Working Papers

No. 21

PALAEOECOLOGICAL EVALUATION OF THE RECENT ACIDIFICATION OF WELSH LAKES

5. The Significance of Land use and Land management change

S.T. Patrick

Editors: A.C. Stevenson & S.T. Patrick

Palaeoecology Research Unit,
Department of Geography,
University College London,
26 Bedford Way,
London WC1H OAP.

Report to the DOE under Contract PECD 7/7/139

The significance of land use and land management change in the recent acidification of Welsh lakes.

S.T. PATRICK

Palaeoecology Research Unit, Department of Geography,
University College London, 26 Bedford Way, London WC1H 0AP.

Contents

Tables

Figures

1.0 Introduction

The acidification of surface waters is frequently ascribed to the impact of acidic precipitation in areas of sensitive (base poor) geology (eg. Overein et al. 1981, La Zerte and Dillon 1984, Battarbee et al. 1985). However, other explanations have been forwarded that centre upon changes in land use and management within lake catchments.

The Palaeoecology research Unit of the Geography Department, University College London, is investigating the history and causes of acidification in ten lakes in mid and north Wales (Fig. 1). The major thrust of this project involves the utilisation of palaeoenvironmental techniques to reconstruct the historical water quality (particularly pH) of these lakes and the history of atmospheric deposition of metals and combustion products as recorded in the lake sediments (cf. Anderson et al. 1986, Jones et al. 1986, Fritz et al. 1987).

The work described in this paper represents a separate theme within the project: the use of documentary sources to examine the significance of land use/management changes in the lake catchments.

The timescale covered by this investigation is limited by the availability of documentary material and broadly encompasses the last 200 years. Palaeoenvironmental reconstruction of lake water pH in Galloway, south-west Scotland (eg. Battarbee and Flower 1985, Battarbee et al. 1985) and preliminary results from Wales (eg. Fritz et al. 1986), suggests that such a timescale adequately covers the period during which recent acidification has occurred.

The potential acidification mechanisms discussed in this paper are frequently described separately or together as 'land use' hypotheses. This paper deals with 'land use' and 'land management' change and it is important that these terms be clearly defined. 'Land use' is the broad use to which the land is put and categories (following Parry and Sinclair 1985) may include rough grazing, improved farmland, or forest. 'Land management' includes practices which, if of low intensity, may remain independent of land use, but if intensively practiced may represent a mechanism responsible for land use change (eg. enclosure, draining, burning, or changing stocking densities and regimes).

2.0 Study sites

The location of the ten study sites in Wales is indicated in Figure 1. They lie between 280-530 m on base poor 'sensitive' geologies (UKAWRG 1985). Lake and catchment specifications are given in Table 1. All the lakes lie in moorland areas. Eight of the catchments comprise open moorland utilised for rough grazing, while two (Llynnaedd Berwyn and Cwm Mynach) have been afforested. The lake waters are acid, pH ranging from 3.5 to 6.1 (Table 1). Fishery decline is well documented in Llynnaedd Berwyn, Conwy, Gamallt and Hir. The fishery status of the other lakes is less certain.

Sediment cores were taken from the lakes in spring and summer of 1985. Palaeoenvironmental analysis of these cores is complete for Llynnaedd

Hir (Fritz et al. 1986), Berwyn (Kreiser et al. 1986), Gynon (Sevenson et al. 1987a) and Cwm Mynach (Kreiser et al. 1987) and is at an advanced stage for Llynnaedd Dulyn, Eiddew Bach, Llagi and Y Bi. Sediment material from Llynnaedd Conwy and Gamallt proved unsuitable and these lakes will require re-coring.

Detailed descriptions of the lakes and their catchments and their reconstructed water quality and atmospheric deposition histories may be found in the following Research Papers of the Palaeoecology Research Unit. Llynnaedd Conwy and Gamallt (Patrick and Stevenson 1986), Llyn Hir (Fritz et al. 1986, Llyn Berwyn (Kreiser et al. 1986), Llyn Gynon (Stevenson et al. 1987a), Llyn Eiddew Bach (Fritz et al. 1987), Llyn Y Bi (Patrick et al. 1987a), Llyn Dulyn (Stevenson et al. 1987b), Llyn Cwm Mynach (Kreiser et al. 1987), Llyn Llagi (Patrick et al. 1987b).

Results (Llynnaedd Berwyn, Hir, Gynon and Cwm Mynach) and preliminary analyses (Llynnaedd Dulyn, Eiddew Bach, LLagi and Y Bi) from sediment cores, suggest that the acidification of these lakes is a 'recent' phenomenon of the past ca.100 years.

Table 1 Lake and catchment characteristics

LAKE	ALTITUDE (m)	LAKE AREA (ha)	CATCHMENT AREA (EXCLUDING LAKE) (ha)	LAKE VOLUME (m^3)	pH 1984-85 (range)	pH 1986[1]	MEAN DEPTH (m)
Berwyn	438	13.04	83.70	417,655	4.1-4.5	5.9[2]	3.25
Conwy	450	40.10	95.90	3,073,846	4.85[3]		7.66
Cwm Mynach	285	5.89	131.54	50,141	5.0-6.4	5.3	2.18
Dulyn	526	1.98	51.67	37,787	4.3-5.4	5.0	1.90
Eiddew Bach	380	1.38	10.94	37,990	4.3-5.4	4.9	7.76
Gamallt	465	13.00	55.47	41,694[4]	4.35[3]		1.50[4]
Gynon	430	25.26	286.16	533,835		5.3	2.18
Hir	435	4.89	17.93	136,367	4.5-5.1	6.1[2]	2.79
Llagi	375	5.68	162.16	331,734	3.5-5.2	5.2	5.80
Y Bi	445	2.71	45.01	42,638	4.3-5.3	4.9	1.58

[1] April 1986
[2] Post liming of lake
[3] 1983-84 mean
[4] Llyn Gamallt Bach only

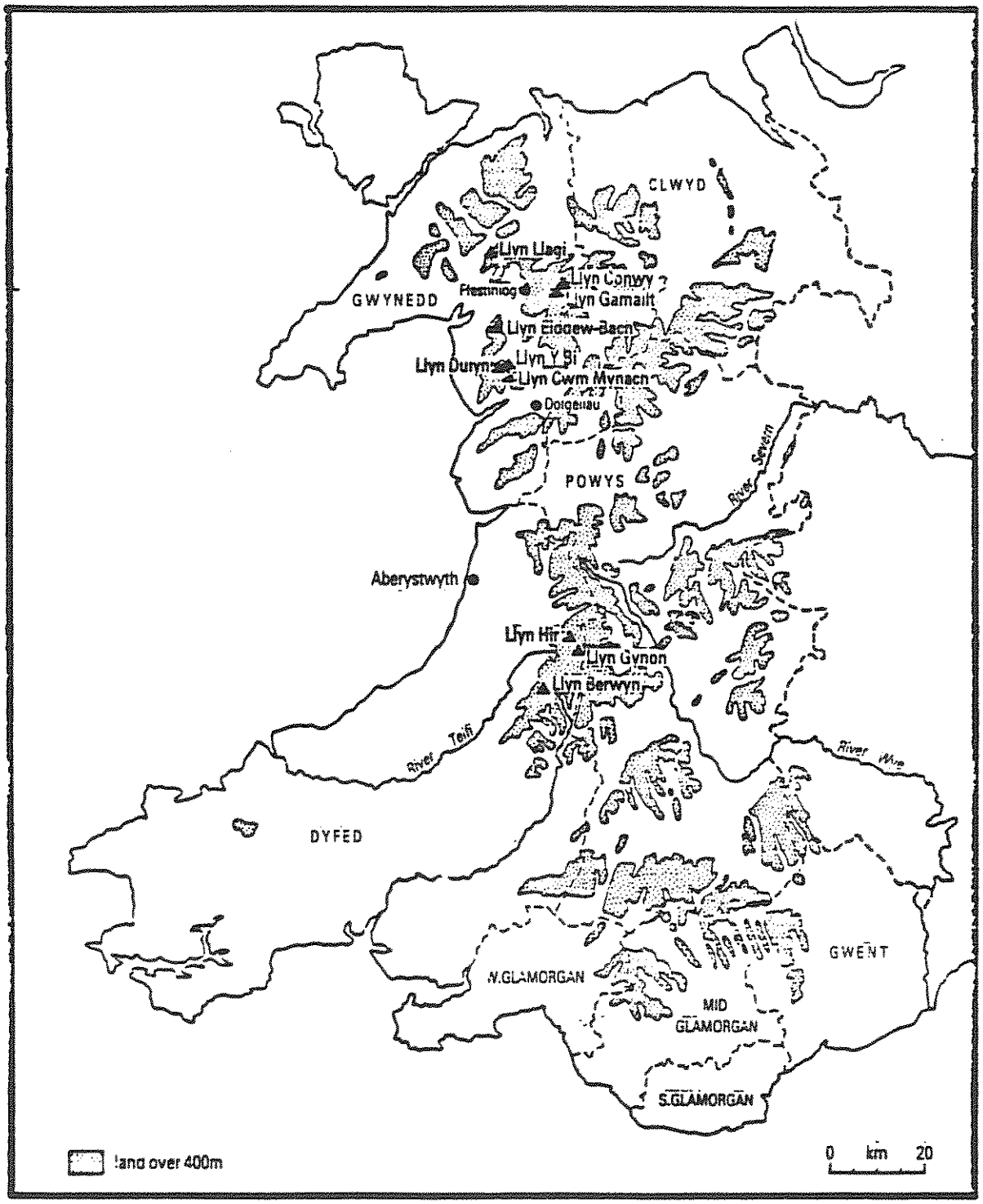


Fig. 1 Location of Study Lakes

3.0 'Land use hypotheses'

3.1 Regeneration of 'acidic' species

Rosenqvist (1977, 1978, 1980, 1981, et al. 1980) considered that ion exchange reactions in raw humus layers and the uptake of cations by plant growth are the most important factors in determining the acidity of runoff waters. The acidification of lakes in southern Norway was attributed to the increased formation of acid humus resulting from the enhanced biomass of acidic heathland (particularly Calluna) and forest species, consequent upon a decline in the intensity of pastoral agriculture in the region. Documentary evidence was produced to illustrate the decline in agricultural activity that followed an era in the eighteenth and nineteenth centuries when increased farming activity had caused heathland and forest to be replaced with grassy vegetation. Particular importance was attributed to the demise of burning which oxidised large parts of the humus cover (Rosenqvist 1981). Streams flowing in areas of burnt forest were shown to possess higher pH and conductivity concentrations than streams flowing in unburnt areas.

Rosenqvist's hypothesis has found limited support as an explanation of contemporary acidification (eg. Krug and Frink 1983), although Pennington (1984) invoked similar mechanisms to explain the long-term acidification of upland soils in Cumbria.

Rosenqvist's hypothesis is open to criticism on several accounts.

Information relating to agricultural decline (eg. farm units, animal numbers) was drawn from broad areas (eg. counties) (Rosenqvist 1978) and did not relate to individual catchments. Although regional trends in land utilisation provide informative background, the nature of lake drainage systems requires that information should be catchment-specific or as close to it as possible, if any influence on water quality is to be surmised. It is a fundamental objective of the work described in this paper to present information at or near the catchment level.

Thorough historical investigation in the areas of southern Norway affected by lake acidification has revealed that acidification and fish decline cannot be related to changes in land utilisation (Walloe and Overrein 1977). Although changes have occurred in pastoral regimes since the nineteenth century, these have often involved an increase rather than a decrease in animal numbers (Drablos and Sevaldrud 1980, Drablos et al. 1980, Timberlid 1980a,b). Similarly Battarbee and Flower (1985) and Battarbee et al. (1985) utilised pollen analysis and information on sheep numbers to refute the argument that a demise in upland farming and an associated development of heathland vegetation was responsible for lake acidification in Galloway in the last 200 years.

Some of the mechanisms proposed by Rosenqvist (1977, 1978, 1980, 1981 et al. 1980) may not be the most significant in promoting acidification. The acidifying effects of coniferous forest on soils is widely accepted (eg. Nihlgard 1971, Grieve 1978, Messenger 1980). However, the relative significance of processes such as humus

accumulation and/or the enhanced capture and transfer of acid precipitation in relation to surface water acidification, is uncertain. Similar uncertainty surrounds the acidifying effects of heathland species (Milner and Jones 1985). The work of Grubb et al. (1969) and Grubb and Suter (1971) on the acidifying effects of Calluna, related to chalk land not acid soils or peats. Controlled, low intensity burning is generally considered to maintain or raise the pH of surface acid soils (eg. Allen 1964, DAFS 1977). However, uncontrolled, high intensity burns may result in the destruction of surface vegetation and initiate erosion, and enhanced surface runoff (eg. Gimmingham 1971, Tallis 1973, Kinako and Gimmingham 1980). The significance of this phenomenon on acid soils or peats in relation to the acidification of surface waters is uncertain.

3.2 Afforestation

Acidification of surface waters has been recognised in several areas where coniferous forest has been planted (as opposed to regenerated) on sensitive geologies.

Harriman and Morrison (1980, 1982) found that in central Scotland afforested streams were always more acid and produced greater concentrations of H^+, Al^{3+}, SO_4^{2-}, Na^+ and Cl^- than adjacent unafforested moorland streams. Similar observations have been reported from central Wales (Stoner et al. 1984, Stoner and Gee 1985) and Galloway (Burns et al. 1984). Palaeoecological studies of lakes with afforested catchments are also beginning to discriminate a clear forest effect (Anderson et al. 1986, Kreiser et al. 1986).

Although the impact of afforestation on surface water acidity has been demonstrated, the processes involved are poorly understood (Harriman and Wells 1984, Hornung 1985). Potential mechanisms include humus accumulation, enhanced capture and transmission of atmospheric acids, evapotranspiration (the 'concentration' effect) and the enhanced uptake of cations (eg. Mayer and Ulrich 1974, Rosenqvist 1980, 1981, Nilsson et al. 1982, Miller and Miller 1983, Binns 1984, Miller 1985). Other potential contributory factors associated with afforestation include the preparation of ground by drainage and ploughing and the consequent effect on runoff hydrology (eg. Newson 1984, Hornung and Newson 1986), net base cation removal through clearfelling (eg. Rosenqvist 1980, Nilsson et al. 1982) and the decreased incidence of fire and associated ash deposition in managed as opposed to 'natural' forests (eg. Rosenqvist 1981, Everett 1983).

3.3 Drainage

Peat and organic soils dominate the catchments of the Welsh study lakes. The seasonal reduction of sulphate followed by reoxidation during a drawdown in the water table in dry weather, constitutes a natural acidification process in peatlands (Bache 1984, Gorham et al. 1984, Hornung 1984). Artificial drainage of such land for agricultural improvement or forestry, may exacerbate this process and produce enhanced quantities of sulphate which is flushed out of the soil by rainfall (Newson 1984, Stoner et al. 1984, Hornung and Newson 1986).

A similar phenomenon may be significant in lakes subject to seasonal fluctuations in water level, notably those utilised for water supply, as enhanced redox reactions occur in peat shorelines that are alternatively exposed then submerged (Milner and Jones 1985).

3.4 Liming

Recognising that extensive areas of grassland in the United Kingdom were formerly limed for agricultural improvement, Ormerod and Edwards (1985) suggested that the decline of this practice following changes in, and the eventual withdrawal (1977) of the lime subsidy, may have resulted in increased surface water acidity as soils were less adequately buffered. A similar mechanism was postulated by Crawshaw (1984) in relation to the Esk and Duddon catchments of west Cumbria.

It is unlikely that such a mechanism would be applicable to the Welsh study lakes. Newbould (1985) has shown that great quantities of lime are required to raise the pH of indigenous hill grassland. Consequently liming was unlikely to be normal practice on poorly buffered upland and forested soils (Rowell and Wild 1985).

The finest spatial resolution for which Ormerod and Edwards (1985) presented data to illustrate the decline in lime use in Wales was for counties. Such statistics can have little relevance to upland lake catchments, particularly if most lime was utilised on lower, more improvable land.

3.5 Mining

Increased acidity of surface waters may result from contamination with waste residues associated with mineral exploitation (eg. Koryak et al. 1972, Clarke 1974, Brugum and Lusk 1986). Drainage from mines, pits and waste tips and effluent from ore concentration processes are the major sources of such contamination. The rivers Rheidol and Ystwyth in mid-Wales, experienced heavy metal pollution from such sources in the nineteenth century (Jones 1958, Jones and Howells 1975).

4.0 Changing land use and management

4.1 The regional background and potential impact

The traditional pastoral economy of the hills of mid and north Wales was characterised by the transhumance system of hendre and hafod, which in some areas persisted into the nineteenth century. In summer, cattle and sheep were driven from the lower grazing areas (including enclosed rough 'fridd' land) surrounding the winter settlement (hendre), to the higher mountain land above the summer settlement (hafod) (Bowen 1950, Davies 1973).

Although rough grazing land was dominated by cattle and sheep, goats and ponies also ranged the hills in significant numbers (eg. Evans 1812, Pennant 1812, Condry 1981). There is considerable debate as to

the relative number of cattle:sheep on the hills up to the mid-nineteenth century (eg. Roberts 1959, Emery 1965, Hughes et al. 1973). In areas which had been Cistercian grange land the dominance of sheep may have dated to the twelth century (eg. Roberts 1959, Hughes et al. 1973). Emery (1965) considered that sheep were probably the dominant hill farm animal in Snowdonia by the sixteenth century.

By the early nineteenth century the hafod - hendre system had generally disappeared and the hafod had evolved into a separate upland farm. Sheep now dominated hill grazing areas (Davies 1935, Davies 1973, Colyer 1983).

Annual agricultural statistics reveal that sheep numbers increased rapidly between 1867-1909, since when they have fluctuated in an upward direction (eg. Williams 1932, Ashby and Evans 1944).

Associated with the increase in sheep numbers from the mid-nineteenth century was a change in the type of sheep and the grazing regime.

Large wether sheep, utilised for mutton and wool had dominated flocks until the mid-nineteenth century. However, as tastes changed towards smaller and more succulent joints of meat, production of sheep for lamb became increasingly prevalent. Consequently the proportion of wethers fell rapidly with a concomitant rise in ewes and lambs, until by the early twentieth century few wethers remained on Welsh hillsides (Harry 1939, Griffith 1945, Roberts 1959).

Many mountain farms that evolved from hafodydd had limited access to winter grazing facilities. Many of the hardy wethers therefore remained on the hill through the winter, while ewes and lambs were sold or driven to winter pastures rented from lowland farms (Kay 1794, Rowlandson 1846, Davies 1935, Colyer 1983). As hill farming became less profitable through the nineteenth and twentieth centuries and population left the land, many high hill farms were subsumed by farms on adjacent lower land. The increase in wintering facilities provided by such mergers, together with the requirement of the increasingly dominant ewes and lambs to leave the hill in winter, resulted in a marked decline and in some areas a virtual cessation, of winter grazing on the high hills through the twentieth century (Williams 1932, Hughes et al. 1973, Hughes et al. 1975).

The characteristics of upland vegetation are controlled by a combination of biotic/land management, climatic and edaphic factors. A change in one or more of these factors may result in a change in vegetation type. The change (upgrading) from heath to grass species as a result of increased biotic pressure and/or management inputs is well documented, as is the reversion to heathland species when change is in the opposite direction (eg. Boulet 1939, Harper 1971, King 1977, Rawes 1983, Grant et al. 1985). However, reversion to heath tends to be a more gradual process (Ball et al. 1982, Mather 1983).

The potential significance of general trends in animal numbers and ratios and grazing regimes descibed above, on the vegetational composition of rough grazing land, is uncertain. In terms of biotic influence cattle and sheep generally complement each other. Cattle, less selective in their grazing, remove the coarser, less palatable

species unfavoured by sheep (eg. Boulet 1939, Hunter 1958, Wannop 1958, King 1977). The disappearance of cattle and to a lesser extent, large wether sheep, from the hills opened up the potential for the spread of heath species such as Calluna, Pteridium, Ulex, and Vaccinium (Davies 1936). However, it is probable that the decline in diversity of grazing animals was more than compensated for by increased numbers of ewes and lambs. Although the intensity of grazing on the higher land in winter has undoubtedly declined, sheep are maintained on the hills during the important period of plant growth.

Subsidiary changes have occurred in aspects of the management of hill flocks during the past two centuries.

The agricultural 'boom' during the Napoleonic wars saw an era of enclosure of common and waste land in Wales (Bowen 1914, Dodd 1926,). Enclosure of moorland at the altitude characteristic of the Welsh study lakes generally represented a land grab by landlords rather than a serious attempt at improvement (Morgan 1959, Thomas 1965). However, by fencing out neighboring flocks it is possible that enclosed rough grazing land was better managed than the unenclosed commons and sheepwalks which had a history of over-stocking (Kay 1794, Royal Commission 1896, Dodd 1968, Colyer 1983).

In more recent years reduced manpower and improved lowland facilities have diminished shepherding operations such as mountain hay making and sheep washing in upland lakes and streams. Increased constraints on management practices such as burning and draining have resulted from the designation of NNRs and SSSIs and National Trust influence. Burning in particular has often been curtailed by the proximity of coniferous afforestation.

At a national and regional level the marked increase of afforested land (generally at the expense of moorland rough grazing) has been a feature of the post 1945 period (Mather 1978, Parry et al 1982, Parry and Sinclair 1985). Two of the study lakes (Llynnaedd Berwyn and Cwm Mynach) have afforested catchments. Although afforestation removes the grazing influence from specific areas, a complimentary effect may be to increase stocking densities on remaining unafforested moorland.

The general trends outlined above provide no evidence for an acidification mechanism that can have operated with ubiquity at all the Welsh study sites. However, a reliable assessment requires the documentation of land use/management histories for specific catchments. The sources utilised in such documentation are outlined below.

5.0 Sources

5.1 Estate plans and records

The earliest records utilised in this study comprised estate plans and papers dating from the late eighteenth century. Most study sites lie on land that was formerly held by large estates (Table 2). Without exception study sites were located at the periphery of estates. Consequently map/plan coverage is sparse and occasionally inaccurate. Accounts and papers rarely refer to rough land away from the demesne and tenant farms. In part this reflects the low intensity of land use and lack of management that occurred in those areas.

Table 2 Study catchments: parishes and estates

LAKE	PARISH	ESTATE
Berwyn	Caron-is-Clawdd	
	Llanddewi Brefi	
Conwy	Penmachno	Penrhyn
Cwm Mynach	Llanaber	
	Llanelltyd	
Dulyn	Llanddwywe-is-y-graig	Corsygedol
Eiddew Bach	Llanddecwyn	Maes y Neuadd
Gamallt	Ffestiniog	Penrhyn
Gynon	Caron-uwch-Clawdd	Crosswood
		Nanteos
Hir	Caron-uwch-Clawdd	Crosswood
	Upper Gwnnws	Nanteos
Llagi	Beddgelert	
Y Bi	Llanddwywe-uwch-y-Graig	Dolmelynllyn
	Llanelltyd	

5.2 Tithe survey documents

The large scale parish maps and associated schedules compiled during the process of tithe commutation in the 1830s-1850s, should provide information on the state of cultivation of land within study catchments (Kain and Prince 1985). In practice the availability, specificity and accuracy of this information varies between parishes as does the terminology utilised to describe land use (Thomas 1965, Kain and Prince 1985). Additional information on farming practice in parishes is occasionally recorded in the associated tithe files.

5.3 Ordnance Survey maps

Surveyors drawings at a scale of 1:126,720 drawn between 1819-1921 do not provide the detailed and comprehensive picture of the landscape, at least in the study catchments, that Thomas (1963) has claimed. The first edition 1:10,560 maps of 1888-1891 are the first series to provide broad land use information for the study areas. Owing to the

remote and mountainous nature of the study areas they were generally not surveyed at 1:2,500.

5.4 Land utilisation and vegetation surveys

Manuscript survey maps of the First Land Utilisation Survey of the 1930s were accessed at the London School of Economics archive. Despite the large scale of these maps (1:10,560) they provide only the most general classification of land use in remote areas. Published county reports of the survey for Merionethshire (Holliday 1940), Cardiganshire (Howell 1946a) and north Wales (Howell 1946b) provide local, but no catchment specific information.

The manuscript survey maps of the Second Land Utilisation Survey were accessed at the Geography Department, King's College London. These maps, at a scale of 1:10,560, were compiled ca.1970 and map vegetation by species at a level of spatial resolution which permits catchment vegetation maps to be compiled.

The survey of Welsh grasslands (Davies 1936) was at too small a scale to permit catchment-specific observations. Stapledon's 1913 ecological map of north Cardiganshire at 1:10,560 (Davies 1936) does not include catchment areas of this study.

5.5 Air photographs

The Air Photograph department of the Welsh Office, Cardiff hold two series of aerial surveys flown by the RAF (1946-1948 and 1962) at a scale of approximately 1:10,000.

Burning patterns, enclosures and extant or relict cultivation and drainage features may be discerned from this source. In association with the 1970 land utilisation maps and contemporary field surveys these photographs permit changes in vegetation to be plotted within catchments between ca.1946-1986.

5.6 Corroborative sources

Two surveys, one of northern Snowdonia 1887-1975 (Parry *et al.* 1982), the other of the mid-Wales uplands 1948-1983 (Parry and Sinclair 1985), have utilised sources corresponding to many employed in this study, to map land use change in areas which include several of the study catchments (Llynnaedd Conwy, Gamallt, Llagi - Parry *et al.* 1982, Llynnaedd Berwyn, Gynon, Hir - Parry and Sinclair 1985). The field data from these surveys was recorded at a scale which allows changes within catchments to be identified.

5.7 Annual parish agricultural returns

As the historical record often provides no direct evidence of vegetation changes that result from variations in livestock numbers and management practices, change must be inferred from a knowledge of fluctuations in livestock numbers (Ball et al. 1982). In this respect a potentially important source was the annual agricultural census.

The finest spatial resolution at which information from the census is available is the parish (Table 2). Instigated in 1867, the census provides data on animal numbers and grazing areas. For the purpose of this study returns held at the PRO (Kew) were analysed at quinquennial intervals. The utilisation and interpretation of parish returns is subject to several constraints.

Data relate to land holdings that lie primarily within one parish. Aggregations of holdings may not therefore coincide precisely with the actual parish boundary. This feature may alter if farms vary their boundaries or change hands (Parry and Sinclair 1985). Many Welsh parishes are relatively large and may encompass areas of hill and lower land. Information on sheep numbers may not therefore relate entirely to upland grazing areas. However, as the returns are made in June it is probable that the great majority of sheep would be on the hills and not on winter pastures (Williams 1932). Information relates to holdings in single occupancy and excludes common land. Consequently the area of rough grazing within a parish is underestimated (Parry and Sinclair 1985). The definition of 'rough grazing' may in itself be a source of error (Davies 1936).

The categories for which data are presented in the returns have not remained consistent since 1867. However, the data can be recorded with a minimum of incompatability so that between 1867-1890 statistics can be collated concerning 'total sheep', 'sheep under one year' and 'sheep over one year', and between 1895-1983 - 'total sheep', 'breeding ewes', 'sheep under one year', 'sheep over one year' and 'area of rough grazing'.

Although the parish returns represent the statistical source that is potentially most applicable to specific catchment areas, it was apparent that in some areas the trends suggested by the returns were not mirrored in individual catchments. Parish data should therefore be viewed as indicative of local trends, at a spatial level below the regional picture discussed above, but above that of individual catchments.

5.8 Miscellaneous sources

Literary evidence was drawn from two major sources. The Board of Agriculture reports of Kay (1794), Lloyd and Turnor (1794) and Davies (1813, 1815) and the 'topographies' of independent travellers (see Thomas 1963). Both provided information which relates primarily to regional and local agricultural trends.

Forestry Commission records, particularly planting maps, were utilised to determine the plantation and management histories of the two

afforested catchments - Llynnaedd Berwyn and Cwm Mynach.

Some lakes include enclosed land within their catchments. However, in no instance were the relevant enclosure documents and maps extant (Bowen 1914, Morgan 1959).

5.9 Personal communications

The majority of sources described above either provided information relating to land use rather than land management, or as with the parish returns, comprised details on land management at a level above that of the individual catchment.

In order to obtain catchment-specific details of land management change, farmers, anglers and other authorities with an interest in, or specific knowledge of individual catchments, were interviewed. Caution must be exercised in the interpretation of such personally communicated information. In general, where two or more independent accounts were in broad accord, their content was accepted. In many cases such sources were the major component of evidence for land management changes.

6.0 Land use and management changes in specific catchments

A detailed account of land use and management change in individual catchments may be found in the series of papers specified in Section 2.0. An abbreviated account of catchment changes is presented below (Section 6.1) together with a summary by land use and individual management practice (Sections 6.2, 6.3).

6.1 Individual lake catchments

6.1.1 Llyn Berwyn

With the exception of small areas of molinia dominated rough grazing to the north-east and south, the catchment is planted with Sitca spruce (*Picea sitchensis*), Lodgepole pine (*Pinus contorta*) and Japanese larch (*Larix kaempferi*) (Fig. 2).

The catchment was afforested between 1960-1963. Before that date documentary sources indicate that the catchment comprised rough grazing land of the 'moorland core'. There is no evidence from air photographs or on the ground (of relict enclosures, drainage or cultivation features) to suggest that any improvement was ever attempted.

At an altitude of over 400 m and comprising wet and exposed land, it is unlikely that the Llyn Berwyn catchment ever supported a significant livestock population. Although a few cattle were grazed on the hills in the locality in summer up to ca.1930, the grazing history of the catchment was dominated by sheep.

Some areas of *Molinia* were cut for hay which until recently represented the only winter fodder in the region. Other areas were frequently burnt to provide an early bite for the sheep. Burning and hay making ceased

with afforestation.

Parish returns for Caron-is-Clawdd (Fig. 12) indicate that there was a gradual rise in sheep numbers in the area up to the plantation of the catchment in 1960. From that period sheep numbers rose rapidly but the potential significance of that trend is limited to a small proportion of the catchment.

The forest planted in the early 1960s is still maturing and no deforestation has taken place. Planting was conducted down to the lake edge. Prior to planting the site was ploughed/drained and fertilised.

By the early 1970s the shallow drains and furrows that had provided rooting and drainage for the young trees were proving inadequate for the needs of maturing trees. Consequently ca.1974 deep drains, approximately 20 m apart were driven through the entire forested area.

6.1.2 Llyn Conwy

The catchment of Llyn Conwy comprises unimproved, unenclosed moorland utilised for rough grazing and game shooting. The blanket peat of the catchment is dominated by mature Calluna (Fig. 3).

The Penrhyn Estate managed most of the Llyn Conwy catchment through much of the nineteenth and early twentieth centuries. The estate was at the forefront of agricultural improvement in Wales, but there is no evidence to suggest that the remote land around Llyn Conwy was considered suitable for improvement.

While the Penrhyn Estate maintained an interest in the Llyn Conwy catchment, particularly from the mid-nineteenth - mid-twentieth centuries, sheep grazing was secondary to the exploitation of game.

For a period from the mid-1950s - mid-1960s when the active control of the Penrhyn Estate had diminished and land in the Llyn Conwy catchment was being transferred to the National Trust in lieu of death duties, continued burning of Calluna for grouse encouraged tenant farmers to increase sheep numbers on the catchment. However, although in 1968 the Trust decided to encourage sheep at the expense of grouse on the catchment, an associated 'ban' on burning proved a disincentive to increase sheep numbers.

The Llyn Conwy catchment was part of an area highly prized as a game moor by the Ystbytty (Penrhyn) Estate and actively managed (primarily for grouse) by gamekeepers of the estate (and later the 'Ystbytty Shoot') until ca.1970. The peat of the eastern slopes of the catchment was drained during the 1920s in an attempt to provide healthier Calluna stands for grouse. The drains were periodically serviced until ca.1970. The catchment was regularly burnt in strips or small patches to yield Calluna stands of varying maturity providing both nutrition and shelter for grouse. Air photographs taken in 1946 show a mosaic of burnt vegetation throughout the catchment. Burning effectively ceased in the catchment ca.1970 as a result of National Trust policy, the designation of the area as part of the Migneint SSSI (1971) and the proximity of maturing forest some 1.5 km to the north-east and 1 km to the

north-west.

Llyn Conwy was 'reservoired' in the late 1950s for potable water supply, the outflow being controlled by a weir structure. The lake is thus subject to periodic fluctuations in water level.

6.1.3 Llyn Cwm Mynach

Some 58% of the catchment is afforested with Japanese larch (Larix leptolepis), Lodgepole pine (Pinus contorta) and Sitca spruce (Picea sitchensis) (Fig. 4). Afforestation took place between ca.1967-1977. The forest is still maturing. Apart from some thinning there has been no deforestation. The non-afforested part of the catchment consists of unimproved, unenclosed moorland, utilised for rough grazing. There is no evidence to indicate that any attempt was ever made to improve land within the catchment.

The Diphwys manganese mines extended into the catchment high on the south-western flank. Mining operations were small scale and confined to the nineteenth century. A small slate quarry was opened within the Llyn Cwm Mynach catchment in the late nineteenth century, but was unprofitable and operated for only a short period.

Although the relics of mining and quarrying are still apparent in the catchment, the practical effect of these operations on surface waters in the area is unknown. In particular, it is not apparent how spoil and tailings were disposed of. It has been suggested that such material was utilised to resurface the track at the west of the lake.

It is possible that the catchment has a long history of sheep grazing. The Cistercian monastery of Cymer Abbey was only five km distant. The Cistercians were renowned graziers, but it is not known with any certainty whether the Llyn Cwm Mynach catchment fell within Cistercian grangeland.

Parish data indicate that sheep numbers fluctuated in the locality between 1867-1983, but the broad trend has been for a slight decrease in recent years. This is confirmed within the catchment by local farmers who note that the now afforested area represented much of the better grazing land.

Before afforestation the catchment was regularly burnt. However, all burning ceased with the first plantation of forest in 1967. Together with a decrease in sheep on the unafforested part of the catchment, the demise of burning has resulted in many areas of Calluna becoming mature and leggy.

The afforested area is privately owned and was planted by the Economic Forestry Group. Planting was conducted down to the lake edge. The drier areas were planted, without first draining or ploughing, with Japanese larch and Lodgepole pine. Sitca spruce was planted on ploughed furrows augmented in some areas with additional drainage.

The moorland to the north of Llyn Cwm Mynach was actively managed for game (primarily grouse) through the nineteenth and early twentieth

centuries. Gamekeepers ceased to patrol the moors in the area in the 1920s, since when grouse numbers have substantially declined.

6.1.4 Llyn Dulyn

The Llyn Dulyn catchment consists of unimproved moorland utilised for rough grazing. In terms of its vegetational composition it contains species representative of both 'grassy' and 'shrubby heath' (Fig. 5).

The catchment lies within an extensive block of moorland in excess of 700 ha, that is 'enclosed' by dry stone walls. It is probable that this 'enclosure' was accomplished between 1800-1815. Enclosure at this altitude probably represented a 'land grab' by the local estate (Corsygedol) and not an attempt to actively improve the rough moorland grazing. It appears that the walls acted as sheepwalk boundaries, the enclosure being too extensive to have encouraged intensified grazing in the area. Indeed, it is possible that grazing was less intensive after the 'enclosure' as stray beasts/flocks from neighboring sheepwalks were now fenced off the enclosed land.

The altitude, soil acidity, exposure, wetness and steep margins determine that the catchment is inherently unimprovable. There is no evidence to suggest that the catchment has ever supported a land use other than rough moorland grazing.

Particulars of the Dulyn area included in a sale brochure of the Corsygedol Estate in 1908 describe the land surrounding the lake as 'sheepwalk - well supplied with water', considered 'one of the best sheepwalks in the district'. The suggestion being that the land was neither under nor over-grazed.

Parish data indicate that sheep numbers have risen in the locality between 1867-1983 (Fig. 12). Within the Llyn Dulyn catchment a broad increase in sheep numbers has been recognised since ca.1950.

Little is known of the history of burning in the catchment. The present grazier suggests that no burning has occurred in living memory, but aerial photographs taken in 1946 indicate patterns that may represent evidence of burning. A later survey in 1962 shows no such evidence.

6.1.5 Llyn Eiddew Bach

The Llyn Eiddew Bach catchment (Fig. 6) consists of unimproved 'graasy heath' moorland utilised for rough grazing. The altitude, soil acidity, wetness of the land immediately to the north of the lake and the rocky terrain to the east (the greater proportion of the catchment), determine that the catchment is inherently unimprovable. There is no evidence to suggest that the catchment has ever supported a land use other than rough moorland grazing.

Although parish data indicate that sheep numbers increased in the locality in the period 1867-1983, within the Llyn Eiddew Bach catchment a broad decrease in sheep numbers has been recognised since ca.1950 (Fig. 12). An example is thus apparent whereby parish data prove

misleading in the context of a small catchment (cf. Section 5.7).

Until the 1970s sheep were washed in the lake prior to shearing. A now derelict sheep pen on the southern shore of the lake was the focus of that activity. Another derelict sheep pen at the western edge of the catchment provides further evidence of a higher intensity of sheep grazing in the past. Contemporary farmers can recall no burning in the catchment since the 1950s.

6.1.6 Llyn Gamallt

Mature Calluna and Festuca dominate the Llyn Gammallt catchment (Fig. 7). The unimproved, partially enclosed moorland is utilised for rough grazing and game shooting.

The western side of the catchment is broadly enclosed with stone walls. This 'enclosure', set within unenclosed moorland, is of some antiquity, dating from before 1784. Although enclosure allows stock numbers to be controlled within a defined area and may thus be utilised as a means towards land improvement, there is no evidence to suggest that 'enclosed' land in the catchment was managed so intensively as to upgrade the moorland vegetation.

Enclosed 'ffridd' land immediately below the open moorland often provided grazing for sheep in winter and cattle in summer. The enclosed area to the west of Llyn Gamallt is known locally as 'Ffridd Gamallt'. Surrounded by open moorland, it is doubtful whether this area functioned as true ffridd land. At an altitude in excess of 400 m, it is unlikely that a suitable habitat was available for cattle in summer, or that it provided any great advantage over the open moorland for sheep in winter.

Sheep grazing on the Llyn Gamallt catchment is effectively confined to the north-western - south-eastern sector. The northern and eastern slopes being too rocky and precipitous. Local farmers report little change in sheep numbers on the catchment since the 1950s.

An area immediately to the west of Llyn Gamallt Fawr was drained in the 1940s to reduce the saturation of the peat and encourage healthier stands of Calluna for grazing sheep. The drains were deep and narrow and although they have not been maintained they comprise an active network of drainage to the lake.

The catchment was regularly burnt in broad patches by tenant farmers until the late 1960s. Aerial photographs taken in 1946 clearly indicate mosaics of vegetation of different ages. National Trust policy to curtail moorland burning has resulted in the western sector of the catchment remaining unburnt for 15 years. The remainder of the catchment is now only infrequently burnt. The long and woody nature of the Calluna that dominates the catchment may be attributed to the lack of burning and concomitant low grazing pressure.

6.1.7 Llyn Gynon

The Llyn Gynon catchment comprises unenclosed, unimproved moorland utilised for rough grazing. The vegetation is dominated by Molinia and Festuca/Nardus grassland with Eriophorum vaginatum characterising the wetter areas (Fig. 8).

During investigations in the peat deposits at the north shore of the lake, Moore (1966) identified the remains of a stone slab trackway leading from what he interpreted as a 'medieaval farmhouse' to a 'butter cooler' (constructed not earlier than the twelth century). The broad chronology of these features coincides with the early exploitation of the area as grazing land by the Cistercians of Strata Florida from the late twelth century (Williams 1889).

If the function of these remains has been correctly interpreted and some permanent or semi-permanent habitation was maintained in the catchment during the medieaval period, then a limited improvement of the moorland from enhanced grazing pressure on land in the immediate vicinity of the 'dwelling', perhaps regulated by enclosure(s).

The frontiers of cultivation and improved pasture reached their upper limit in Cardiganshire during the agricultural boom of the Napoleonic wars. However, there is no evidence to suggest that the catchment has ever supported a land use other than rough moorland grazing.

The central issue of land management in the catchment concerns its utilisation for sheep grazing. This practice dates to at least the late twelth century when the Cistercians of Strata Florida acquired the area and used it as rangeland for their flocks.

Parish data indicate no overall trend towards an increase or decrease of sheep numbers in the area from the late nineteenth century (Fig. 12). Within the Llyn Gynon catchment a broad increase in sheep numbers has been recognised since ca.1945.

Burning of grassland was a regular practice in the catchment until the 1950s. Burning patterns may be faintly distinquished from aerial photographs flown in 1948. The proximity of the extensive Towy forest to the south has made grassland fires an inappropriate and rarely sanctioned method of land management in the area since the early 1960s.

While the farm of 'Gareg Lwyd' was occupied areas of Molinia in the catchment were occasionally cut for hay to provide winter fodder.

In the nineteenth century turbaries were established on the peats at the west of the Llyn Gynon catchment. These peat cuttings are depicted on a map of 'Gareg Lwyd' of 1831 and were utilised by the tenants of that farm. Evidence of their existence may still be observed.

6.1.8 Llyn Hir

The Llyn Hir catchment consists of unimproved, unenclosed moorland dominated by Nardus and Festuca (Fig. 9) and utilised for rough grazing.

The central issue of land management in the catchment concerns its utilisation for sheep grazing. This practice dates to at least the late twelth century when the Cistercians of Strata Florida acquired the area and used it as rangeland for their flocks.

The management of part of the Llyn Hir catchment by the Crosswood Estate, and the proximity of a major droving route ensured that the catchment was regularly grazed throughout the nineteenth century.

Parish data suggest that sheep numbers have increased in the area since the late nineteenth century (Fig. 12). More recently a broad increase in sheep numbers has been recognised by local farmers. Estimates of the extent of this increase vary between two-fold since ca.1930 to three-fold since ca.1945.

Management of grassland by burning has not been a regular feature in the catchment within living memory. Air photographs flown in 1946 and 1947 show no evidence of burnt patches. The proximity of the extensive Towy forest to the south has made grassland fires an inappropriate and rarely sanctioned method of land management in the area since the early 1960s.

6.1.9 Llyn Llagi

The Llyn Llagi catchment comprises unimproved moorland characterised by Festuca and Nardus on the drier land and Eriophorum vaginatum on the wetter areas, utilised for rough grazing (Fig. 10).

Land immediately adjacent to the lake and below the steep cwm wall is 'enclosed' with rough dry stone walls. The date of this enclosure is unknown but the notation 'Ffridd y Llyn' on Ordnance Survey maps and the absence of enclosure Acts relating to this locality, suggests that the enclosure(s) may have been established before the more expansive moorland enclosures of the early nineteenth century.

Within the 'enclosed' area two or three shallow drains run downslope for a short distance from the lake. The date of this 'drainage' is unknown. Only a few metres of 'drain' actually lie within the catchment.

Although 'enclosure' and 'drainage' may have represented an attempt to improve the grazing quality of the land and have inevitably affected its management), there is no evidence that the small section of the catchment involved, experienced a change in land use as a result.

Llyn Llagi lies in the vicinity of the major Croesor quarrying and and mining region. The remains of at least two small 'excavations' can be seen on the northern slope of the catchment. However, there is no evidence from documentary sources to suggest that any mineral was ever actively exploited within the lake catchment.

Until the mid nineteenth century black cattle were an important component of the pastoral economy of north Wales. Cattle were grazed on and occasionally above ffridd land in summer, but at over 350 m the ffridd within the LLagi catchment was probably too high for that activity. The central issues of pastoral management in the catchment concern its

utilisation for sheep grazing.

Sheep numbers in the parish of Beddgelert have fluctuated between 1867-1983 but the overall trend in the parish has been for numbers to rise, particularly at the beginning and end of this period (Fig. 12). Similarly, within the Llyn Llagi catchment a broad increase in sheep numbers has been recognised in recent years.

The catchment has been infrequently burnt, with the 'enclosed' area adjacent to the lake being burnt more often than the upper catchment. Hay making and sheep washing were occurred in the lower part of the catchment in the past.

The different intensity of land management between the upper and lower catchments is a theme that runs through the land management of the catchment. The lower catchment has been 'enclosed', partly 'drained', cut for hay and more regularly burnt. It is probable that grazing intensities were (and are) higher than on the exposed upper catchment.

6.1.10 Llyn Y Bi

The Llyn y Bi catchment consists of unimproved but enclosed moorland utilised for rough grazing. In terms of its vegetational composition it may be categorised as 'shrubby heath' and is dominated by Calluna and Vaccinium (Fig. 11).

The Llyn y Bi catchment comprises the most northern of four adjacent blocks of land enclosed by dry stone walls. Enclosure probably dates from the early nineteenth century, and at 400 m was unlikely to have represented an attempt to actively improve the land. Aside from the altitude, soil acidity and wetness of the catchment, the rocky terrain and particularly the precipitous back wall are inherently unimprovable. There is no evidence to suggest that the catchment has ever supported a land use other than rough moorland grazing.

Parish data indicate that sheep numbers in the area have declined through the twentieth century (Fig. 12). Much of the catchment is unsuited for sheep grazing. Until the National Trust purchased the area in ca.1930 it was managed primarily for grouse rather than sheep. The long, rangy Calluna of the catchment is indicative of low intensity management and grazing pressure. This is particularly apparent when compared with the two enclosures immediately to the south of the catchment where the continued maintenance of a higher sheep population and more regular burning has resulted in vegetation dominated by short Calluna and grassy species.

When managed primarily for grouse (mid-nineteenth century - ca.1930) the catchment was regularly burnt in small patches. Since that date the frequency and extent of burning declined. Aerial photographs show no evidence of 'recent' burning in the catchment in 1946 and 1962. A combination of National Trust policy, the proximity of the Rhinog National Nature Reserve immediately to the north and extensive tracts of forest 2 km to the south-east and 3 km to the east, determine that the catchment is now burnt very infrequently.

Fig. 2 Llyn Berwyn: Catchment Vegetation

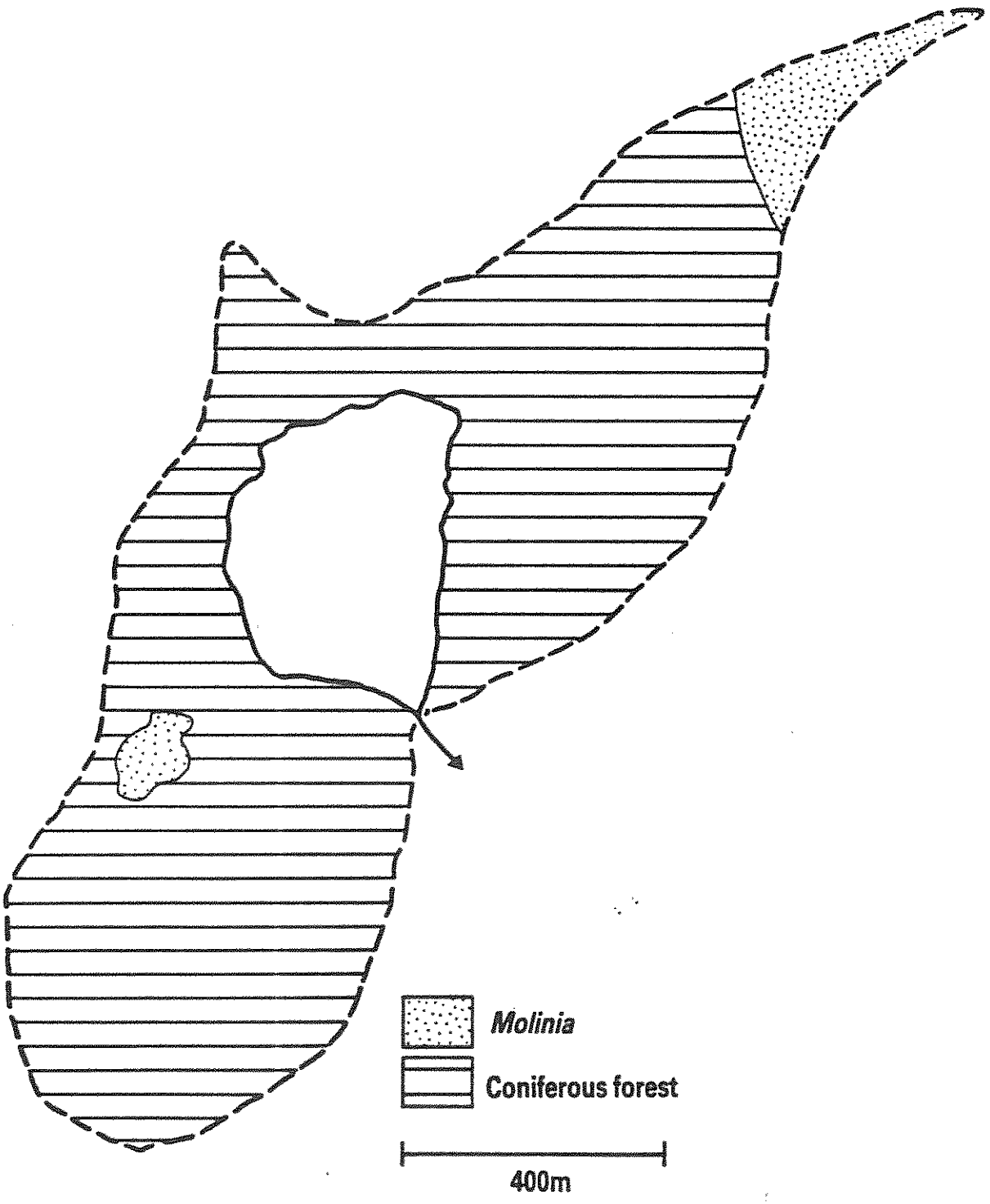
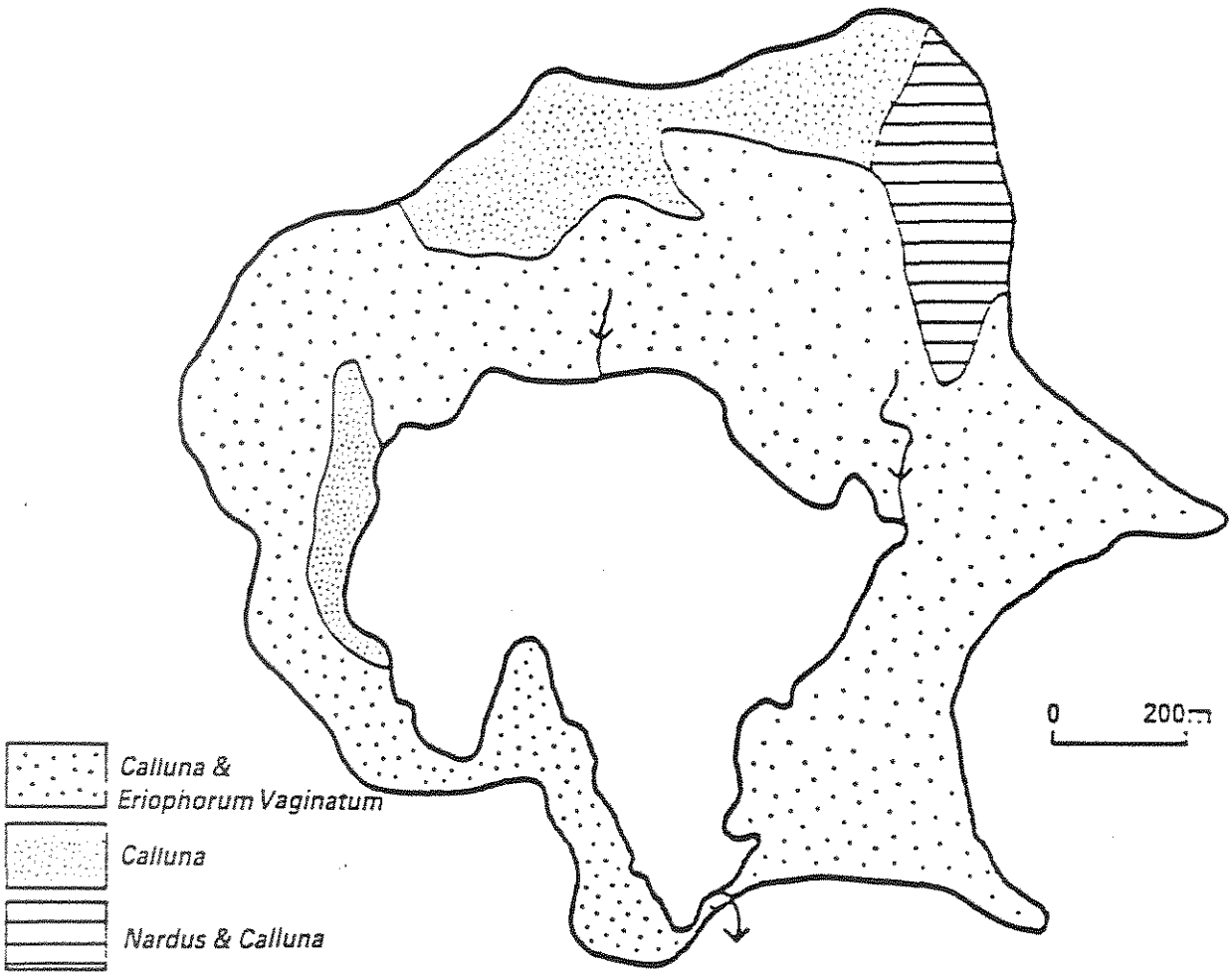


Fig. 3 Llyn Conwy: Catchment Vegetetion



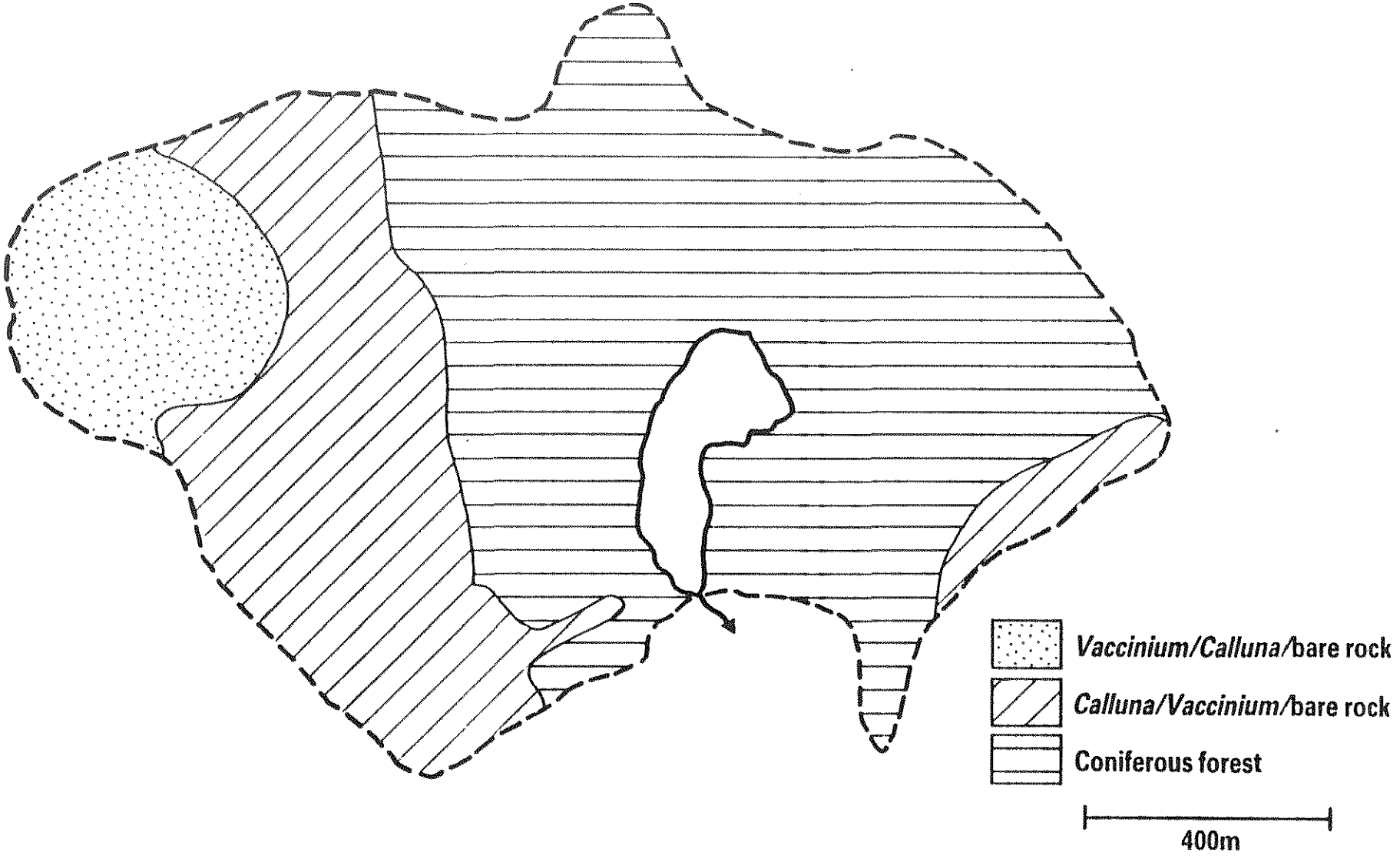


Fig. 4 Llyn Cwm Mynach: Catchment Vegetation

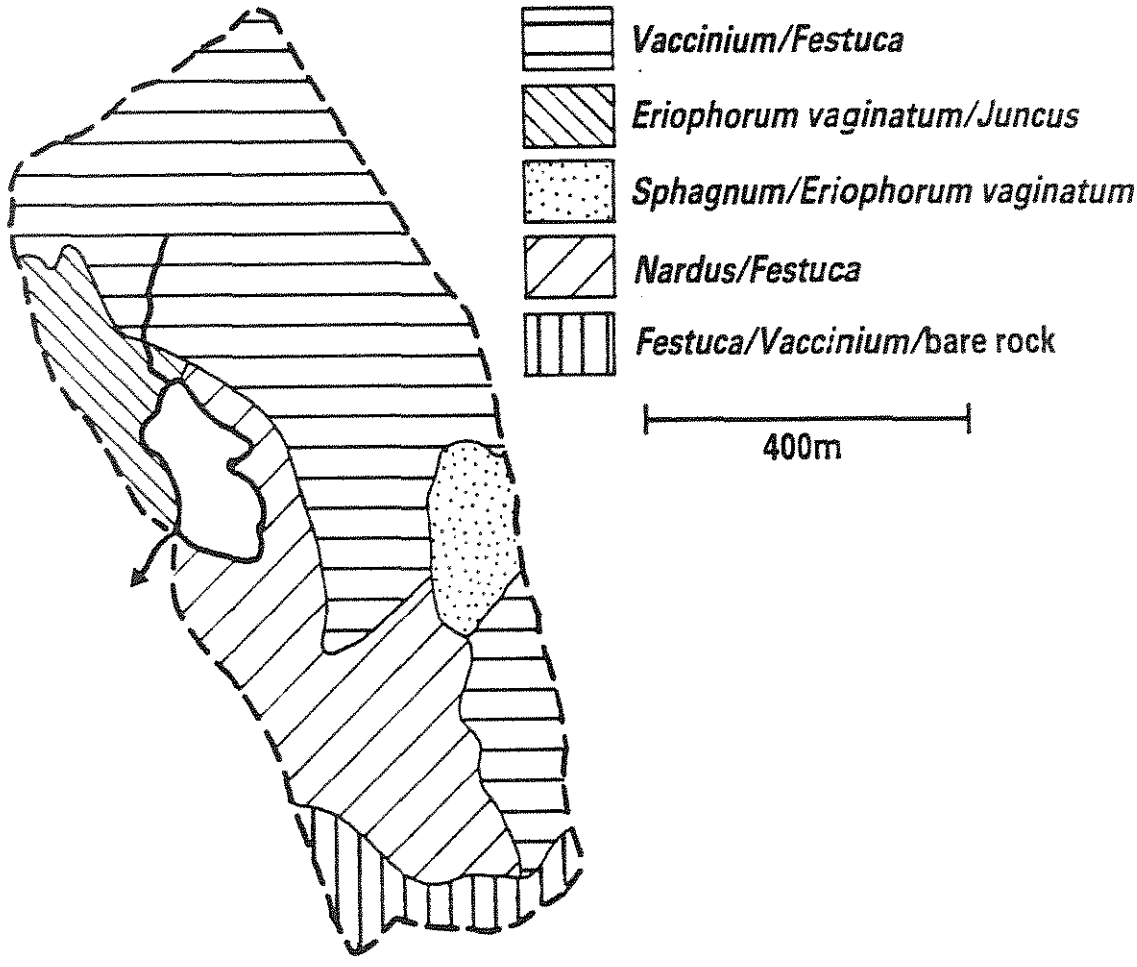


Fig. 5 Llyn Dulyn: Catchment Vegetation

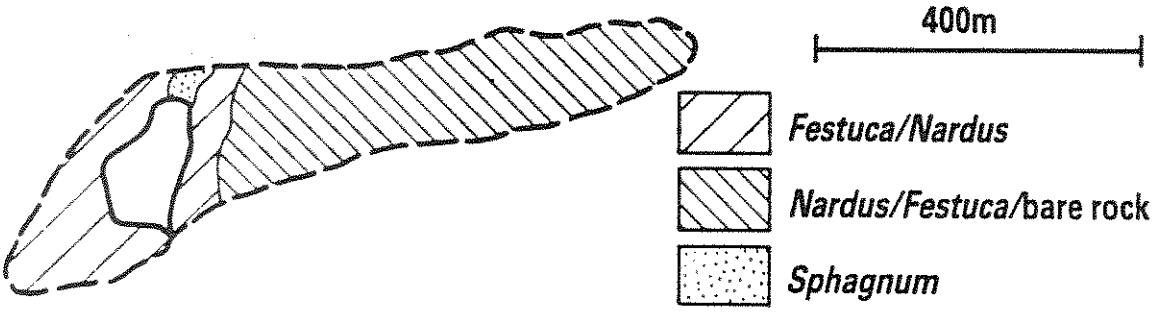


Fig. 6 Llyn Eiddew Bach: Catchment Vegetation

Fig. 7 Llyn Gamallt: Catchment Vegetation

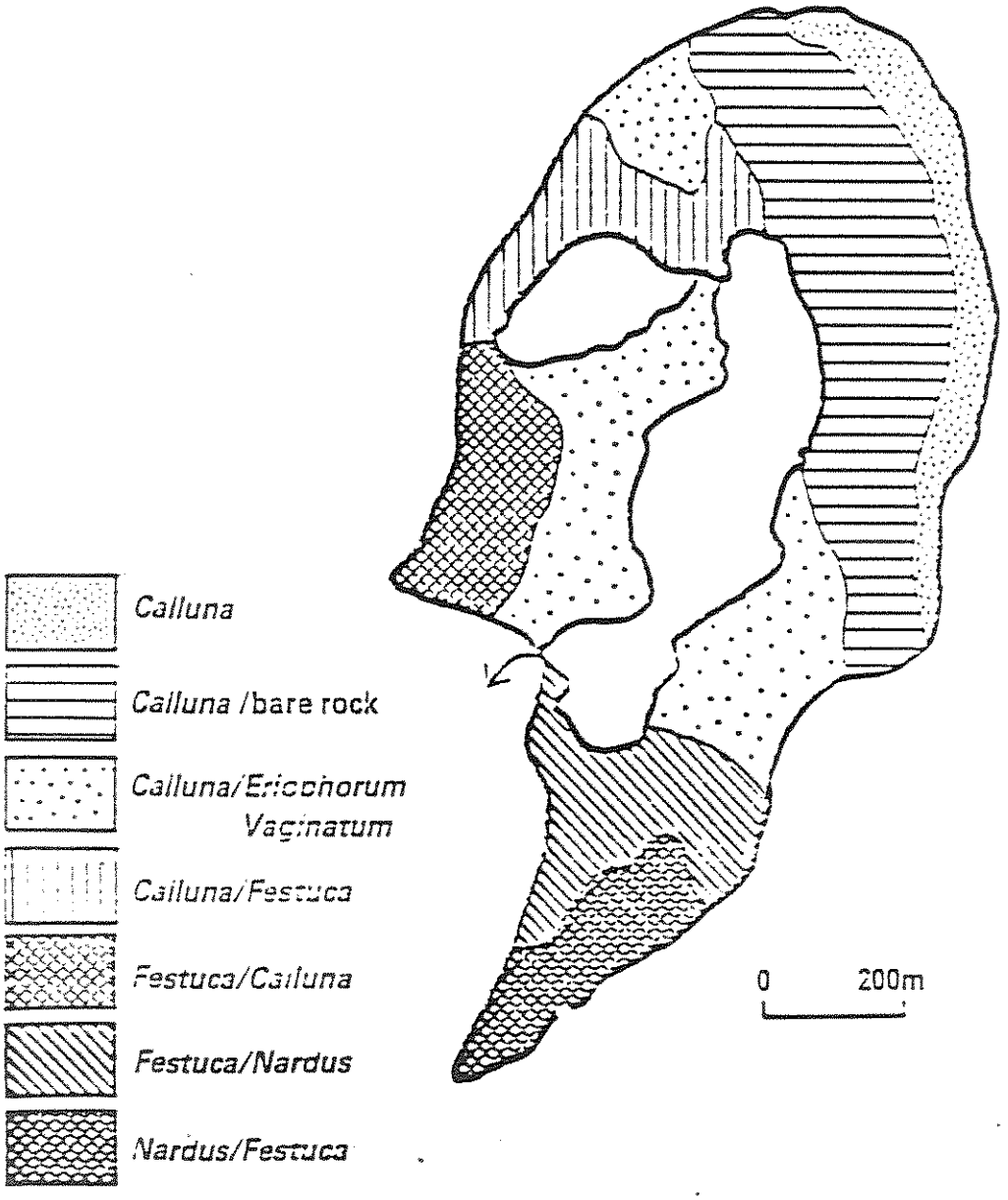
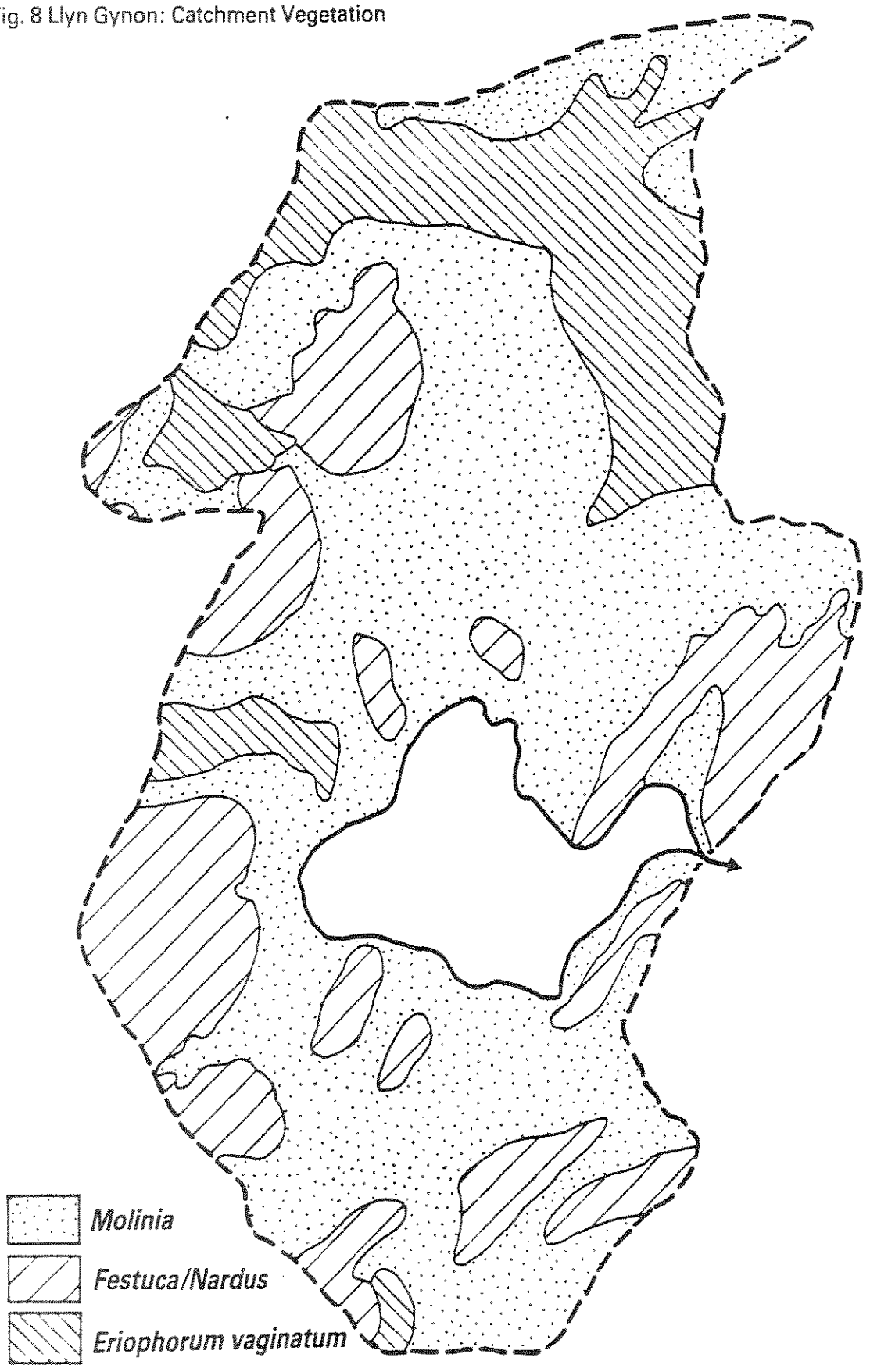


Fig. 8 Llyn Gynon: Catchment Vegetation



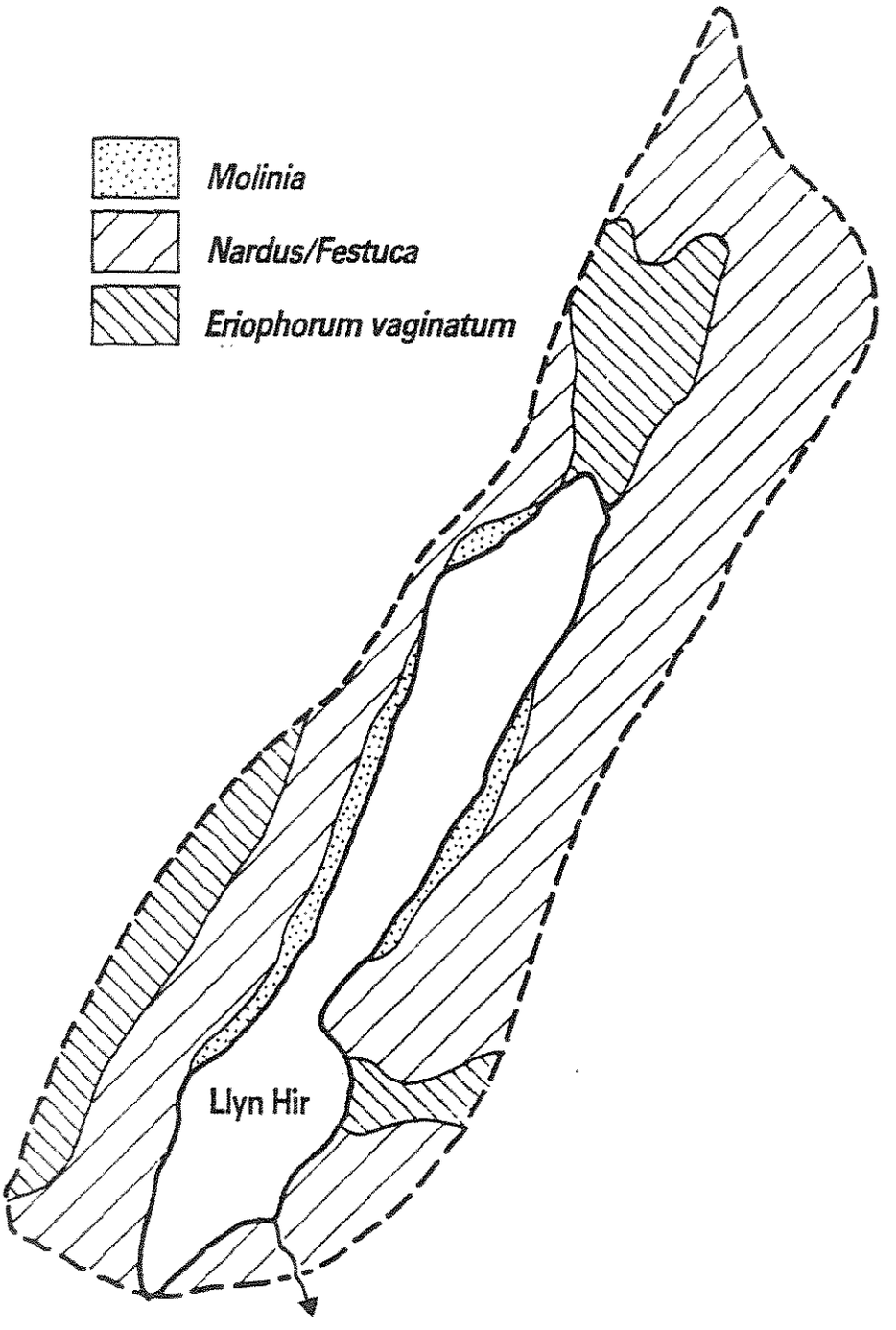


Fig. 9 Llyn Hir: Catchment Vegetation

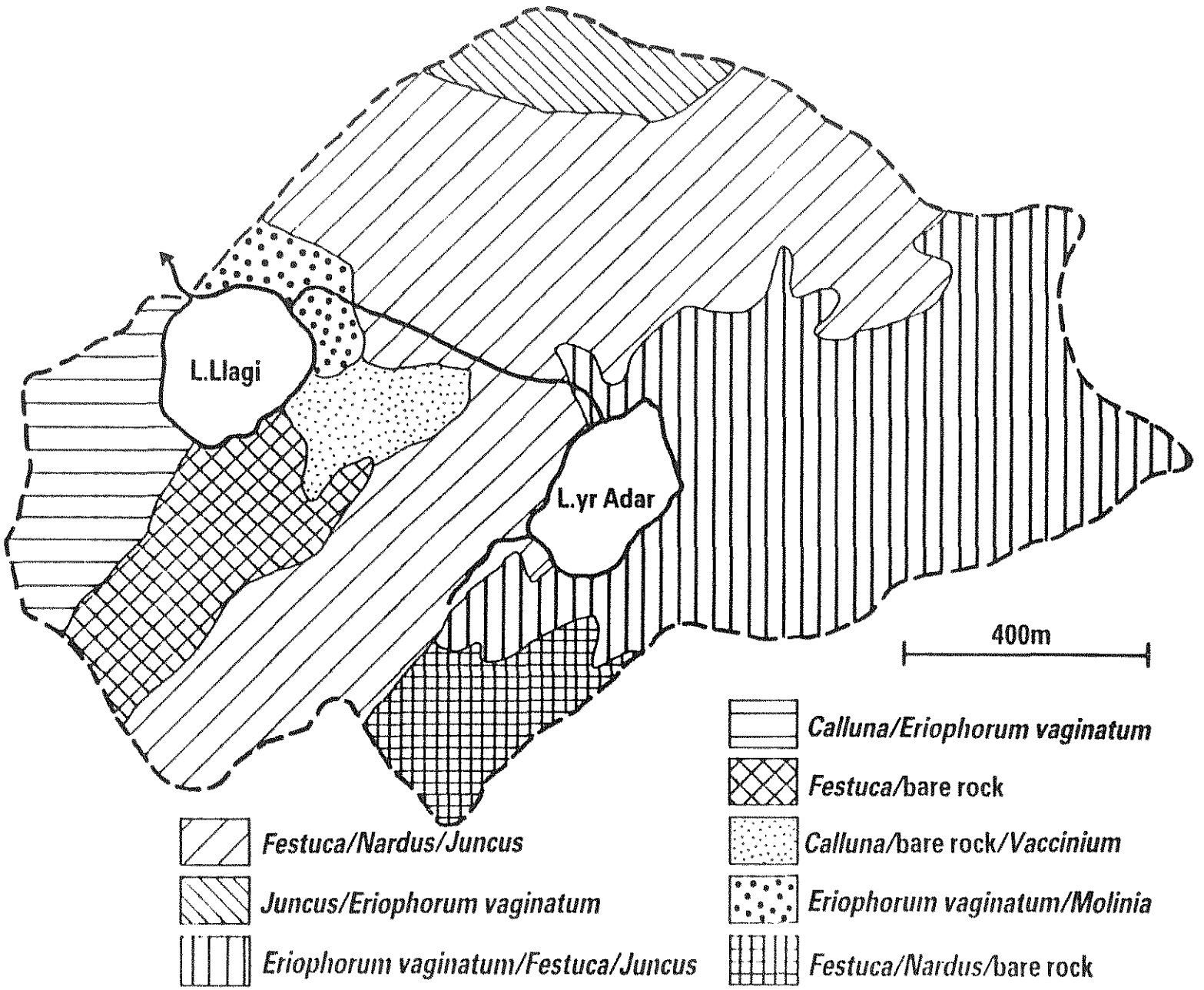
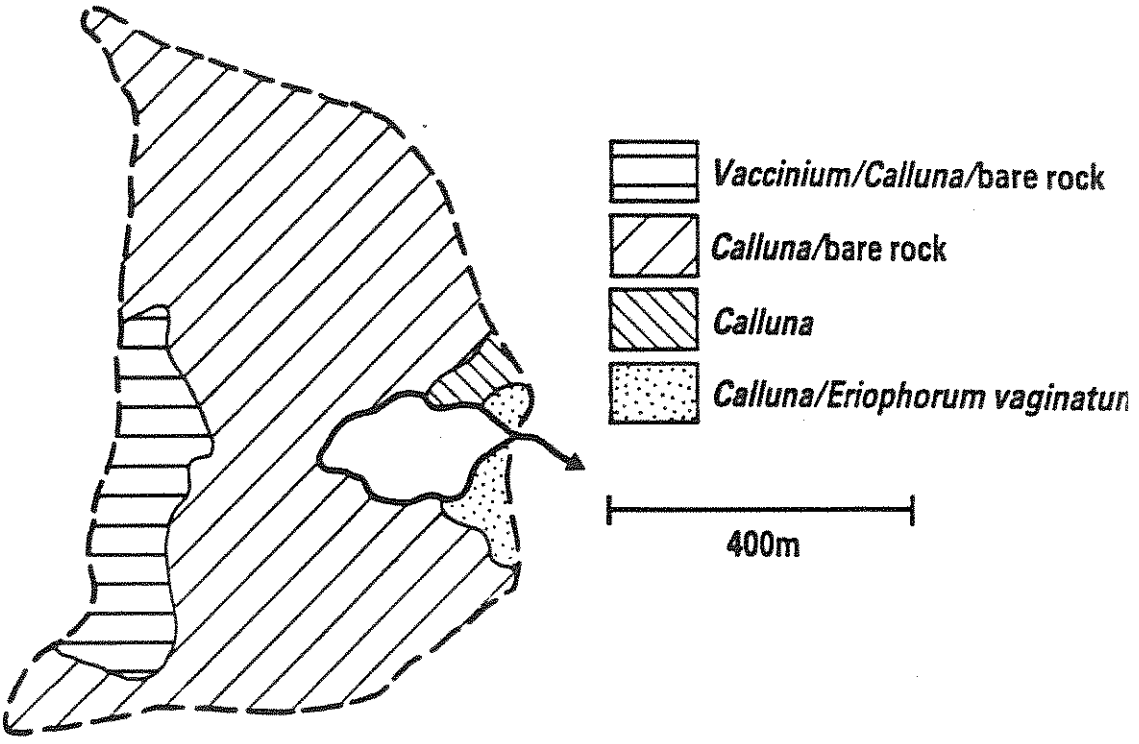


Fig. 10 Llyn Llagi: Catchment Vegetation


Vaccinium/Calluna/bare rock
Calluna/bare rock
Calluna
Calluna/Eriophorum vaginatun
400m

6.2 Land use: summary

Llyn Cwm Mynach is the only catchment where commercial extraction of minerals (managanese and slate) has occurred, albeit for a short period (primarily in the nineteenth century) and at a low level of exploitation.

The Llyn Berwyn and Llyn Cwm Mynach catchments that previously comprised unimproved moorland have been afforested. The Llyn Berwyn catchment was planted with Sitca spruce (*Picea sitchensis*), Lodgepole pine (*Pinus contorta*) and Japanese larch (*Larix kaempferi*) between 1960-1963. The Llyn Cwm Mynach catchment was planted with the same species between ca. 1967-1975.

All other catchments (including Llynnaedd Berwyn and Cwm Mynach prior to afforestation) comprise unimproved rough grazing of the moorland core, for which there is no evidence of any land use change in the past ca.200 years. In terms of the ADAS land capability classification the catchments consist of land of categories H3 - 'improvements generally severely limited' and H4 - 'generally not improvable' (MAFF 1980). The vegetation of the catchments of Llynnaedd Conwy, Gamallt and Y Bi may be categorised as 'shrubby heath' and those of Llynnaedd Dulyn, Eiddew Bach, Gynon and Hir, as 'grassy heath' (King 1977, Ball *et al.* 1982).

In general, altitude, exposure, remotenesss, wetness and soil acidity have determined that land in the catchments is unsuitable for improvement and therefore that no reversion from an improved status and associated regeneration of acidic species has occurred.

6.3 Land management: summary

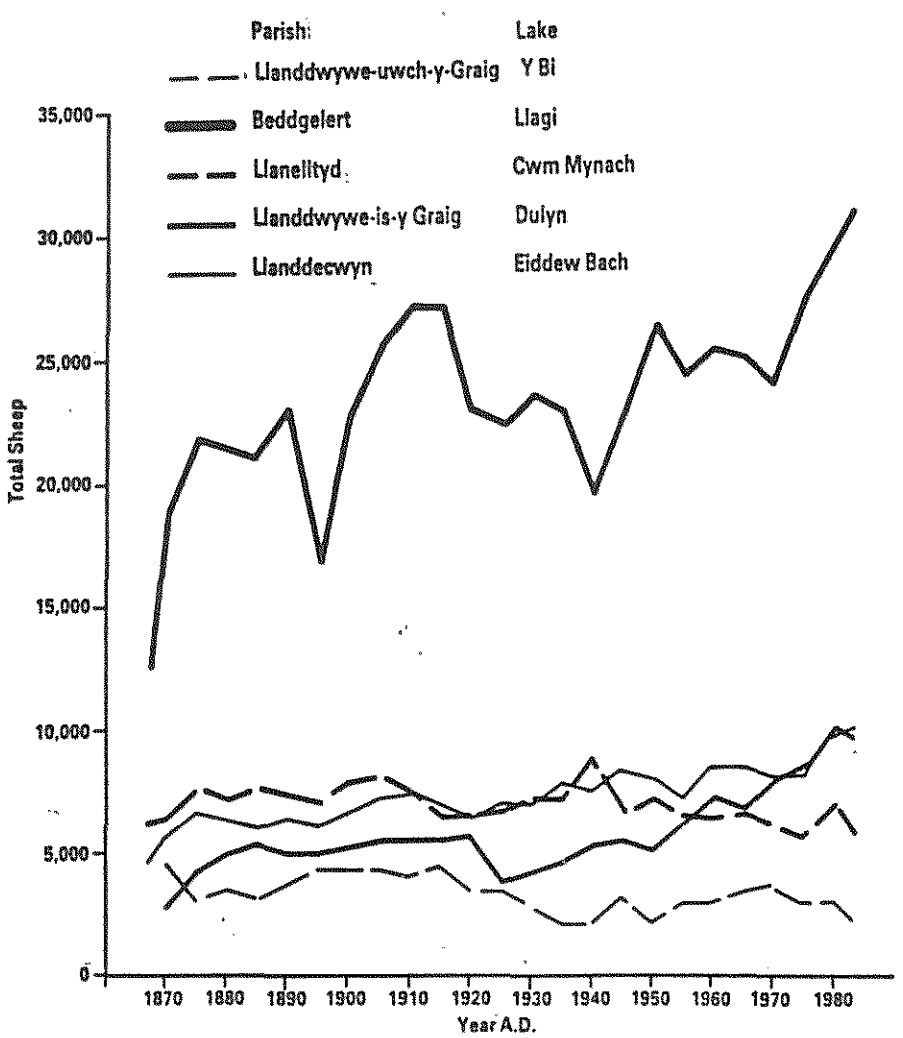
In the absence of land use change it is possible that changes in management procedures may have affected the relative abundance and development of vegetation type and individual species, or have given rise to a potential acidification mechanism in their own right.

6.3.1 Sheep numbers and grazing regimes

Cattle, goats and ponies have not constituted a significant component in the grazing regimes of the catchments in the last 150 years.

At a local level parish data reveal that although sheep numbers have fluctuated since 1867, an (often substantial) increase has occured particularly ca.1945 (Fig. 12). The parish data also reveal the increasing importance of ewes and lambs at the expense of wether sheep over the past century.

However, it was apparent from individual communicants that an increase in sheep numbers has not been recognised in all catchments in the past ca. 20-40 years. In the catchments of Llynnaedd Conwy, Eiddew Bach and Y Bi a decline in sheep numbers has been observed. In the catchments of Llynnaedd Dulyn and Gamallt no significant change has been recognised. Sheep grazing in the Llyn Berwyn catchment virtually ceased and in the Llyn Cwm Mynach catchment, decreased substantially, following



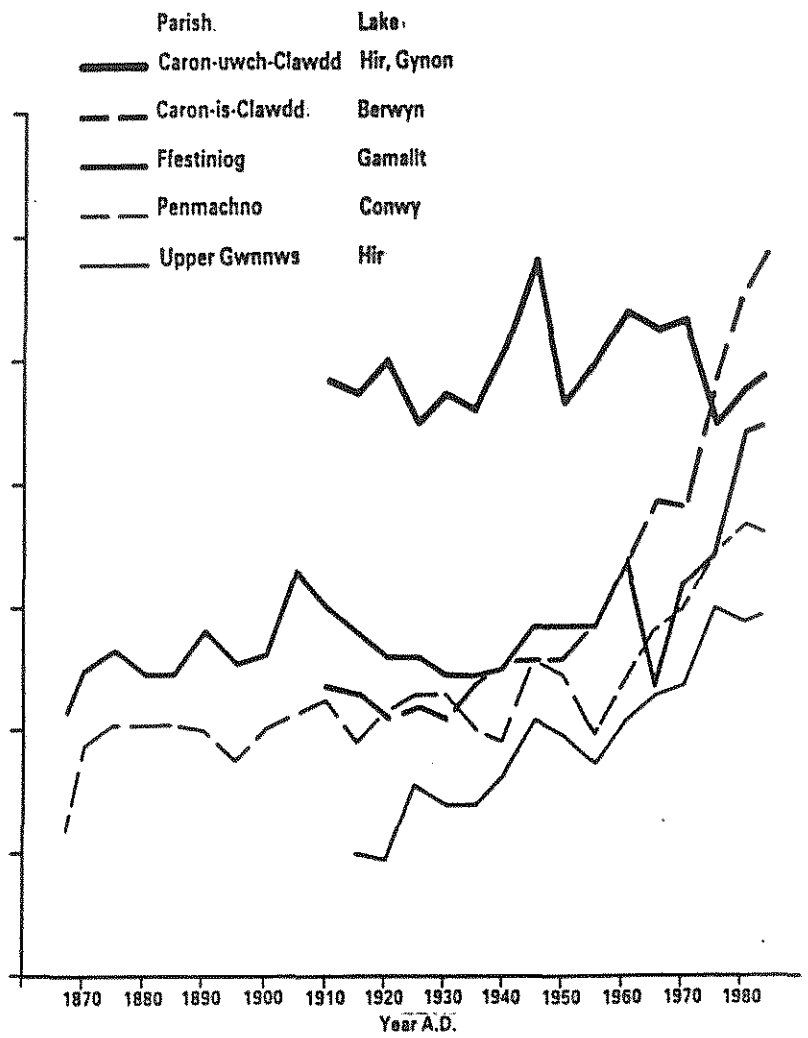


Fig. 12 Parish returns: Total sheep numbers

afforestation.

In all catchments communicants recognised a decrease in the number of sheep on the hills in winter.

6.3.2 Enclosure

The Llynnaedd Dulyn and Y Bi catchments comprise enclosed moorland. Precise details are uncertain but it is believed that enclosure occurred in the early nineteenth century.

Land within the Llynnaedd Gamallt and Llagi catchments is partially enclosed. The description 'ffridd' that is attributed to these areas from cartographic sources suggests that enclosure pre-dated the nineteenth century. However, it is considered unlikely that these areas functioned as true ffridd land owing to their altitude and remoteness.

6.3.3 Drainage

Artificial drainage of peat has occurred in just two catchments. Around Llyn Conwy an extensive area was drained during the 1920s in an attempt to provide healthier stands of Calluna for grouse. An area to the west of Llyn Gamallt Fawr was drained during the 1940s, this time to improve the Calluna for sheep grazing.

6.3.4 Burning

With the exception of Llynnaedd Eiddew Bach and Hir, burning of Calluna or Molinia constituted a management practice of varying regularity and extent in the past. The practice was generally to improve sheep grazing, but in the Llynnaedd Conwy and Y Bi catchments it was for grouse.

Since ca.1960 a virtual cessation of burning has occurred in all catchments owing to either afforestation, proximity of forest or NCC or National Trust management policy.

6.3.5 Liming

There is no evidence for, nor rational expectation of the application of lime to land in any of the study catchments. All catchments are remote from sources of lime which in the nineteenth century, when brought from a distance over poor roads, was an expensive commodity (eg. Davies 1813, 1815). Contemporary farmers and authorities confirmed that liming was not a realistic management option owing to the inherent unimprovability of the catchments.

6.3.6 Lake level change

Llyn Conwy was reservoired for potable water supply in the late 1950s and is subject to water level fluctuation as a result of periodic drawdown, particularly in summer.

The only other study site where a documented manipulation of lake water level has occurred is Llyn Cwm Mynach. Aerial photographs of 1946 indicate a weir structure at the outflow. The lake level was raised in the mid-1960s prior to afforestation.

7.0 Discussion: the Significance of Land Use and Management Changes

A full analysis of the significance of land use and management change in relation to lake acidification is precluded at present, as diatom based pH reconstruction has yet to be completed for all study sites.

It is immediately apparent that no one mechanism of land use or management change can account for the acidification of the 10 Welsh study lakes.

With the exception of the afforestation of the Llyn Berwyn and Llyn Cwm Mynach catchments, there has been no net land use change. The exploitation of managanese and slate in the Llyn Cwm Mynach catchment was a small scale and short lived feature of the nineteenth century.

pH reconstruction (Fig. 13) suggests that the recent acidification of Llyn Berwyn was enhanced by afforestation and possibly by the deep drainage of the catchment in 1974 (Kreiser *et al.* 1986). At Llyn Cwm Mynach a slight acidification has occurred from a mean pH of 6.1 proir to 1920 to a mean pH of 5.6 - 5.7 at the surface of the core (Fig. 14). There is no indication that this acidification was accelerated by afforestation in the catchment in the 1960s.

All catchments have experienced changes in management practices, but of a varying nature, extent and historical occurrence.

The regional and local trends toward the replacement of wether flocks by ewes and lambs from the mid-nineteenth century and the decline in winter stocking densities, were realised in all catchments. However, in the post war period some catchments have experienced a significant increase in summer stocking densities. Enclosure in certain catchments may have resulted in a rationalisation and possible decrease in sheep grazing intensity. However, the early date of such enclosure suggests that it was not an important process.

With the exception of the Llynnaedd Eiddew Bach and Hir catchments which were never regularly burnt, there has been a decline or cessation of burning within the past ca.20 years. However, only in the Llynnaedd Conwy, Gamallt, Y Bi and the unafforested section of Cwm Mynach catchments is there evidence of regeneration of heathy species, in the form of mature, leggy *Calluna* stands, (*Pteridium* is not present in any catchment). With the exception Of Llyn Gamallt, effects of the cessation of burning in these catchments has been accentuated by a decline in grazing intensity. pH reconstruction is not complete for these lakes, but well documented fishery decline from the early 1960s in Llynnaedd Conwy and Gamallt (Milner and Jones 1985, Patrick and Stevenson 1986) suggests that acidification commenced before burning ceased in the mid-late 1960s.

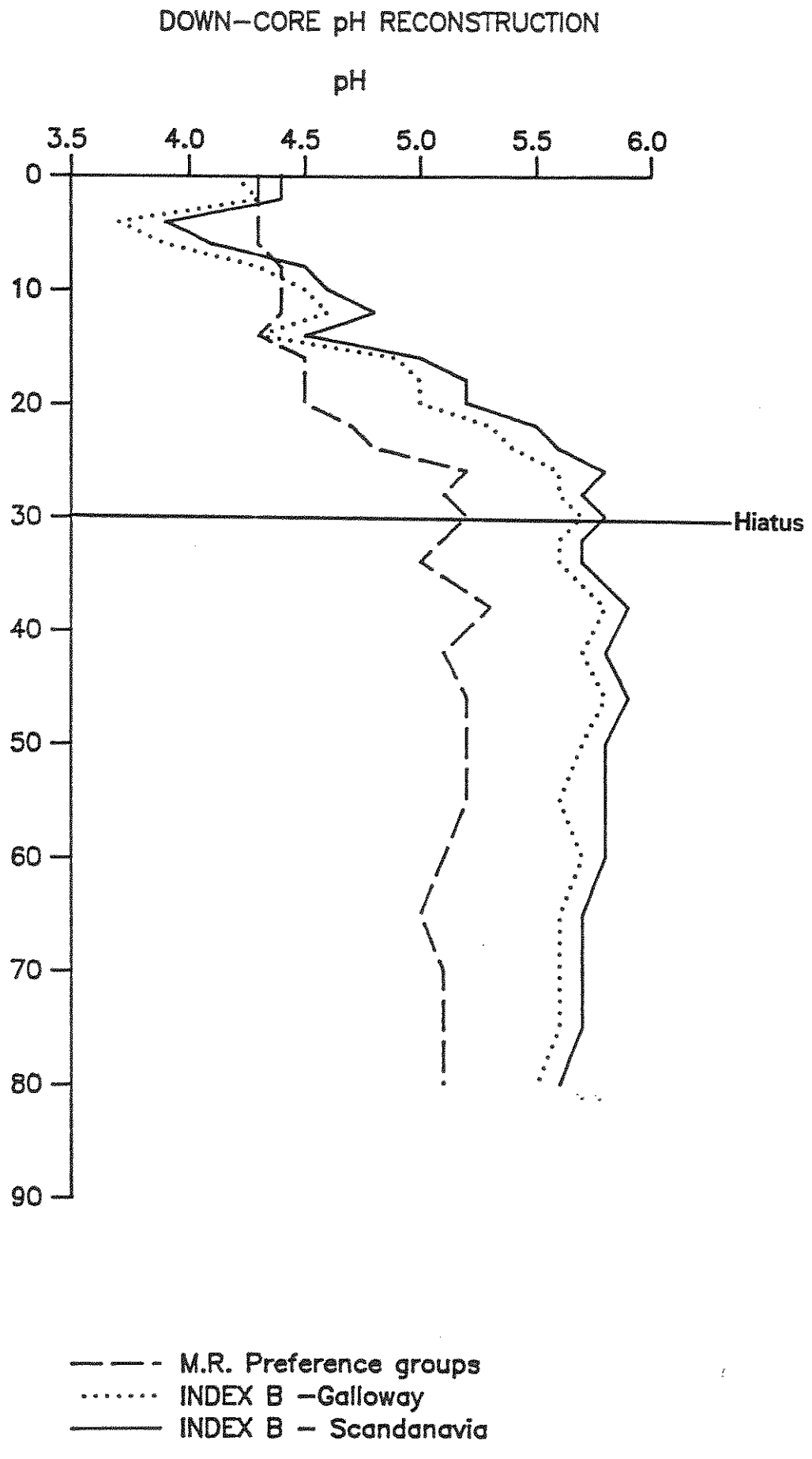
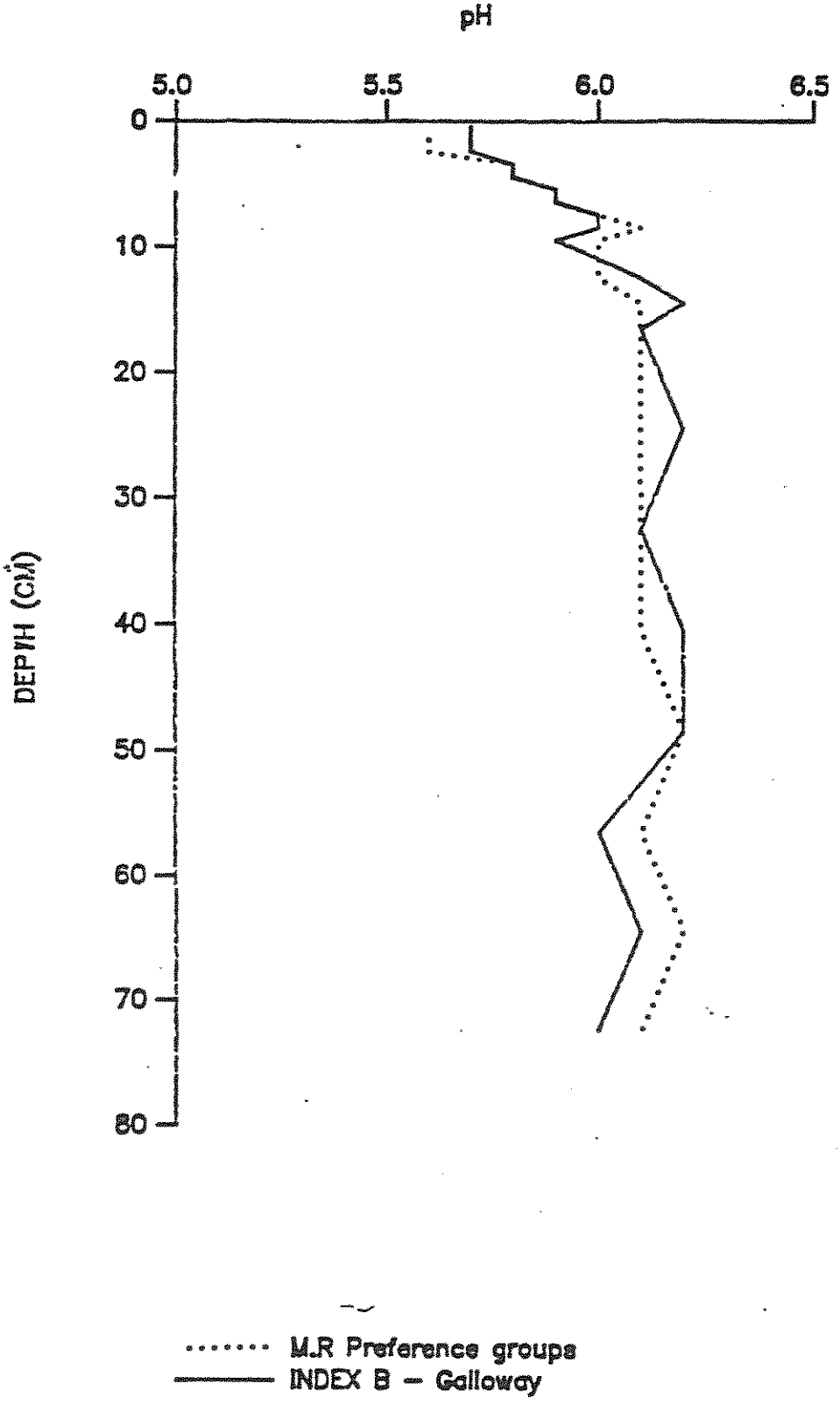


Fig. 13 Llyn Berwyn: pH reconstruction

Fig. 14 Llyn Cwm Mynach: pH reconstruction



Similarly the drainage of peat in the catchments of Llynnaedd Conwy (1920s) and Gamallt (1940s) occurred before documented fishery decline. Drainage was only undertaken in the catchment of Llyn Gamallt Fawr, yet the lake has a very similar chemistry to that of the undrained Llyn Gamallt Bach (Milner and Jones 1985, Patrick and Stevenson 1986).

There is no evidence for the practice of liming in any catchment. Therefore the cessation of that practice may be excluded as a potential acidification mechanism.

The reservoiring and subsequent water level fluctuation of Llyn Conwy was temporally coincident with fish decline in the early 1960s. The significance of that coincidence will be determined only when pH reconstruction, a more stringent measure of water quality change than fish decline, is accomplished.

To date reconstructed water quality is available for two non-afforested lakes - Llyn Hir (Fig. 15) (Fritz et al. 1987) and Llyn Gynon (Fig. 16) (Stevenson et al 1987a).

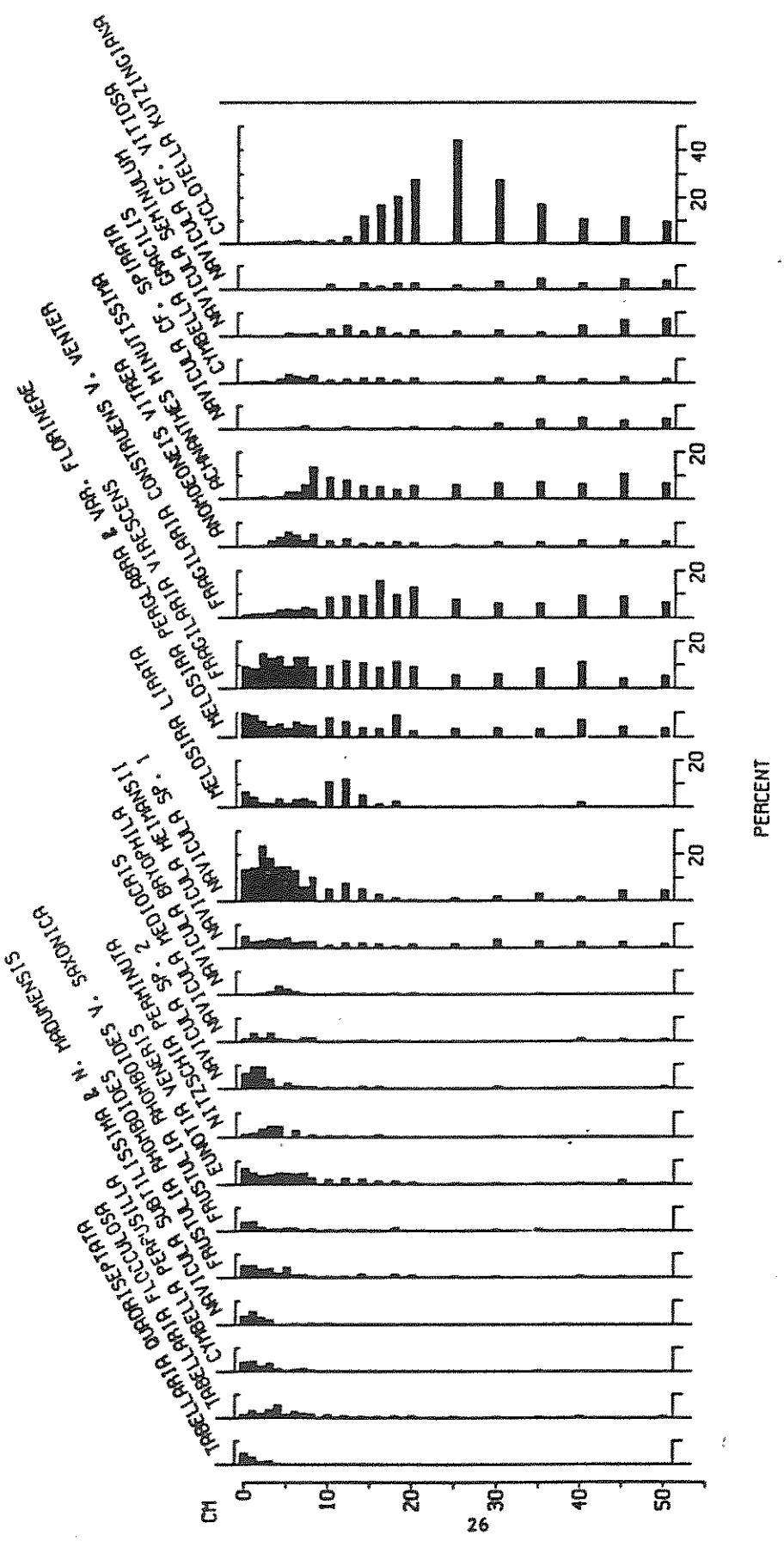
Consideration of documented land use and management histories in conjunction with historical water quality indicates that changes in the catchments are unlikely to account for the observed acidification of the lakes.

The unenclosed, undrained Nardus/Festuca grassland of the Llyn Hir catchment has a long history of sheep grazing, which over the period of major acidification (ca.1940-1980 - Fig. 15), increased in intensity. Burning was not a regular management practice and the catchment was never limed.

The recent acidification of Llyn Gynon is primarily a post-1950 phenomenon (Fig. 16). There has been no land use change or significant land management change in the catchment immediately prior to, or during this period, except a cessation of grassland burning from the late 1950s.

Together with evidence from soot and metal analyses, the failure to attribute acidification of these non-afforested lakes to catchment processes, argues strongly for an explanation in terms of acid precipitation.

Fig. 15 Llyn Hir: Diatom summary



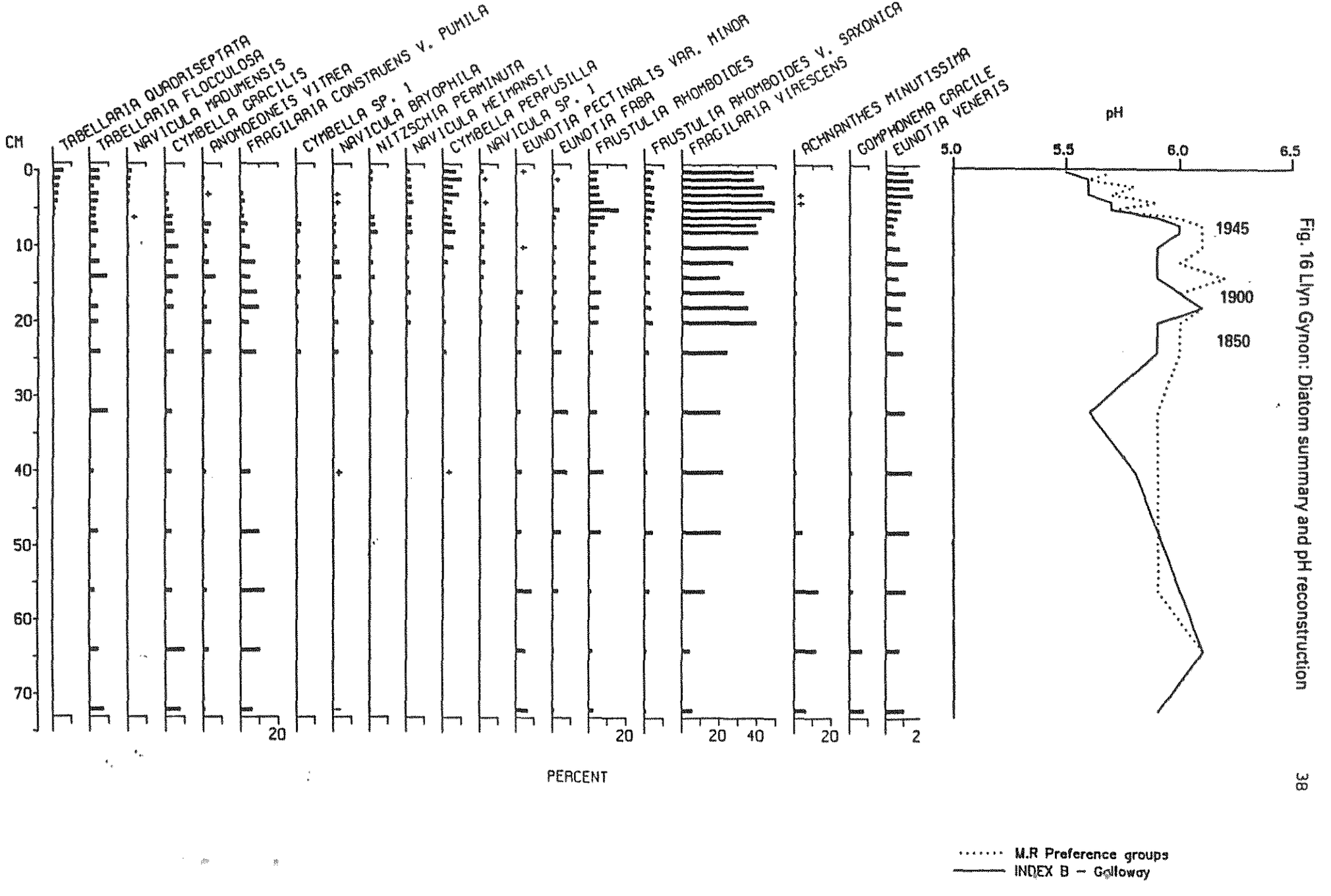


Fig. 16 Llyn Gynon: Diatom summary and pH reconstruction

Acknowledgements

The author wishes to thank Drs A.C. Stevenson and R.W. Battarbee for their comments on this paper. The diagrams were prepared by Claire Bourne and Lauren McClue.

References

ALLEN, S.E. (1964) 'Chemical aspects of heather burning', *J. Appl. Ecol.* 1: 347-367

ANDERSON, N.J., BATTARBEE, R.W., APPLEBY, P.G., STEVENSON, A.C., OLDFIELD, F., DARLEY, J. and GLOVER, G. (1986) 'Palaeolimnological evidence for the recent acidification of Loch Fleet, Galloway', *Palaeoecology Research Unit, University College London, Research Paper*, 17.

ASHBY, A.W. and EVANS, I.L. (1944) *The agriculture of Wales and Monmouthshire* (Cardiff)

BACHE, B.W. (1985) 'Soil acidification and aluminium mobility', *Soil use and Management*. 1: 10-13

BALL, D.F., SHEAIL, J and HEAL, O.W. (1982) *Vegetation change in upland landscapes*. (Institute of Terrestrial Ecology, Bangor)

BATTARBEE, R.W., and FLOWER, R.J. (1985) 'Palaeoecological evidence for the timing and causes of lake acidification in Galloway, southwest Scotland', *Palaeoecology Research Unit, University College London, Research Paper*, 8

BATTARBEE, R.W., FLOWER, R.J., STEVENSON, A.C. and RIPPEY, B. (1985) 'Lake acidification in Galloway: a palaeoecological test of competing hypotheses', *Nature*. 314: 350-352

BINNS, W.O. (1984) 'Acid rain and forestry', *Forestry Commission Research and Development Paper*, 134

BOULET, L.J. (1939) 'The ecology of a Welsh mountain sheepwalk', unpubl. Ph.D. thesis, University College Wales

BOWEN, E.C. (1950) 'The monastic economy of the Cistercians at Strata Florida', *Ceredigion*. 1: 34-37

BOWEN, I. (1914) *The great enclosures of common land in Wales* (London)

BRUGUM, R.B. and LUSK, M. (1986) 'Diatom evidence for neutralization in acid surface mine lakes', in SMOL, J.P., BATTARBEE, R.W., DAVIS, R.B. and MERILAINEN, J. (eds) *Diatoms and lake acidity*. (Dordrecht) pp. 115-129

BURNS, J.C., COY, J.S., TERVET, D.J., HARRIMAN, R., MORRISON B.R.S. AND QUINE, C.P. (1984) 'The Loch Dee project: a study of the ecological effects of acid precipitation and forest management on an upland catchment in south-west Scotland. 1. Preliminary investigations', *Fish. Mgmt.* 15: 145-167

CLARKE, R. (1974) 'The effects of effluents from metal mines on aquatic ecosystems in Canada. A literature review', *Fisheries and Marine Service, Canada. Technical Report*. 488

COLYER, R.J. (1983) 'Aspects of the pastoral economy in pre-industrial Wales', *J. Roy. Agric. Soc. Eng.* 144: 45-60

CONDRY, W. (1981) *The natural history of Wales* (London)

CRAWSHAW, D.H. (1984) 'The effect of acid run-off on the chemistry of streams in Cumbria', *North West Water Rivers Division Report.* TSN84/3

DAVIES, E. (1935) 'Seasonal movements of sheep in Wales', *Journal of the Manchester Geographical Society.* 45: 24-40

DAVIES, E. (1973) 'Hendre and hafod in Merioneth', *Journal of the Historical and Record Society.* 7: 13-27

DAVIES, W. (1813) *General view of the agriculture of north Wales* (London)

DAVIES, W. (1815) *General view of the agriculture of south Wales* (London)

DAVIES, W. (1936) 'The grasslands of Wales - a survey' in STAPLEDON, R.G. (ed) *A survey of the agricultural and waste lands of Wales* (London) pp. 13-107

DEPARTMENT of AGRICULTURE and FISHERIES FOR SCOTLAND (1977) *A guide to good muirburn practice* (Edinburgh)

DODD, A.H. (1926) 'The enclosure movement in north Wales', *Bull. Bd. Celtic Studies.* 3: 210-238

DODD, A.H. (1968) *A history of Caernarvonshire* (Caernarvon)

DRABLOS, D. and SEVALDRUD, I. (1980) 'Lake acidification, fish damage, and utilization of outfields. A comparative survey of six highland areas, southeastern Norway', in DRABLOS, D. and TOLLAN, A. (eds) *Ecological impact of acid precipitation, SNSF project report* (Oslo) pp. 354-355

DRABLOS, D., SEVALDRUD, I. and TIMBERLID, J.A. (1980) 'Historical land-use changes related to fish status development in different areas in southern Norway', in DRABLOS, D. and TOLLAN, A. (eds) *Ecological impact of acid precipitation, SNSF project report* (oslo) pp. 367-370

EMERY. S.V. (1965) 'A note on the sheep - cattle ratio in Snowdonia, 1570', *University College of Wales, Aberystwyth, Symposia in Agricultural Meteorology, Memorandum.* 8: 54-55

EVANS, Rev. J. (1812) *The beauties of England and Wales, Vol. 17, north Wales* (London)

EVERETT, A.G. (1983) 'The complexity of the acid rain - surface water acidity problem', paper presented at the Twelth International Conference on the Unity of the Sciences. (Chicago)

FRITZ, S.C., STEVENSON, A.C., PATRICK, S.T., APPLEBY, P.G., OLDFIELD, F., RIPPEY, B., DARLEY, J. and BATTARBEE R.W. (1986) 'Palaeoecological evaluation of the acidification of Welsh lakes. I: Llyn Hir, Dyfed', *Palaeoecology Research Unit, University College London, Research Paper.* 16

FRITZ, S.C., STEVENSON., A.C., PATRICK, S.T., APPLEBY, P.G., OLDFIELD, F., RIPPEY, B., DARLEY, J. and BATTARBEE, R.W (1987) 'Palaeoecological evaluation of the acidification of Welsh lakes. VI: Llyn Eiddew Bach, Gwynedd', *Palaeoecology Research Unit, University College London, Research Paper.* in press.

GIMMINGHAM, C.H. (1971) 'Calluna heathlands: use and conservation in the light of some ecological effects of management', in DUFFEY, E. and WATT, A.S. (eds) *The scientific management of animal and plant communities for conservation* (Oxford) pp. 91-103

GORHAM, E., BAYLEY, S.E. and SCHINDLER, D.W. (1984) 'Ecological effects of acid deposition upon peatlands: a neglected field in "acid-rain" research', *Can. J. Fish. Aquat. Sci.* 41: 1256-1268

GRANT, S.A., BOLTON, G.R. and TORVELL, L. (1985) 'The responses of blanket bog vegetation to controlled grazing by hill sheep', *J. Appl. Ecol.* 22: 739-751

GRIFFITH, M. (1945) 'Sheep farming in Wales', in THOMAS, J.F.H. (ed) *Sheep* (London)

GRIEVE, I.C. (1978) 'Some effects of the plantation of conifers on a freely drained lowland soil, Forest of Dean', *Forestry.* 51: 21-28

GRUBB, P.J. and SUTER, M.B. (1971) 'The mechanism of acidification of soil by calluna and ulex and the significance for conservation', in DUFFEY, E. and WATT, A.S. (eds) *The scientific management of animal and plant communities for conservation* (Oxford) pp. 115-133

GRUBB, P.J., GREEN, H.E. and MERRIFIELD, R.J.C. (1969) 'The ecology of chalk heath: its relevance to the cacicole - calcifuge and soil acidification problems', *J. Ecol.* 57: 175-212

HARPER, J.L. (1971) 'Grazing, fertilizers and pesticides in the management of grasslands', in DUFFEY, E. and WATT, A.S. (eds) *The scientific management of animal and plant communities for conservation* (Oxford) pp. 15-31

HARRIMAN, R. and MORRISON, B. (1980) 'Ecology of acid streams draining forested and non-afforested catchments in Scotland', in DRABLOS, D. and TOLLAN, A. (eds) *Ecological impact of acid precipitation, SNSF project report* (Oslo) pp. 312-313

HARRIMAN, R. and MORRISON, B.R.S. (1982) 'Ecology of streams draining forested and non-forested catchments in an area of central Scotland subject to acid precipitation', *Hydrobiologia.* 88: 251-263

HARRIMAN, R. and WELLS, D.E. (1985) 'Causes and effects of surface water acidification in Scotland', *J. Wat. Pollut. Control.* 84: 215-222

HARRY, E.L. (1939) 'Some aspects of the sheep industry in Wales', *Welsh Journal of Agriculture.* 15: 129-150

HOLLIDAY, L.A. (1940) 'Merioneth', in STAMP, L.D. (ed) *The land of Britain* (London) part 33

HORNUNG, M. (1984) 'Precipitation - canopy and soil - water interactions', *Institute of Water Pollution Control and Institution of Water Engineers and Scientists joint meeting on acid rain* (Birmingham)

HORNUNG, M. (1985) 'Acidification of soils by trees and forests', *Soil use and Management.* 1: 24-27

HORNUNG, M. and NEWSON, M.D. (1986) 'Upland afforestation: influences on stream hydrology and chemistry', *Soil Use and Management.* 2: 61-65

HOWELL, E.J. (1946a) 'Cardiganshire', in STAMP, L.D. (ed) *The land of Britain* (London) part 40

HOWELL, E.J. (1946b) 'North Wales', in STAMP, L.D. (ed) *The land of Britain* (London) parts 41-43

HUGHES, R.E, DALE, J., WILLIAMS, E. and REES, D.I. (1973) 'Studies in sheep population and environment in the mountains of north-west Wales. I The status of the sheep in the mountains of north-west Wales since mediaeval times', *J. Appl. Ecol.* 10: 113-132

HUGHES, R.E., DALE, J., MOUNTFORD, M.D. and ELLIS-WILLIAMS, I (1975) 'Studies in sheep populations and environment in the mountains of north-west Wales. II Contemporary distribution of sheep populations and environment', *J. Appl. Ecol.* 12: 165-178

HUNTER, R.F. (1958) 'Hill land improvement', *Advmt. Sci.* 15: 194-196

JONES, J.R.E. (1958) 'A further study of the zinc-polluted river Ystwyth', *J. Anim. Ecol.* 27: 1-14

JONES, A.N. and HOWELLS, W.R. (1975) 'The partial recovery of the metal-polluted river Rheidol', in CHADWICK, M.J. and GOODMAN, G.J. (eds) 'The ecology of resource degradation and renewal', *British Ecol. Soc. Symp.* 15: 443-459 (Oxford)

JONES, V.J., STEVENSON, A.C. and BATTARBEE, R.W. (1986) 'Lake acidification and the land-use hypothesis: a mid-post-glacial analogue', *Nature.* 322: 157-158

KAIN, R.J.P. and PRINCE, H.C. (1985) *The tithe surveys of England and Wales* (Cambridge)

KAY, G. (1794) *General view of the agriculture of north Wales* (Edinburgh)

KINAKO, P.D.S. and GIMMINGHAM, C.H. (1980) 'Heather burning and soil erosion on upland heaths in Scotland', *J. Environ. Mgmt.* 10: 277-284

KING, J. (1977) 'Hill and upland pasture', in DAVIDSON, J. and LLOYD, R. (eds) *Conservation and agriculture* (Chichester) pp. 95-119

KORYAK, M., SHAPIRO, M.A. and SYKORA, J.L. (1972) 'Riffle zoobenthos in streams receiving acid mine drainage', *Water Res.* 6: 1239-1247

KREISER, A., STEVENSON, A.C., PATRICK, S.T., APPLEBY, P., OLDFIELD, F., RIPPEY, B., DARLEY, J. and BATTARBEE, R.W. (1986) 'Palaeoecological evaluation of the recent acidification of Welsh lakes. II. Llyn Berwyn, Dyfed', *Palaeoecology Research Unit, University College London, Research Paper.* 18

KREISER, A., STEVENSON, A.C., PATRICK, S.T., APPLEBY, P., OLDFIELD, F., RIPPEY, B., DARLEY, J., and BATTARBEE, R.W. (1987) 'Palaeoecological evaluation of the recent acidification of Welsh lakes. IX. Llyn Cwm Mynach, Gwynedd', *Palaeoecology Research Unit, University College London, Research Paper.* in press

KRUG, E.C. and FRINK, C.R. (1983) 'Acid rain on acid soil: a new perspective', *Science.* 221: 520-525

LA ZERTE, B.D. and DILLON, P.J. (1984) 'Relative importance of anthropogenic versus natural sources of acidity in lakes and streams of central Ontario', *Can. J. Fish. Aquat. Sci.* 41: 1664-1677

LLOYD, T. and TURNOR, D. (1794) *General view of the agriculture of Cardigan* (London)

MATHER, A.S. (1978) 'Patterns of afforestation in Britain since 1945', *Geography.* 63: 157-166

MATHER, A.S. (1983) 'Land deterioration in upland Britain', *Progress in Physical Geography.* 7: 210-228

MAYER, R. and ULRICH, B. (1974) 'Conclusions on the filtering action of forests from ecosystem analysis', *Oceologia Plantarum.* 9: 157-168

MESSENGER, A.S. (1980) 'Spruce plantation effects on soil moisture and chemical element distribution', *Forestry Ecology and Management.* 3: 113-125

MILLER, H.G. (1985) 'The possible role of forests in streamwater acidification', *Soil Use and Management.* 1: 28-29

MILLER, H.G. and MILLER, J.D. (1983) 'The interaction of acid precipitation and forest vegetation in northern Britain', *Water Quality Bulliten.* 8: 121-126

MILNER, N.J. and JONES, B.E. (1985) 'Sport fisheries and biology of brown trout in some north Wales lakes: with special reference to the effects of acid water', *Welsh Water Authority Area Fisheries Technical Unit (North) Report.* 85/1

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD. (1980) 'The classification of land inthe hills and uplands of England and Wales', *MAFF Booklet* 2358

MOORE, P.D. (1966) 'Stratigraphical investigation of upland peats in western Wales', unpubl. PhD. thesis, Univ. College Wales, Aberystwyth.

MORGAN, C. (1959) 'The effect of parliamentary enclosure on the landscape of Caernarvonshire and Merioneth', unpubl. Ph.D. thesis, Univ. College Wales, Aberystwyth

NEWBOULD, P. (1985) 'Improvement of native grasslands in the uplands', *Soil Use and Management.* 1: 43-49

NEWSON, M.D. (1984) 'Slope and channel runoff processes in upland catchments: interfaces between precipitation and streamflow acidity', *Institute of Water Pollution Control and Institution of Water Engineers and Scientists joint meeting on acid rain.* (Birmingham)

NIHLGARD, B. (1971) 'Pedological influence of spruce planted on former beech forest soils in Scania, southern Sweden', *Oikos.* 22: 302-314

NILSSON, S.I., MILLER, H.G. and MILLER, J.D. (1982) 'Forest growth as a possible cause of soil and water acidification: an examination of the concepts', *Oikos.* 39: 40-49

ORMEROD, S.J. and EDWARDS, R.W. (1985) 'Stream acidity in some areas of Wales in relation to historical trends in afforestation and the usage of agricultural limestone', *J. Environ. Mgmt.* 20: 189-197

OVERREIN, L.N., SEIP, H.M. and TOLLAN, A. (eds) (1981) *Acid precipitation - effects on forest and fish. Final reports of the SNSF project.* (Oslo)

PARRY, M. and SINCLAIR, G. (1985) 'Mid Wales uplands study', *Countryside Commission Report.* CCP 177

PARRY, M.L., BRUCE, A. and HARKNESS, C.E. (1982) 'Changes in the extent of moorland and roughland in northern Snowdonia national park', *Surveys of Moorland and Roughland Change, Moorland Change Project, Univ. Birmingham.* 8

PATRICK, S.T. and STEVENSON, A.C. (1986) 'Palaeoecological evaluation of the recent acidification of Welsh lakes. III. Llyns Conwy and Gamallt, Gwynedd', *Palaeoecology Research Unit, University College London, Research paper.* 19

PATRICK, S.T., FRITZ, S., STEVENSON, A.C., APPLEBY, P., OLDFIELD, F., RIPPEY, B., DARLEY, J. and BATTARBEE, R.W. (1987a) 'Palaeoecological evaluation of the recent acidification of Welsh lakes. V. Llyn y Bi, Gwynedd', *Palaeoecology Research Unit, University College London, Research Paper.* in press

PATRICK, S.T., FRITZ, S., STEVENSON, A.C., APPLEBY, P., OLDFIELD, F., RIPPEY, B., DARLEY, J. and BATTARBEE, R.W. (1987a) 'Palaeoecological evaluation of the recent acidification of Welsh lakes. VIII. Llyn Llagi, Gwynedd', *Palaeoecology Research Unit, University College London, Research Paper.* in press

PENNANT, T. (1810) *Tours in Wales.* (London)

PENNINGTON, W. (1984) 'Long-term natural acidification of upland sites in Cumbria: evidence from post-glacial lake sediments', *Freshwater Biological Association Annual Report.* 52: 28-46

RAWES, M. (1983) 'Changes in two high altitude blanket bogs after cessation of sheep grazing', *J. Ecol.* 71: 219-235

ROBERTS, R.A. (1959) 'Ecology of human occupation and land use in Snowdonia', *J. Ecol.* 47: 317-323

ROSENQVIST, I. TH. (1977) *Acid soil - acid water* (Oslo)

ROSENQVIST, I. TH. (1978) 'Alternative sources for the acidification of river water in Norway', *Science of the Total Environment.* 10: 39-49

ROSENQVIST, I. TH. (1980) 'Influence of forest vegetation and agriculture on the acidity of fresh water', in PFAFFLIN, J.R. and ZIEGLER, N. *Advances in environmental science and engineering* (New York) pp. 56-79

ROSENQVIST, I. TH. (1981) 'Importance of acid precipitation and acid soil in freshwater lake chemistry', *Vann.* 4: 402-409

ROSENQVIST, I. TH., JORGENSEN, P. and RUESLATTEN, H. (1980) 'The importance of natural H^+ production for acidity in soil and water', in DRABLOS, D. and TOLLAN, A. (eds) *Ecological impact of acid precipitation, SNSF project report* (Oslo) pp. 240-241

ROWELL, D.L. and WILD, A. (1985) 'Causes of soil acidification: a summary', *Soil Use and Management.* 1: 32-33

ROWLANDSON, T. (1846) 'Agriculture of north Wales', *J. Roy. Agric. Soc.* 7: 553-588

ROYAL COMMISSSION ON LAND IN WALES AND MONMOUTHSHIRE (1896) *Report of the Commission* (London)

STEVENSON, A.C., FRITZ, S., PATRICK, S.T., APPLEBY, P., OLDFIELD, F., RIPPEY, B., DARLEY, J. and BATTARBEE, R.W. (1987a) 'Palaeoecological evaluation of the recent acidification of Welsh lakes. IV. Llyn Gynon, Dyfed', *Palaeoecology Research Unit, University College London, Research paper* in press

STEVENSON, A.C., FRITZ, S., PATRICK, S.T., APPLEBY, P., OLDFIELD, F., RIPPEY, B., DARLEY, J. and BATTARBEE, R.W. (1987b) 'Palaeoecological evaluation of the recent acidification of Welsh lakes. VII. Llyn Dulyn, Gwynedd', *Palaeoecology Research Unit, University College London, Research Paper* in press

STONER, J.H. and GEE, A.S. (1985) 'The effects of forestry on water quality and fish in Welsh rivers and lakes', *Journal of the Institution of Water Engineers and Scientists.* 39: 27-45

STONER, J.H., GEE, A.S. and WADE, K.R. (1984) 'The effects of acidification on the ecology of streams in the upper Tywi catchment in west Wales', *Environ. Pollut. Ser. A.* 35: 125-157

TALLIS, J.H. (1973) 'Studies on southern Pennine peats', *J. Ecol.* 61: 1-22

THOMAS, C (1965) 'The evolution of rural settlement and land tenure in Merioneth', unpubl. Ph.D. thesis, University College Wales, Aberystwyth

THOMAS, D. (1963) *Agriculture in Wales during the Napoleonic Wars* (Cardiff)

TIMBERLID, J.A. (1980a) 'Have changes in use of land influenced the regional lake acidification?', in DRABLOS, D. and TOLLAN, A (eds) *Ecological impact of acid precipitation, SNSF project report* (Oslo) PP. 352-353

TIMBERLID, J.A. (1980b) 'A historical survey of the utilisation of the outlying fields in inner parts of the counties of Telemark, Agder and Rogaland', *SNSF Project Internal Report.* IR69/80

UNITED KINGDOM ACID WATERS REVIEW GROUP (1985) *Acidity in United Kingdom fresh waters.* interim report to DOE.

WALLOE, L. and OVERREIN, L.N. (1977) 'Sur nedbor og noen alternative kilder som arsak til forsuring av vassdrag', *SNSF project report.* (Oslo)

WANNOP, A.R. (1958) 'A review of hill farm problems', *Advat. Sci.* 15: 189-194

WILLIAMS, S.W. (1889) *The Cistercian abbey of Strata Florida.* (London)

PALAEOECOLOGY RESEARCH UNIT
RESEARCH PAPERS

No. 1 Patrick, S. & Battarbee, R.W. 1981 The influence of sanitary and other social changes on the eutrophication of Lough Erne since 1850: Project introduction and a consideration of the potential role of metabolic wastes. 43 pp.

No. 2 Battarbee, R.W. 1983 Diatom analysis of River Thames foreshore deposits exposed during the excavation of a Roman waterfront site at Pudding Lane, London. 18 pp.

No. 3 Patrick, S. & Battarbee, R.W. 1983 Rural sanitation in the Lough Erne catchment: History and influence on phosphorus loadings. 26 pp.

No. 4 Patrick, S. 1983 The calculation of per capita phosphorus outputs from detergents in the Lough Erne catchment. 23 pp.

No. 5 Patrick, S. 1983 Phosphorus loss at sewage works in the Lough Erne region. 36 pp.

No. 6 Flower, R.J. & Battarbee, R.W. 1983 Acid lakes in the Galloway uplands, South West Scotland: catchments, water quality and sediment characteristics. 56 pp.

No. 7 Patrick, S. 1984 The influence of industry on phosphorus loadings in the Loch Erne region. 46 pp

No. 8 Battarbee, R.W. & Flower, R.J. 1985 Palaeoecological evidence for the timing and causes of lake acidification in Galloway, South West Scotland. 79 pp.

No. 9 Raven, P.J. 1985 The use of aquatic macrophytes to assess water quality changes in some Galloway lochs: an exploratory study. 76 pp.

No. 10 Anderson, N.J. & Battarbee, R.W. 1985 Loch Fleet: bathymetry and sediment distribution. 18 pp.

No. 11 Battarbee, R.W. *et al.* 1985 Diatoms and acid lakes: proceedings of a workshop.

No. 12 Battarbee, R.W. and Renberg, I. 1985 Royal Society Surface Water Acidification Project (SWAP) Paleolimnology Programme. 18 pp.

No. 13 Raven, P.J. 1986 Occurrence of Sphagnum moss in the sublittoral of several Galloway lochs, with particular reference to Loch Fleet. 40 pp.

No. 14 Flower, R.J., Rippey, B. & Tervet, D. 1986 34 Galloway Lakes: Bathymetries, Water quality & Diatoms.

No. 15 Flower, R.J. & Nicholson, A. 1986 Bathymetries, water quality and diatoms of lochs on the island of South Uist, The Outer Hebrides, Scotland. 42pp

No. 16 Fritz, S.C., Stevenson, A.C., Patrick, S.T., Appleby, P.G., Oldfield, F., Rippey, B., Darley, J. & Battarbee, R.W. 1986 Palaeoecological evaluation of the recent acidification of Welsh lakes. I: Llyn Hir, Dyfed.

No. 17 Anderson, N.J., Battarbee, R.W., Appleby, P.G., Stevenson, A.C, Oldfield, F., Darley, J & Glover, G. (1986) Palaeolimnological evidence for the recent acidification of Loch Fleet, Galloway.

No. 18 Kreiser, A., Stevenson, A.C., Patrick, S.T., Appleby, P.G., Rippey, B., Darley, J. & Battarbee, R.W. (1986) Palaeoecological evaluation of the recent acidification of Welsh lakes: II. Llyn Berwyn, Dyfed.

No. 19 Patrick, S.T. & Stevenson, A.C. (1986) Palaeoecological evaluation of the recent acidification of Welsh lakes: III. Llyn Conwy & Llyn Gammalt, Gwynedd.

No. 20 Stevenson, A.C., Patrick, S.T., Fritz, S.C. Appleby, P.G., Rippey, B., Oldfield, F., Darley, J. Higgitt, S.R. & Battarbee, R.W. (1986) Palaeoecological evaluation of the recent acidification of Welsh lakes: IV. Llyn Gynon, Dyfed.

No. 21 Patrick, S.T. (1987) Palaeoecological evaluation of the recent acidification of Welsh lakes: V. The significance of land-use and land management.

For copies of Research Papers* or further information, please contact Dr. R.W. Battarbee, Palaeoecology Research Unit, Department of Geography, University College London, 26 Bedford Way, London WC1H OAP.
(*NB There is a nominal cost of £2 for each copy. Please make cheques payable to University College London).