are negligible) and then weathering fluxes. These are mapped as

Table II Fluxes of alkalinity from the Loch Fleet catchment, and resultant lake concentrations. Dep = deposition, wet in the case of ions, dry in the case of SO_2. W = Weathering rate.

Input	*Concentration* $\mu eq\,l^{-1}$	*Flux* $meq\,m^{-2}\,yr^{-1}$	*Alk Flux to Loch* $keq\,yr^{-1}$	*Resultant* [*Alk*] $\mu eq\,l^{-1}$
$*Ca^{2+}$ Dep	6.8	15.5		
$*K^{+}$ Dep	1.4	3.2		
Weathering		50 or 20		
Sum (W = 50)		68.7	+76.2	+38.7
Sum (W = 20)		38.7	+43.0	+21.8
Groundwater			+71.7	+36.4
H^{+} Dep (1985)	27.3	−62.3		
NH_4^{+} Dep (1985)	21.0	−48.0		
SO_2 Dep (1985)		−50.0		
Sum acids (1985)		−160	−178	−90.0
H^{+} Dep (1850)	5.0	−11.4		
NH_4^{+} Dep (1850)	13.3	−28.0		
SO_2 Dep (1850)		−9.1		
Sum acids (1850)		−48.5	−53.8	−27.3

a range (Langan and Wilson, 1993) of 20 to 50 meq m^{-2} yr^{-1}: calculations for both extremes are given. Finally, L. Fleet was discovered to have a substantial base-rich groundwater input (Cook *et al.*, 1991) and the value in Table II has been recalculated from their paper. All these figures can be translated into fluxes from the catchment and "dissolved" in the volume of runoff to give a resultant lake concentration, as shown in the last column of Table II.

Acid inputs are shown in the next section of Table II. Because essentially all ammonium falling on the catchment is retained, and essentially none of the nitrate is, the acidification due to nitrogen transformations can be approximated as the ammonium input (van Breemen *et al.*, 1983). Dry deposition of sulphur dioxide has to be added, the value used being that needed to balance the sulphur budget of the catchment in 1985. This may not all be dry deposited sulphur dioxide. Conditions in 1850 (taken, somewhat unhistorically, as pre-industrial) are less certain. Non-marine sulphate in rain was 37.6 μeq l^{-1} in 1985, whereas background sulphate derived from natural emissions is thought to be 6–8 μeq l^{-1} (e.g. Whelpdale *et al.*, 1988). If this background is partitioned between hydrogen ions and ammonium in the ratio 72:28 (derived by attributing all the non-marine sulphate to sulphuric acid in 1985 with the balance to ammonium and retaining the same proportions in 1850), and dry deposition reduced by the same proportion, the values are as shown in the last part of Table II.

Different scenarios can be explored simply by algebraic addition of the concentrations in the last column of Table II. Thus, if weathering is assumed to be 50 meq m^{-2} yr^{-1}, lake alkalinity in 1985 should have been $38.7 + 36.4 - 90.0$, or -15 μeq l^{-1}, corresponding to a pH of about 4.8 (pH-alkalinity equivalents are taken from a large US lake data set (Baker *et al.*, 1990)). This is somewhat higher than the observed pH of about 4.5, showing that the effective alkalinity inputs must have been lower or acidity inputs higher. The lower end of the weathering rate band gives an alkalinity input of -32 μeq l^{-1} or about pH 4.5–now close to the observed value. Without the groundwater input, the alkalinity in 1985 would have been -68 μeq l^{-1} corresponding to pH 4.2. In 1850, high weathering would lead to alkalinity $+48$ μeq l^{-1}, or pH 6.5, low weathering to alkalinity of 31 μeq l^{-1}, or pH 6.1. According to the diatom stratigraphy (Battarbee *et al.*, 1992), the preacidification pH was around 6.0, hence once again the lower weathering rate gives a closer correspondence to observation. Without the groundwater input alkalinity would have been around -5.5 μeq l^{-1}, or pH 5.0

Predicting the future: the MAGIC model

The simple calculations above demonstrate the importance to the Loch Fleet catchment of the base-rich groundwater input, and some of the reasons for the poor quality of water in such areas. In particular, the high rainfall means that even background sulphate concentration leads to considerable acid deposition. The nitrogen relationships of the catchment are also important. Prediction of the dynamic behaviour of the catchment, however, and especially consideration of recovery times, requires the application of an acidification model. In this section we apply the MAGIC model to the Loch Fleet catchment.

A detailed description of the principles underlying MAGIC will be found in Cosby *et al.* (1985 a, b). In outline, the soil processes modelled are: carbonic acid equilibria; ion exchange represented by a Gaines-Thomas formulation of Al^{3+}-base cation exchange; $[Al^{3+}]$ determined by equilibrium with $Al(OH)_3$; adsorption of sulphate, represented by a Langmuir adsorption isotherm; mineral weathering, represented by an input of base cations; and organic acid outputs, specified by total outputs and acid dissociation constants. The total anion content of the soil water determines cation leaching, in accordance with the mobile anion hypothesis; the proportions of cations in the leachate are thus determined by their ratios to aluminium on the soil exchange surfaces. Base saturation is therefore a key state variable in the model. On leaving the soil, water is assumed to lose carbon dioxide to reach equilibrium with a predetermined level, changing the pH and associated variables. Inputs to the water which bypasses the soil are allowed in the latest version. The model has performed well in validation tests against laboratory data (Grieve, 1989; Skeffington and Roberts, 1993) although its treatment of organic acidity and organic–aluminium relationships is clearly a weakness. While its results should not be accepted uncritically, it embodies the major features of current understanding of acidification and de-acidification processes.

Parameterizing MAGIC

MAGIC was set up using the parameters in Tables III and IV. Directly–measured quantities were used where possible (e.g. precipitation concentration). Priority in the initialisation process was given to reproducing the pre-liming (1985) lake concentrations. Weathering rates for the surrounding catchment were taken from estimates made for the UK Critical Loads Advisory Group (see Langan and Wilson, 1993). "Soil" parameters in MAGIC are lumped over the whole catchment, and so are not directly comparable with measurements, but the values adopted resemble those measured. Precipitation concentrations for the base year (1985) and the years at the beginning of the hindcast (1850) and the end of the forecast (2120) are shown in Table IV. Since individual years can give a misleading picture of long-term trends, the "1985" values are in fact mean values from 1985–90 (Dalziel *et al.*, 1992). Sulphate deposition during the hindcast was varied in proportion to European sulphur emissions according to Bettelheim and Littler (1979). The forecast assumes currently-agreed reduction plans for sulphur emission in Europe, which amount to a reduction of 70% on 1980 emissions by 2005 and 80% by 2010 for the UK, together with slightly smaller commitments for continental Europe as a whole. Feeding these emission reductions into an emission-deposition model leads to reductions in precipitation of non-marine sulphate at Loch Fleet of 60% of 1980 values by 2003, and 70% by 2010. The concentrations of calcium and ammonium have also been adjusted slightly for the forecast and hindcast in proportion to the changes in sulphate.

MAGIC forecasts

Loch Fleet acidified much later than other similar lochs in Galloway, according to diatom stratigraphy (Battarbee *et al.*, 1992), undergoing rapid acidification in the 1970s in contrast to the 19th century acidification of other lochs. This timing is not entirely

Table III Parameters used to model Loch Fleet.

Parameters	*Note*	*Soil*	*Lake*
Depth		0.35 m	6.58 m
Porosity		0.75	
Bulk density		118 kg m^{-3}	
CEC		650 meq kg^{-1}	
C	1	150 meq m^{-3}	
E_{MX}	1	0.1 meq kg^{-1}	
Q (outflow)		1.75 m yr^{-1}	
QP (inflow)		2.285 m yr^{-1}	
pCO_2		0.0025 atm	0.0009 atm
Temp		7.7 °C	7.7 °C
log K_{Al}	2	7.70	7.90
log S_{AlCa}	3	−1.74	
log S_{AlMg}	3	0.04	
log S_{AlNa}	3	−0.86	
log S_{AlK}	3	−4.58	
Organics			
Concentration		30 mmol.m^{-3}	10 mmol.m^{-3}
pK_1	4	3.40	4.00
pK_2	4	4.00	5.00
pK_3	4	10.00	10.00
pK Al-org	5	0.00	−11.5
pK Al-org$^+$	5	5.00	0.00
Weathering			
Ca (meq m^{-2} yr^{-1})	6	10	332
Mg (meq m^{-2} yr^{-1})	6	10	100
Na (meq m^{-2} yr^{-1})	6	5	28
K (meq m^{-2} yr^{-1})	6	0.1	0
Base saturation (1850)			
E_{Ca}	5.54%		
E_{Mg}	4.06%		
E_{Na}	1.50%		
E_K	0.57%		

1. Parameters in the Langmuir sulphate adsorption isotherm:

$$\text{Adsorbed } SO_4 = \frac{E_{MX}[SO_4]}{C + [SO_4]},$$

where E_{MX} is the maximum sulphate adsorption capacity, and C is a coefficient representing the solution concentration at which the adsorbed sulphate is half its maximum value.

2. Parameter in the equation

$$K_{Al} = \frac{[Al]}{[H]^3}$$

3. Selectivity coefficients, (S) i.e.

$$S_{AlCa} = \frac{[Ca]^3 E_{Al}{}^2}{[Al]^2 E_{Ca}{}^3}$$

4. First, second and third dissociation constants for the hypothetical triprotic acid which is used to model organic concentrations.
5. Dissociation constants for the hypothetical Al-organic complex which is used to model organic aluminium concentrations.
6. Soil weathering rates refer to the area of the terrestrial catchment. Lake "weathering rates" estimate the direct input of groundwater to the area of the *lake*. Inputs to the whole system are obtained by multiplying the "soil" weathering rates by 0.87, and the "lake" weathering rates by 0.13.

Table IV Precipitation concentrations used for the base year (1985) and assumed for the forecast and hindcast years.

Species	*Precipitation concentration* (*μeq L*$^{-1}$)		
	1850	"1985"	2120
Ca^{2+}	5.2	12.0	8.0
Mg^{2+}	23.0	23.0	23.0
Na^{+}	118.0	118.0	118.0
K^{+}	2.6	4.0	4.0
NH_4^{+}	16.0	21.0	18.0
[1]SO_4^{2-}	21.0	51.0	27.0
Cl^{-}	138.0	138.0	138.0
NO_3^{-}	16.0	16.0	16.0
F^{-}	0.1	0.1	0.1
pH	4.97	4.56	4.98

[1] SO_4^{2-} deposition is increased by 40% to allow for dry deposition of SO_2.
"1985" Values see text.

consistent with the fishing records (Turnpenny, 1992) which show an approximately constant catch from 1935 to 1951 followed by decline and extinction by about 1975, but the two techniques agree on the late arrival of acidification. Figures 1–3 show one possible reason: the groundwater input at L. Fleet delays the onset of acid conditions until about 1950, when there is a steep rise in aluminium and fall in pH. The

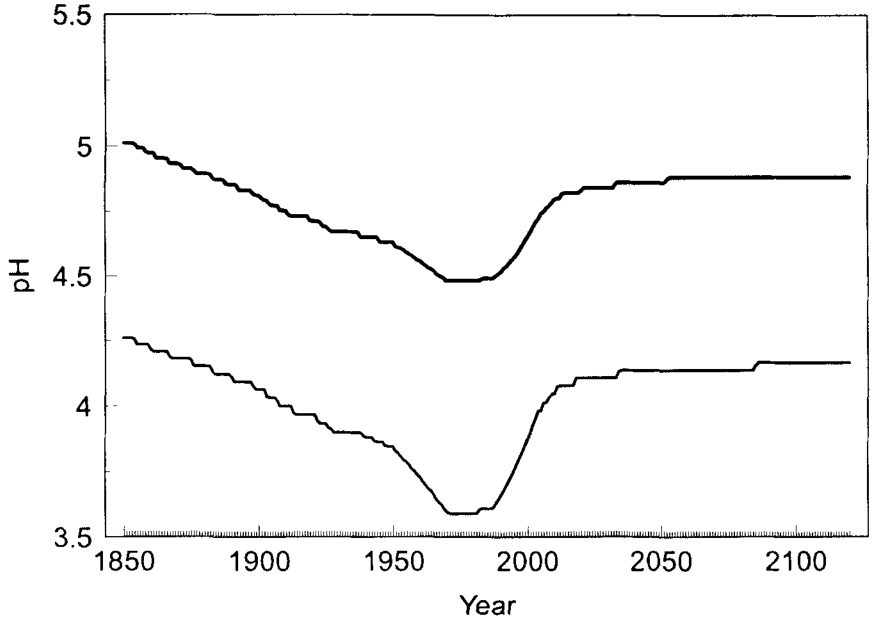

Figure 1 MAGIC simulations of the response of the pH of Loch Fleet to changes in S deposition due to (1) the pattern of SO_2 emissions in Europe between 1850 and 1990 and (2) currently agreed maximum SO_2 emissions in Europe between 1990 and 2120. Thick line: Loch Fleet as observed; thin line: Loch Fleet without groundwater input.

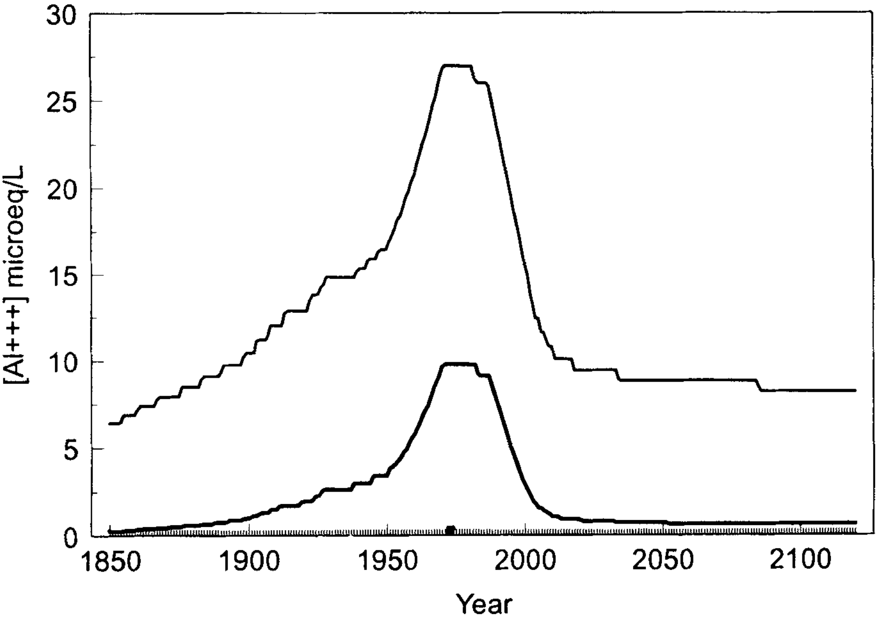

Figure 2 MAGIC simulations of the response of Al^{3+} in Loch Fleet to changes in S deposition as in Figure 1. Thick line: Loch Fleet as observed; thin line: Loch Fleet without groundwater input.

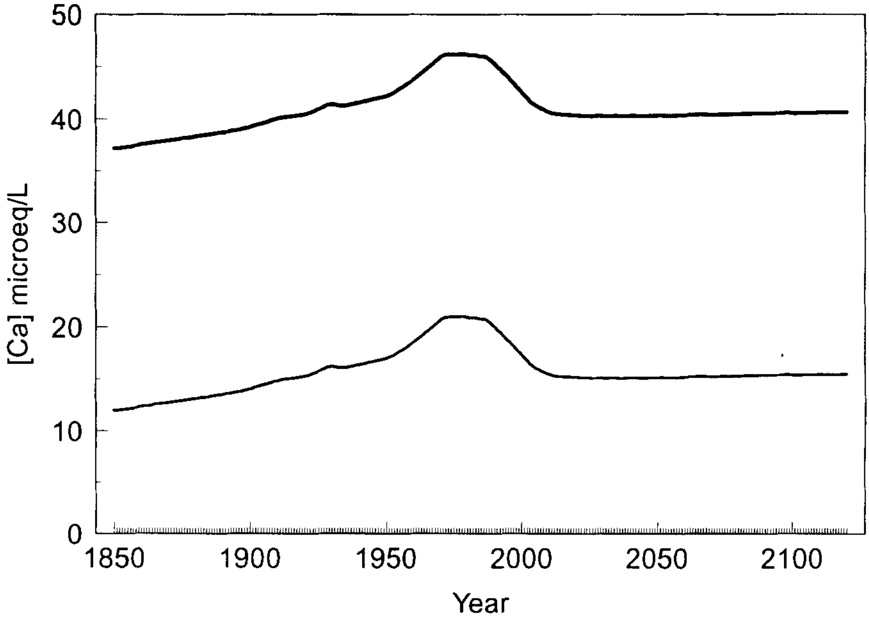

Figure 3 MAGIC simulations of the response of Ca^{2+} in Loch Fleet to changes in S deposition as in Figure 1. Thick line: Loch Fleet as observed; thin line: Loch Fleet without groundwater input.

ameliorating effect of groundwater can be seen clearly in Figures 1-3. The groundwater raises the pH and calcium, and lowers the aluminium concentrations. Without the groundwater input, the Loch would have been unsuitable for fish at the start of the simulation, in 1850. While there is considerable uncertainty about some of the parameters in the model, the general principle that the buffering mechanisms of the Loch were not overwhelmed until the increase in deposition in the 1950s is probably valid.

As a corollary of the slow acidification, recovery is relatively rapid: the model predicts that without liming the Loch would have returned, by the year 2005, to a pH and aluminium concentration which were apparently suitable for fish in the 1940s, though calcium concentrations would have been slightly lower. Underlying all these changes are changes in soil base saturation (Figure 4). This decreases only slowly with acidification, and recovers to its original value by the year 2026, which is fast compared to the recovery rates of the most acid-sensitive areas (Skeffington and Brown, 1992). The reasons for the rapid response of L. Fleet compared to some other areas are not clear: they may include the lack of sulphate desorption in the catchment (set to a very low level in the absence of any information); a soil with a very low density and thus a very low exchange capacity on an areal basis; and unrealistic selectivity coefficients (a parameter about which there is little information). Although the model predicts fairly rapid recovery for L. Fleet, low calcium concentrations would remain a problem. Howells and Dalziel (1994) suggested 100 $\mu eq\,l^{-1}$ as the target calcium concentration. The geochemical modelling above shows that calcium can never have been so high, and that liming will be necessary to maintain such a concentration. On the other hand, as

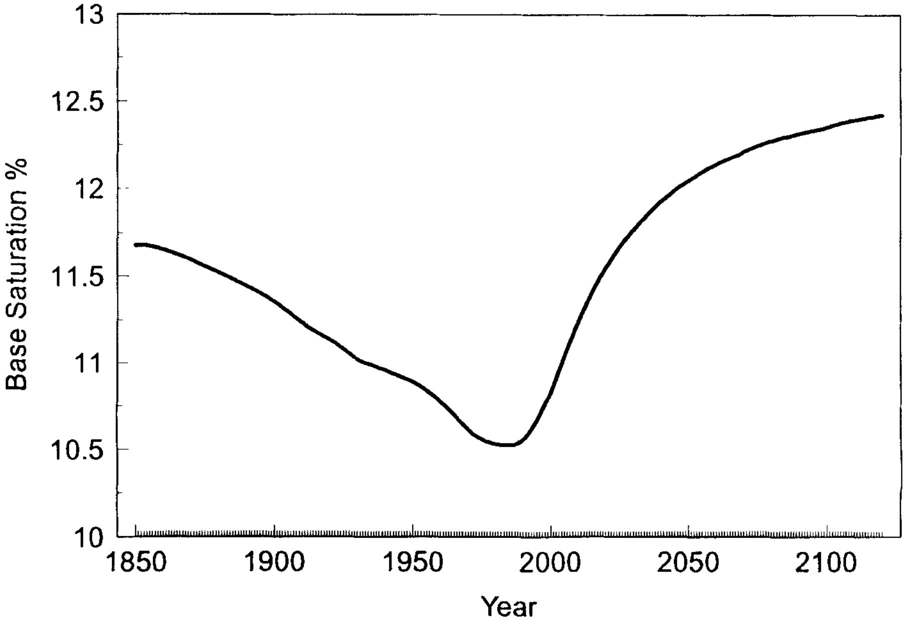

Figure 4 MAGIC simulations of the response of soil base saturation in the Loch Fleet catchment to changes in S deposition as in Figure 1. This is independent of groundwater input to the lake.

fish have apparently survived and reproduced at lower calcium concentrations in the past, this target perhaps provides a rather high margin of safety.

COMPARISON OF LIMING AND REDUCTION OF SULPHUR DEPOSITION

Liming and reduction of sulphur deposition should not be considered as alternatives in devising strategies for amelioration of surface water acidification but as complementary approaches. Nevertheless, it is worth comparing them, because they have different characteristics which should be taken into account in devising management strategies. Table V compares the techniques for restoring acid-sensitive waters. Some explanation and caveats are needed. It is possible, in principle, to restore any water quality parameter affected by acidification to its hypothetical pristine state by liming, but it is not possible to restore all water quality parameters simultaneously while sulphur deposition remains higher than its pristine level. This is simply a consequence of ion balance: the additional sulphate in surface water has to be balanced by a cation. Acid neutralising capacity (ANC) and pH can be restored to their pristine values by ensuring that the extra sulphate is balanced by a base cation (say Ca^{2+}). Alternatively, base cations can be restored to their pristine level, but this will mean a lower pH and ANC. The former would normally be the strategy of choice. Reducing sulphur deposition will lead initially to an aquatic system with lower pH and calcium than natural if the soil has been acidified and thus lost calcium. At Loch Fleet, MAGIC predicts that the soil will eventually recover. In situations with lower weathering, such as Southern Norway, recovery will be much slower, if it happens at all (Skeffington and Brown, 1992). In these cases, liming *and* deposition reduction would be needed to restore surface waters fully.

Immediate recovery due to liming attains the objective more quickly, and thus may be preferred over the slower recovery which deposition reduction would bring. Although the response of water chemistry is immediate, organisms respond more slowly. Weatherley (1988) reviewed the biological effects of liming, concluding that many years were needed to establish a stable ecosystem. Fish respond quickly because they are mobile and often re-stocked, but other components of aquatic ecosystems respond in a more variable way, as at Loch Fleet (Battarbee *et al.*, 1992). Dise *et al.*

Table V Comparison of liming and reduction of S deposition as techniques for mitigation of acidification. (Dr. D. J. A. Brown, pers. comm.).

Liming	*Desulphurization*
Restores acid waters and soils only	Corrects damage to other targets (e.g. materials, crops, visibility)
Produces aquatic system with higher pH and Ca than natural	Initially produces aquatic system with lower pH and Ca than natural
May damage terrestrial ecosystems	No damage to terrestrial ecosystems
Relatively cheap	Relatively expensive
Recovery immediate	Recovery slow
High probability of success (if done properly)	Success variable
Can be targeted towards specific catchments	Can be targeted only at large areas downwind (e.g. Southern Norway)

(1994) suggested that the shock effect of (lake) liming could lead to instability, whereas the slower recovery consequent on deposition reduction leads to a more orderly succession. Catchment liming should be less of a shock, and there was no evidence of shock effects on organisms during the Loch Fleet Project.

The "variable" success of deposition reduction arises from the difficulty of restoring the most sensitive catchments. Emission reduction alone may not restore these, or not restore them adequately (Skeffington and Brown, 1992). In contrast, liming can, in principle, restore any catchment, and treatments can be targeted towards the catchments that need it.

The policy which might flow from this discussion clearly depends on the weight given to the advantages of liming as compared to the disadvantages. No doubt a mixed strategy will usually be most appropriate, and Table V may help in its selection.

NATURE CONSERVATION OBJECTIONS TO LIMING

Ecological effects of catchment liming

Terrestrial liming inevitably has an effect on the vegetation and associated animal communities. Most severely affected are *Sphagnum* species and other bryophytes, which take in water and solutes directly through their leaves. Direct application of lime, or exposure to limed water, killed one species of *Sphagnum* at Loch Fleet (Clymo *et al.*, 1992; Bragg and Clymo, 1994) though other species survived the treatments or even thrived. Loss of *Sphagnum* cover led to a small increase in erosion in a limited areas (Bragg and Clymo, 1994), though erosion rates here were only about 10% of those measured on unlimed bare peat hags in the adjacent area. The effects of liming on terrestrial invertebrate populations in various studies have been complex and variable, with unpublished reports of work at Llyn Conwy in Wales indicating an overall reduction in abundance due to liming. Clymo *et al.*, (1992) could find no effects of liming on beetles and spiders at L. Fleet: later resurveys (Foster *et al.*, 1994) showed a significant increase in abundance of only one species of beetle on limed areas and none declined. Some exotic immigrants were found. Moving higher up the food chain, liming reduced the numbers of female pygmy shrews *Sorex minutus*, but not common shrews, *S. araneus*, at Loch Fleet (Shore and Mackenzie, 1993). There was no difference in nutritional condition between shrews captured on limed and unlimed plots, showing that these differences could not be attributed to lack of prey.

These effects, and some speculated, such as effects on birds, have led the statutory nature conservation bodies in the UK to warn against indiscriminate catchment liming (Woodin, 1989; Woodin and Skiba, 1990; Farmer, 1992). These concerns are entirely legitimate, but have extended to an almost blanket prohibition of liming unless there is no other way of meeting a nature conservation objective. Since this would remove a potentially useful technique from the landscape manager's toolbox, it is worth examining these objections more critically. If the aim of liming is to replace calcium leached from the soil by acid deposition, and to remove soil acidity generated by the same cause, it sounds less objectionable. The problems arise from the transient effects of applying free lime to catchment components. Of particular concern is the liming of hydrological source areas, as these are often flushed habitats which are the most productive and species-diverse components of moorland (Pearsall, 1950). Ironically, they owe their diversity partly to their enhanced supply of nutrients, especially bases, compared with the acidic open moorland. Alternatively, hydrological source areas can owe their conservation interest to specialised acidophilic vegetation which develops in wet areas, as at Loch Fleet. The concern about such areas has led to suggestions that catchment liming, if practised at all, should avoid hydrological source areas (e.g. Rimes, 1992). Unfortunately, as noted above, this policy would lead to liming having less effect on the target water body.

Some solutions

Some of the concern about liming is clearly motivated by a desire to avoid liming being used as a substitute for emission reduction. This is not happening. Increasingly stringent emission reductions are being agreed in international negotiations. Liming is being used (1) as a holding operation to maintain species diversity while emissions reduce and (2) as a repair mechanism for damaged catchments. Given that some catchments will not recover under any conceivable degree of emission reduction (e.g. Skeffington, 1994), additional action is essential. In view of that, a range of possibilities should be considered as practical landscape management options in which the benefits to water quality are balanced against any deleterious effects in the terrestrial environment. These may include:

Identifying source areas of lesser conservation interest. Not all hydrological source areas are base-rich flushes. The variable source area concept of runoff generation (see Ward, 1975) implies that there is a whole hierarchy of source areas which contribute to streamflow during increasingly wet conditions. It is these areas which contribute the acid episodes during spates and thus should be good liming targets. If these can be identified then the base-rich areas could be spared lime. Incidentally, the variable source area concept implies that lime added to the non-source areas may eventually have an effect on water quality, but possibly not for a long time as water flowing through such areas may take several years to reach to the stream.

Liming some source areas but not others. This is a variant of the above in which only some source areas are targeted. Clearly it is better, other things being equal, to choose areas of lesser conservation interest. Shore and Mackenzie (1993) suggested patchy liming as a strategy for limiting effects on small mammals.

Use liming materials other than calcium carbonate. Sanger *et al.* (1993) proposed the use of calcium phosphate for liming peat, creating less abrupt pH changes. This would however be more expensive and raise questions of eutrophication due to phosphorus input.

Accept some terrestrial damage as the price of repairing the aquatic system. Put at its starkest, this argument states that the preference of the public would probably be to restore fisheries even if this meant the loss of some *Sphagnum* and asssociated species. In practice, the situation is not likely to be as bad as this . *Sphagnum* species and animal populations may be affected temporarily but the evidence so far from Loch Fleet shows that they are recovering or have recovered. Further long-term data are needed: biological and chemical monitoring at Loch Fleet and other limed sites must be continued to answer these questions.

CONCLUSION

Liming in relation to acidification has been characterized as "treating the symptoms rather than the disease." This is not an accurate analogy: liming is more akin to treating the disease rather than the cause. But the cause is being treated in parallel, and no medical practitioner would deny the victim of accidental poisoning the drugs his body needs to help it recover on the grounds that he is no longer taking the poison. Ten years of work at Loch Fleet have demonstrated that catchment liming – used with care, forethought, skill and discrimination – is an invaluable tool for restoration of acidified catchments and their drainage waters.

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