CAUSES OF DECLINE OF COMMON SCOTER (*MELANITTA NIGRA*) IN NORTH SCOTLAND: EVIDENCE FROM PALAEOLIMNOLOGY

Thesis submitted for the degree of Doctor of Philosophy

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I, Hannah Jane Robson, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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ABSTRACT

The common scoter (*Melanitta nigra*) is a UK priority species that has experienced severe declines in breeding numbers over the last 30 years. The Flow Country in north Scotland is an internationally important wetland, where the decline of iconic species, such as the common scoter, is particularly concerning. This thesis takes a unique approach to investigating the causes of waterbird decline by combining detailed contemporary ecological data with geospatial modelling and palaeolimnological reconstructions.

Detailed surveys were undertaken to characterise the current physical, chemical and biological conditions within 18 Flow Country lochs. These data were used for exploratory analyses and as explanatory variables in a general linear model that examined the predictors of common scoter loch value (SLV). Statistically significant predictors of SLV proved to be dissolved organic carbon, water depth and sediment type. The landscape scale features associated with common scoter distribution in the Flow Country were explored using a species distribution modelling (Maxent) approach. Influential landscape features were found to be proportion of surrounding forestry close to a loch, the soil moisture and bedrock geology. Two theories for common scoter decline were developed using these contemporary data sources; (i) the competitive balance between brown trout and common scoter has altered in recent decades, resulting in less food, (ii) the physico-chemistry of lochs has been altered by afforestation adversely affecting physical loch structure and/or invertebrate food supply.

Theories for decline were explored using two palaeolimnological approaches. Multi-proxy top-bottom analysis of cores from 18 lochs demonstrated that these are dynamic environments which have undergone substantial change over the last 150-200 years. Multi-proxy analysis of high temporal resolution cores from four lochs indicated that the study sites have gradually become more productive over the last 150 years, with a distinct shift towards more meso-oligotrophic conditions since the 1980s. These data strongly support the theory that forestry has affected the lochs of the Flow Country, probably due to drainage and fertiliser application resulting in the lochs becoming less oligotrophic. The associated shifts in community composition could have resulted in the lochs being less profitable or suitable for common scoter who typically breed at low nutrient, oligotrophic sites

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CHAPTER 6: MULTIPROXY ANALYSIS OF LARGE BORE SEDIMENT CORES TO EXAMINE FINE RESOLUTION ENVIRONMENTAL CHANGE AT FOUR FLOW COUNTRY LOCHS AND ASSESS THE IMPLICATIONS FOR COMMON SCOTER DECLINES …………………..213

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Acronyms and abbreviations

CRS Constant Rate of Supply Model

GAM General additive model

GLM General linear model

LOI Loss on ignition

RBBP Rare Breeding Birds Panel

RSPB Royal Society for the Protection of Birds

SDM Species Distribution Modelling

SNH Scottish Natural Heritage

WWF World Wildlife Fund

WWT The Wildfowl & Wetlands Trust

XRF X-ray Fluorescence

CHAPTER 1: INTRODUCTION

1.1 Background

Freshwater is vital to human existence and supports a disproportionately large number of species (ca. 10% of species globally) relative to its surface area (<0.02% , Moss, 2010). In addition to being an important biodiversity hotspot, anthropogenic demand on freshwater is also increasing. However, the associated consequences of this increased demand include pollution, over-abstraction, the spread of invasive non-native species together with habitat loss, degradation and fragmentation (Strayer and Dudgeon, 2010). Such pressures can result in fundamental changes to both the structure and functioning of freshwaters and the species that depend on them. Species declines in freshwaters far outnumber those occurring in terrestrial and marine systems. The WWF Living Planet Report (2014) details a 76% decline in freshwater species globally since the 1970s, compared to 38% and 36% declines in terrestrial and marine species respectively (McLellan, 2014). The State of Nature Report (2013) details similar declines in British freshwaters with a 57% decline in freshwater and wetland species, 29% of which have declined strongly (Burns *et al.,*2013). The economic value of the world's wetlands is estimated at $70 billion annually (Schuyt and Brander, 2004), in addition to which wetlands are one of the most culturally valuable (and yet vulnerable) resources (Millennium Ecosystem Assessment, 2005). Declines in sensitive freshwater species leading to reductions in biodiversity can be the first, most easily discernible sign of ecosystem degradation (Dudgeon *et al.,* 2006). Research that focuses on understanding freshwater species declines and associated habitat degradation, with the potential to identify appropriate and sustainable management solutions, is both timely and important.

Wetland birds are integral to a range of ecosystem services (Green and Elmberg, 2014). They are particularly sensitive to changes in habitat quality and have therefore been shown to be key indicators of wetland health (Lehikoinen *et al.,* 2016). The common scoter (*Melanitta nigra*) is a UK priority wetland bird species that has experienced severe declines in breeding numbers over the last 30 years. Common scoter breed at oligotrophic, upland lochs. Declines in breeding numbers could be indicative of wider issues of wetland degradation in these sensitive low nutrient systems -issues such as acidification, eutrophication, erosion and climate change.

Whilst evidence to date has been able to identify some loch characteristics associated with common scoter presence in Scotland, such as high conductivity and pH and the abundance of large bodied invertebrates (Fox and Bell, 1994; Hancock *et al.,* 2015), the effects of landscape associations have only been examined at a rudimentary level (Harris, 1995). Species distribution modelling (SDM) is an approach which could be used to establish whether there are associations between landscape-scale variables and current common scoter distribution in the Flow Country. It involves examining correlations between records of species presence and environmental variables, and can be used to determine both species niches and factors predicting a species distribution. Techniques such as maximum entropy (Maxent) are particularly robust for dealing with datasets of presence-only records (Elith *et al.,* 2011), and have been successfully applied to a number of waterbird species (Maleki *et al.,* 2016; Ochoa-Quintero *et al.,* 2010; Santiago-Quesada *et al.,* 2014; Wen *et al.,* 2016). Whilst SDM approaches, such as Maxent, have the potential to provide useful insights into the landscape scale features determining common scoter distribution, there also remains a paucity of long term environmental data contemporaneous to that of scoter decline. This temporal perspective is ultimately vital if spatially correlated variables associated with competing hypotheses for decline are to be disentangled.

Palaeolimnology is a technique which can address gaps in long term environmental data. By examining information archived in lake sediments, palaeolimnology is able to examine recent environmental change over annual, decadal or longer temporal scales. Uptake of palaeolimnological approaches by the conservation community has been limited (Froyd and Willis, 2008) and examples of its use for examining waterbird decline are extremely rare (Allott *et al.,* 1994; Brooks *et al.,* 2012).

This thesis investigates the suitability of SDM and palaeolimnological approaches to fill gaps in landscape-scale and long-term datasets, with a view to addressing an issue of current conservation concern, namely the decline of the common scoter.

The Flow Country in north Scotland is an internationally important wetland (Lindsay *et al.,* 1988), and the decline here of iconic species, such as the common scoter, is particularly concerning. The common scoter population breeding in the Flow Country has been monitored more closely than at any other site in Scotland, and indeed it was in the Flow Country where concerns about declining numbers were first formally studies in Scotland (Hancock, 1991).

The first chapter of this thesis provides an overview of common scoter in Scotland, including details of population trends, breeding biology and research and conservation action to date. This is followed by a review of the species distribution modelling and palaeolimnology approaches employed in this thesis. The chapter concludes by identifying the overall focus and specific research aims, together with an outline of the thesis structure.

1.2 Common scoter

The common scoter is a medium-sized, plump-bodied diving duck. The males have black plumage and a bill with a distinctive ridge and yellow patterning (Figure 1.1). The females, with brown colouration, lack a ridged bill and have pale markings that extend along the cheeks into the neck (Cramp and Simmons, 1977). The species spends nine months of the year at sea, forming large flocks in near-shore coastal waters. In the summer they migrate inland to freshwater lakes, bogs and marshes to breed (del Hoyo *et al.,* 1992). Figure 1.2 illustrates the breeding and wintering ranges of common scoter in Europe and north Africa.

Whilst the distribution of common scoter was well documented across Europe, there was, until recently, no evidence concerning how the wintering and breeding populations overlapped and/or how much delineation existed between populations occurring in different geographic regions. In 2009 a study in Iceland began tracking the movements of breeding females using geolocators fitted to birds caught on nests. The findings from this study indicated that birds from a single breeding ground are dispersing throughout the wintering range (I.K. Peterson pers. comm.). Additionally, birds were shown to be highly site faithful, using the same wintering grounds in successive years and returning to nest within a few hundred metres of previous nest sites each year (I.K. Peterson pers. comm.). The findings from this study have now been replicated in common scoter populations breeding in both Scotland and Norway (E. Burrell and I.K. Peterson pers. comm.). Although the data currently only relate to females in the population it provides strong evidence that breeding ground declines are related to local, breeding ground issues rather than to localised wintering ground issues encountered by all birds from a particular breeding ground.

Figure 1.1 Pair of common scoter, male left and female right (photo credit P. Cranswick)

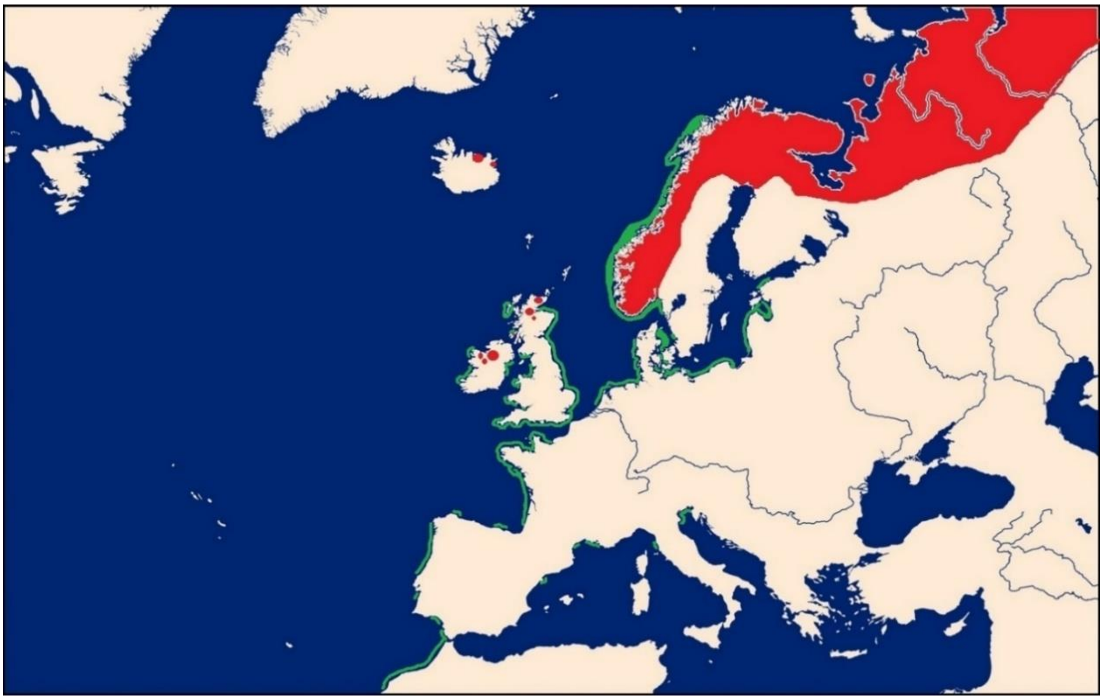


Figure 1.2 The breeding (red) and wintering (green) distribution of common scoter (*Melanitta nigra*)

1.2.1 Population trends, with a particular focus on Scotland

There are conflicting data concerning overall European common scoter population trends, although the total European population is estimated at 600,000-1,200,000

(Delany, 2006). National surveys of breeding populations indicate severe declines in Britain amounting to 47% in 12 years, (Balmer *et al.,* 2013), whilst data from Scandinavia suggest a stable or slightly increasing breeding population (Birdlife International, 2017).

The first published record of common scoter breeding in the UK is from the Flow Country in Northern Scotland in 1855 (Millais, 1913). However, it is difficult to determine whether the first records in the literature document the first occurrences of common scoter breeding in the UK or whether these early records instead are the first time the species was officially recorded. Other species of duck, such as wigeon (*Anas penelope*) and pintail (*Anas acuta*) are both thought to have colonised Scotland at a similar time (1834, wigeon and 1869, pintail (Balmer *et al.,* 2013). This appears to support the theory that duck species with a breeding range covering northern Europe and north-east Russia were colonising new sites, like the UK, on the south-western edge of their range during this time. The Scottish and Irish populations of common scoter are thought to have increased gradually throughout the early part of the twentieth century and peaked in the 1970s and 1980s (Balmer *et al.,* 2013; Gibbons *et al.,* 1993; Sharrock, 1976; Thom, 1986). Population declines and site abandonment have occurred throughout the Scottish and Irish populations since the population peak in the 1970s and 1980s.

Throughout the late 1800s and early 1900s records of breeding common scoter extended southwards from Northern Scotland. Breeding was regularly recorded in Tayside, the West Highlands and Tiree (Berry, 1939). The first record of common scoter breeding in Ireland was in 1905 at Lower Lough Erne (Holloway, 1996). The 50-year interval between first being recorded in the Flow Country and their arrival at Lough Erne (a distance of 500km) perhaps supports the theory that first colonisation was in the middle of the 1800s in Northern Scotland followed by southward progression during the latter half of the 19th century. Indeed Irish birds continued to colonise loughs in a southerly and westerly direction from Lower Lough Erne in the early part of the twentieth century (Parslow, 1973).Records for the early part of the twentieth century are accepted as being less reliable. No national, standardised surveys were conducted for breeding birds in the UK prior to 1968 and local surveys did not typically extend to remote parts of Scotland. However, overall trends of gradually increasing common scoter breeding numbers together with a southward extension of range appears plausible despite needing to be considered with some caution.

During the 1970s and early 1980s in Scotland, common scoter breeding was concentrated between the Flow Country (55 pairs) and Inverness-shire (35 pairs), Argyllshire (5 pairs in 1970), Tayside (3 pairs), Loch Lomond (peaked at 9 pairs in the mid-1970s) and Islay (7 pairs by the mid-1970s). Targeted surveys of all known and a number of potential common scoter breeding sites in Ireland were carried out in 1985 and 1986 (Ruttledge, 1987). Of the 160 loughs visited, the population (ca. 120 pairs) was found to be spread across just five sites; Lough Conn (30 pairs), Lough Cullin (24 pairs), Lough Corrib (7 pairs), Lough Ree (40 pairs); the population at Lower Lough Erne peaked in the mid-1970s with 163 pairs but by 1986 had fallen to just 11-21 pairs before final abandonment of the site. Site abandonment was also observed in the Scottish breeding population during the 1980s (Balmer *et al.,* 2013; Gibbons *et al.,* 1993), particularly at larger lochs such as Loch Lomond (Thom, 1986), which held its last breeding pair in 1987. Declines in populations were observed at the remaining Scottish sites during the 1980s, albeit relatively slowly. Invernesshire and the Flow Country remained important strongholds for the species (Batton *et al.,* 1990).

National breeding atlas data began to be collected from 1968 and is based on standardised survey approaches, with each 10km square in the UK being covered by an experienced surveyor. The format of these surveys does not, however, specifically target elusive species of duck breeding in remote locations in Scotland and it is therefore possible that estimates of total common scoter numbers may have been underestimated during this period. Whilst overall abundance figures should perhaps be treated with caution, overall trends in breeding common scoter could be considered as relatively robust for the latter part of the twentieth century. Particularly as there is strong agreement between standardised breeding atlas survey data and expert opinion in terms of the direction and timescale of population trends. Population declines in the 1980s resulted in increased survey effort in the Flow Country, particularly in relation to controversial afforestation activities taking place on the blanket bog during this time (Fox and Bell, 1994; Hancock, 1991; Hancock and Avery, 1998). The first coordinated national survey for breeding common scoter in

Britain and Ireland was undertaken in 1995 (Underhill *et al.,* 1998). All known and a random selection of potential breeding sites (approximately 400 sites in total) were visited. A total of 195 pairs was estimated for Scotland and Ireland. 100 pairs were recorded across three sites in Ireland, whilst the remaining 95 pairs were located in 23 10km grid squares across Scotland. The highest density remained in the Flow Country with 35 pairs. The range extended from the Flow Country southwards, through parts of the West Highlands and Tayside to Islay, suggesting the species range remained fairly stable since early colonisation between 1850 and 1950. Using data from the 1995 survey data and data from the Rare Breeding Birds Panel (RBBP) Gregory *et al.,* (2002) estimated a decline between 1973 and 1995 of approximately 29%. In 2007 a second national survey was carried out in Scotland, during which 600 sites (including the 400 from the 1995 survey) were visited following the same methodology as the 1995 survey. In the 12 years between surveys, the number of breeding common scoter in Scotland had declined to 52 pairs, a decline of 45% from 1995. Range constriction had also occurred with a 17% decline in the number of 10km grid squares in which breeding birds were recorded (RSPB/WWT unpublished data). The 2007 survey did not cover sites in Ireland. However, in 2012 pre-breeding and brood surveys were carried out at the four remaining known breeding sites in Ireland; Loughs Corrib, Ree, Conn/Cullin (treated as one site) and Arrow. A maximum of 39 pairs was estimated for these loughs, representing a decrease of 61% for these four sites since the mid-1980s.

Overall the evidence of breeding scoter population trends must be treated with some caution, particularly in relation to colonisation dates and early trends prior to standardised breeding bird surveys in the 1960s. Whilst it is difficult to be certain that the first records of the species breeding in the Scotland mark initial colonisation, the consistency with other similar species appears to suggest ca. 1850 is an appropriate estimate for initial colonisation. Whilst data is limited and not particularly robust for the 1850-1950 period, an overall trend of increasing numbers and southward range expansion appears highly probable based on data from a range of expert and amateur sources. This trend holds during the early period of more standardised survey effort between the 1960s and 1980 with increases in populations observed across Scotland and Ireland. Declines documented in breeding bird surveys since the

1980s have been substantiated by focused local and national common scoter breeding surveys (Hancock 1991 Underhill *et al.,* 1995, RSPB/WWT unpublished data). Recent evidence documenting the severity of recent declines and range constrictions are therefore well substantiated.

1.2.2 Breeding Biology

1.2.2.1 Site selection and nesting habitat

Common scoter breed close to oligotrophic, upland lakes, which vary in their size and landscape setting. The smallest lakes can have a surface area of less than 0.04km^2 and are typically set in low-lying moorland bogs, such as the Flow Country in Northern Scotland. Larger lakes can range from 1 to over 100km^2 and can be located at a range of altitudes from sea level up to at least 700m. Sites can also include hydro lakes whose water level fluctuates in response to anthropogenic demand. The setting of these lakes includes upland peatbogs and moorlands in addition to sub-arctic marshes/wetlands and boreal forests (Ussher 1905, Ferguson, 1968, 1971; Underhill *et al.,* 1998).

The factors influencing breeding site selection are not well understood. Variables including invertebrate food availability, substrate type and water chemistry have been compared between lakes used by breeding scoters and those which historically (but no longer) held scoter. Hancock *et al.,* (2015) examined 26 lochs across the north of Scotland and found that the presence of large bodied invertebrates was strongly associated with scoter lake use. An unpublished RSPB report based on data gathered during the 2007 survey found conductivity in Scottish breeding sites to be significantly higher than at unoccupied sites; occupied sites were also found to have a significantly higher pH than unoccupied sites. This confirmed earlier work by Fox *et al.,* (1989) and Harris, (1995) on Flow Country lochs which identified a statistically significant association between sites with high pH and conductivity (and islands) and scoter presence. Conductivity and pH can influence and be influenced by aquatic macrophyte communities, and can be used to provide an indication of a lake's trophic status, with low conductivity and acidity typically being associated with low nutrient conditions. Scottish freshwaters are under pressure from a number of anthropogenic activities, such as pollution, agriculture, fish farming, forestry, water impoundment and atmospheric deposition (Maitland *et al.,* 1994). Many of these activities can influence the abiotic and biotic characteristics of freshwaters and could have implications for species such as common scoter. However, for remote areas of Scotland, such as the Flow Country, there is a lack of long term ecological or water quality data. It is therefore not possible to determine whether significant changes in water chemistry, and consequently loch ecology, have occurred at scoter sites since declines began.

Common scoter breeding in Scotland typically construct their nests in long heather (*Calluna vulgaris*) or bilberry (*Vaccinium myrtillis*) , close to either small lakes set in moorland bogs, or in proximity to larger lakes (Sharrock, 1976). At some sites, Lomond, Islay and Lough Erne, wooded islands and peninsulas have also been used (Ruttledge, 1987; Ussher, 1905). It is difficult to assess a typical nesting distance from the shoreline. Whilst some authors have found the distance from the water's edge to be less than 20m (Sharrock, 1976), others have suggested it can be far greater, up to several hundred metres (Berry, 1939). At breeding lakes in north west Iceland, scoters nest in dwarf willow (*Salix herbacea*) and heather located in the drier areas of marshland, typically within 1km of a larger lake (Bengtson, 1970; Gardarsson, 1979, I.K. Peterson pers. comm.).

1.2.2.2 Diet

Common scoter predominantly feed in waters of less than 10m in depth on benthic invertebrates and macrophytes; the exact taxa consumed varies between marine and freshwater habitats throughout the year (Bengtson, 1971; Cramp and Simmons, 1977; Fox, 2003). When overwintering at sea, common scoters are known to favour molluscs and gastropods, of less than 4cm in length, that live on the surface or within the upper 3cm of clean, coarse sandy sediment (Fox, 2003). They are also recorded as feeding on crustaceans, annelids, echinoderms and small fish such as sticklebacks (Cramp and Simmons, 1977; Fox, 2003). The exact means of feeding is not well understood. Based on marine diet, Fox, (2003) suggests that the bill is inserted into the sediment which is then sifted or siphoned in some way. However, observations of female common scoter breeding on freshwater lochs in Scotland suggest that beds of aquatic macrophytes containing invertebrates may also be important feeding habitats (L. Griffin, pers. comm.).

Investigations into the breeding diet of common scoters has been possible at lake Myvatn in Iceland by examining stomach contents of dead birds caught in illegally applied gill nets. Stomach contents of 93 common scoter were inspected by Bengtson, (1972); chironomid larvae together with the crustaceans *Eurycercus lamellatus* and *Lepidurus arcticus* were found to be important food resources that constituted 85% of stomach contents examined. Other invertebrate components of scoter diet included the cladocera *Daphnia longispina*, and the molluscs *Pisidium caeertanum* and *Lymnea peregra*. In addition to invertebrates, three-spined sticklebacks and plant fragments (from *Cladophora aegagropila* and *Potamogeton filiformis*) were also identified. No statistically significant difference was observed between the feeding intensity of sexes upon arrival at Flow Country lochs (Hancock *et al.,* in prep). However, in Iceland Bengtson (1971) did identify differences in the composition of food consumed between the sexes and broods. Females were found to have predominantly consumed fish eggs and molluscs together with some seeds. Males too showed a preference for fish eggs, but they were also found to consume chironomids, cladocera and seeds in smaller amounts. Young ducklings were found to have consumed some adult insects indicating they spent some time surface feeding, but older ducklings were found with predominantly chironomids and cladocera as their primary food items. It is, however, difficult to generalise from findings at Myvatn as it is a very unusual site due to its thermal waters which increase productivity and result in unusually large populations of chironomids, cladocera and small fish.

A large marsh in the northern part of Aðaldal is another important breeding site for scoters in northern Iceland. It is situated less than 1.5km from the coast. Faecal analysis of incubating females from this site has shown that female birds have a diet of principally marine composition; primarily amphipods (probably *Gammarus duebeni*), together with fish eggs, sticklebacks and some vegetative material (I K Peterson, pers. comm).

Outside Iceland there is little data concerning the diet of breeding common scoter. However, a study in Northern Russia (Kondratyev, 1999) also found *Lepidurus* *arcticus* and *Eurycercus lamellatus* constituted an important part of the diet, along with Trichoptera. There are limited data from faecal analysis of birds breeding in Britain, but evidence indicates that whilst on lakes they feed on a range of aquatic invertebrates and macrophytes including Trichoptera*,* Hemiptera*,* Coleoptera and Odonata (G.M. Hilton, pers. comm.).

1.2.2.3 Climate

Climate change

Climate change is acknowledged as one of the greatest current threats to global biological diversity. Wetlands in particular are identified as being amongst the most sensitive habitat types (Erwin, 2009; Junk *et al.,* 2013). Despite this, much ornithological research focuses on terrestrial bird species. Ducks, for whom freshwaters are vital, could be particularly at risk from climate induced changes to freshwater wetlands (Guillemain *et al.,* 2013).

An extensive study of the effects of climate change on European breeding birds (including the common scoter) was conducted by Huntley *et al.,*(2007). The study used bioclimatic variables and a “middle of the road” emissions scenario (Prentice *et al.,* 2001) to predict future species distributions in the latter part of the 21st century. The climate characteristics identified as favourable for common scoter included areas where i) there is little to no annual moisture deficiency, ii) the annual sum temperature is between ca. 200 and 1000-degree days above 5°C and iii) the coldest monthly mean temperature is less than -5°C. As part of the model validation process, the same model was used to predict current distributions of common scoter across Europe. The model failed to predict current scoter breeding in either Scotland or Ireland. Common scoter have been breeding in these localities since at least the 1850s (possibly), and the failure of the model to predict their presence here could indicate that other factors, besides climate, have made these areas suitable breeding habitats, particularly as the climate data used to generate the models relates to a time of peak scoter populations in Britain.

1.2.2.4 Predation and competition

The success of breeding wildfowl is known to be effected by mammalian, avian and fish predators, with several studies demonstrating increased breeding success being associated with predator removal (Balser *et al.,* 1968; Dessborn *et al.,* 2011; Duebbert and Lokemoen, 1980; Kauhala, 2004; Schranck, 1972). Mammals including foxes, pine martins, stoats, cats, mink, and otters, together with birds such as corvids, gulls and raptors are all known to predate on both nesting females and ducklings (Ogilvie, 1975). Partridge and Smith (1988) used artificial nests to investigate predation on common scoter breeding at Lough Erne. Well concealed nests were found to be targeted less frequently by avian predators than less well concealed nests. Traylor *et al.,* (2004) also found that survival of white winged scoters (*Melanitta fusca deglandi*) nesting in North America was positively correlated with degree of concealment. Whilst avian species such as gulls (*Larus* sp.) are known to predate on scoter ducklings, being close to breeding colonies of gulls (and also terns, *Sterna* sp.) can have benefits for ground nesting ducks, like scoter. Such colonies can act as both an early warning system and protection for nesting ducks. The colonies can alert nesting females to the presence of other predators, such as mammals and raptors, and react as a group to fend off potential predators to protect their own nests and young. Hancock *et al.,*(2015) investigated the associations between the presence of both mammalian and avian predators and probability of common scoter presence at Flow Country lochs. Only one relationship was found to be statistically significant: that young broods occurred more often where there were fewer avian predators. Other associations between predator's distribution and common scoter loch use were found to be non-significant, suggesting the presence of predators is not a key driver of common scoter loch use in the Flow Country.

In addition to mammalian and avian predators, ducklings are also susceptible to predation by large fish such as pike. Dessborn *et al.,*(2011) examined the effect of pike predation on breeding ducks by monitoring wildfowl lake use before and after adult pike introduction. Whilst the number of adult pairs using the lake did not decrease following pike introduction, the abundance of ducklings on the lakes with pike did show a statistically significant decrease. Pike do not occur in Flow Country lochs but anecdotal evidence suggests pike are an issue for scoter on larger Scottish lochs in the West Highlands.

Common scoter typically breed in areas of low breeding wildfowl density, suggesting they may be poor competitors for resources. As diving ducks, scoters feed primarily in benthic habitats where their main competitors (other than diving wildfowl) are fish. In the oligotrophic lochs typically used by breeding scoter, trout, roach, pike and sticklebacks are the main fish competitors. Reduced lake use by birds resulting from increased competition for invertebrate food resources has been documented for other diving duck species (common goldeneye, *Bucephala clangula*) on oligotrophic lakes (Eriksson, 1979). The relationship between invertebrate abundance and diversity and fish can be complex, particularly when multiple fish species are involved and piscivory occurs (Sánchez-Hernández, 2015). Whilst some invertebrate groups can be reduced under fish pressure, other groups or size classes can increase as they are released from larger invertebrate or small fish predation pressure (Dobson and Frid, 2009). Fish introductions and/or management can also have indirect implications for invertebrates through changes to habitat quality or quantity (Zambrano *et al.,* 2001). Partridge, (1987) suggested roach competition may have been influential in the decline of common scoter at Lower Lough Erne. However, a number of coinciding factors (eutrophication, and the arrival of invasive mink populations) made it difficult to disentangle the individual impact of these potentially influential drivers of decline. The abundance of brown trout in Flow Country lochs has been shown to be negatively associated with the abundance of large bodied invertebrates, and additionally scoter were found to be positively associated with lochs containing large bodied invertebrates. However, no direct relationship could be established between measures of common scoter loch use and brown trout abundance (M Hancock *et al.,* 2015).

1.3 Research action to date

Research into the causes of common scoter declines was first undertaken in Northern Ireland at Lough Erne where substantial declines had been observed between the 1960s and 1980s, before the species went locally extinct in 1989. Early research in 1985 and 1986 indicated that a combination of water pollution (eutrophication) and mink predation were responsible for scoter declines. The introduction of roach to Lough Erne in the 1930s was also thought to be exacerbating the declines by putting further pressure on diminishing resources. The coincidence of events at Lough Erne made it difficult to identify the most pertinent issue for scoter (Partridge, 1989).

Although it only ever supported a maximum of nine pairs, local extinction had also occurred at Loch Lomond in Scotland by 1987 (Mitchell, 1977), and at the time this was attributed to increases in mink predation and disturbance from powerboats (Smith, 2005). However, no coordinated research was attempted. Subsequent research not related to common scoter decline has established that Lomond contemporaneously became eutrophified (Bennion *et al.,* 2004) which could also have contributed to scoter abandonment of the site.

The first research focusing on breeding common scoter in Scotland was undertaken in the late 1980s and early 1990s. With anecdotal and local evidence indicating declines, research initially focused on breeding habitat characterisation with a particular emphasis on the Flow Country (Fox *et al.,* 1989; Fox and Bell, 1994; Hancock, 1991; Harris, 1995)

Following the first national survey in 1995, the species was Red Listed and a Biodiversity Action Plan (BAP) group created with representatives including Scottish Natural Heritage (SNH), Royal Society for the Protection of Birds (RSPB) and The Wildfowl & Wetlands Trust (WWT). From this group, the following actions were identified for the support of breeding populations;

- Conduct standardised annual monitoring of breeding numbers, productivity and threats;
- Investigate breeding ecology of common scoter with a view to informing breeding loch/catchment management action and prediction of climate change effects;
- Maintain or implement appropriate site management, to be further informed by results of research.

As a result, an annual monitoring program was implemented by RSPB Forsinard reserve from 2002 which involved coordinated counts of around 100 Flow Country lochs and pool systems during 3 key periods of the breeding season. The first large scale research project into common scoter declines in Scotland took place between

2009 and 2011, and was led by RSPB with involvement from WWT, SNH and BTCV Scotland. The study sites included 26 lochs across the two remaining stronghold areas of the Flow Country (20 sites) and the West Highlands (6 sites). The sites were equally split between those which had consistently held breeding scoter since the 1980s and those which had scoter during the 1980s and early 1990s but which had not had records of breeding scoter since 2000. The aims of this research were to gather detailed data on scoter use within the lochs, together with larger scale spatial patterns in scoter distribution between lochs in particular in relation to aquatic invertebrate abundance, fish competitors and the presence of predators. A key finding of this research was that female scoters were found to be positively associated with lochs containing greater numbers of large bodied invertebrates. Suggesting food supply was a key influence on female scoter loch use. In addition, fewer large fish (brown trout) and more small fish (stickleback) were also found be positively associated with lochs containing more large-bodied invertebrates. This could indicate either that large bodied invertebrates experience reduced predation pressure from large trout which instead feed upon larger prey (such as small trout and/or stickleback). Changes in fish population structure could therefore have implications for common scoter who feed on the same invertebrate food resources. However, the study was unable to identify any statistically significant relationship between common scoter and brown trout or stickleback populations. The fish survey method employed (rod and line surveys for a standardised time period) made it difficult to establish with confidence whether any of the lochs was in fact without fish, particularly as other sources (such as estate stocking data and trout fishing literature e.g. Sandison, 2015) suggested several lochs where no fish were caught, did in fact contain fish. Ultimately, changes in the abundance of either trout or key resources (such as invertebrates) since the start of common scoter declines could not be established using contemporary data sources which left important questions unanswered concerning the influence of fish. Further research focusing on the impact of brown trout on common scoter in the Flow Country began in 2014, when the RSPB began experimentally increasing fishing pressure on a number of Flow Country lochs with the aim of assessing the impact of reduced brown trout numbers on the abundance of freshwater invertebrates and common scoter. The results of this study are not currently available at the time of writing.

Since concerns around declines were first raised, research has focused on spatial comparisons between lochs used by scoter and control lochs (either historically used or similar ecologically). Whilst this approach has enabled characterisation of lochs used by breeding scoter it has not been able to identify links between key resources and landscape or climate drivers, nor has it been possible to establish the extent of change in the lochs either physically or biologically over the time of decline. This thesis aims to use multidisciplinary approach to address this. The main methods employed will be reviewed in the following sections.

1.4 Species distribution modelling

1.4.1 Overview and applications

Species distribution models (SDMs) can be used to gain ecological insights into species niches, understand relationships between a species and its environment, and test hypotheses concerning ranges and distributions (Franklin, 2010). Determination is based upon correlations between recorded species presences and a variety of habitat or climatic variables. The technique commonly results in the production of maps representing habitat suitability at landscape, regional, global or temporal scales. The approach can be used in a conservation context to assess the impacts of habitat degradation (Convertino *et al.,* 2014) or restoration (Wilson *et al.,* 2011), predict species responses to issues such as climate change (Loarie *et al.,* 2008; Milanovich *et al.,* 2010), and can also be used to evaluate the colonisation of new or re-introduced species (Adhikari *et al.,* 2012). Applying SDMs to freshwater research has the additional benefit of enabling links between within system features (such as aquatic community abundance and/or composition) and potential landscape drivers (such as catchment land use or geology) to be highlighted.

Maximum entropy (Maxent) is a robust generative SDM approach, comparable to GLMs and GAMs. However, unlike these discriminative (GLM and GAM) approaches the maximum entropy approach does not require knowledge of species absences, and can function using a relatively small amount of training data (Franklin, 2010). Maxent was specifically designed to use species-only data to model the relative suitability of a site (rather than the probability of species occurrence at a site). It also generates environmental response functions which detail the likelihood of species presence at different environmental gradients, which can provide useful insights into species niches. The Maxent approach has been shown to outperform other presence-only modelling methods (such as GARP and BIOCLIM (Elith *et al.,* 2011; Phillips and Dudík, 2008)), and has been used extensively in both freshwater (Ba *et al.,* 2011; Kumar *et al.,* 2009; Pittman and Brown, 2011) and water bird research (Ochoa-Quintero *et al.,* 2010; Wen *et al.,* 2016)

1.5 Palaeolimnology

1.5.1 Overview

A paucity of long term monitoring data is a problem common to many research projects examining species decline. However, because wetlands and many aquatic systems preserve a record of their development over time it is possible to extend the range of modern day freshwater datasets by complementing contemporary data with that derived from lake sediment cores, thus providing a temporal perspective. Lake sediments are composed of both allochthonous and autochthonous materials. In lentic systems sediment accumulates on the lake bottom in a depth-time sequence, with older materials being found at deeper sediment depths and more recent sediments nearer to the surface (Smol, 2008). Palaeolimnology involves the analysis of an undisturbed core of sediment taken from the accumulation zone of a waterbody. The core can then be subsampled or sliced to provide different time-depth intervals. The palaeolimnological approach can provide direct evidence of community composition (by reconstructing species distributions and abundance), and indirect indications of the physio-chemical conditions (by complementing ecological knowledge or using transfer functions). Whilst single indicators can provide useful insights, the benefits of multi-indicator studies to enable the interpretation of complex and dynamic freshwater environments is now well established (Birks and Birks, 2006; Sayer *et al.,* 2000).

1.5.2 Core Chronology

Accurate dating of lake sediments is vital in palaeolimnological studies. Establishing the temporal scale and resolution of a core determines which research questions can be addressed, and assigning a date to each core slice enables interpretation of the archived remains (Oldfield and Appleby, 1984). The most commonly used methods for dating lake are sediments radiometric analyses. These methods are based on the rapid uptake of atmospheric radioisotopes by lake sediments. By determining rates of isotopic decay the age of sediment along the length of a core can be determined (Appleby, 2002). For longer (<200 year) timescales C^{14} is used, as it has a decay half-life of 5,730 years; for studies examining short timescales (150-200 years) ^{210}Pb is the most commonly used isotope, with its half-life of about 22 years. In addition to these naturally occurring radioisotopes, anthropogenic markers can also be identified in recent sediments, in particular the nuclear weapons testing peak in 1963 and the Chernobyl nuclear power station accident in 1985. Both events led to a large release of radioisotopes and the associated peak in the record is commonly used to validate and strengthen ^{210}Pb dating models (Appleby, 2008). Radiometric analysis of sediments is a costly and time intensive process. Alternative methods have been developed for recent sediments using other anthropogenic markers from atmospheric pollution such as Spheroidal Carbonaceous Particles (SCPs) (Rose, 1998) and heavy metals (Callender and Metre, 1997). Whilst these approaches are less costly they also provide a less precise date for sediment records.

1.5.3 Non-biological indicators

Initial analysis of lake sediment cores typically involves examination of core lithostratigraphy, physical characterisation and geochemical methods for determination of compounds such as heavy metals, SCPs and isotope concentrations (Appleby, 2002; Boyle, 2001; Last and Smol, 2006; Meyers and Teranes, 2002).

Lithostratigraphic techniques include the determination of dry weight, wet density and organic matter content for samples along the length of a core, all of which can give an indication of the cores stratigraphy and whether sediment mixing may have occurred. Lithostratigraphic profiles can also be used to cross-correlate multiple cores taken from the same system (Berglund, 1986).

Geochemical palaeolimnological techniques have been used to examine concentrations of heavy metals in freshwaters, particularly in relation to those from anthropogenic sources such as smelting and mining of metal ores and burning of fossil fuels (Smol, 2008). Metals entering aquatic systems via both atmospheric and/or groundwater/catchment sources are readily deposited in lake sediments, and consequently the concentrations of metals in the sediments are typically higher than those present in the water column (Boyle, 2002). Whilst some metals have been shown to be mobile post-deposition (and therefore difficult to interpret palaeolimnologically) others (such as Pb) are less mobile and can be used to examine trends in metal pollution at both local and regional scales from diffuse and point sources (Blais *et al.,* 1999; Olli and Destouni, 2008; Steinnes *et al.,* 1997). Trends in metal concentrations in lake sediments have primarily been used to determine the effects of metal pollution on aquatic organisms, identify sources, and determine the effectiveness of pollution regulations. However, observable trends in heavy metals concentrations related to anthropogenic sources can also be used to estimate the dates of recent sediments. Recent profiles of, for example, Pb, show steadily increasing concentrations from the onset of industrialisation (ca. 1850), with more rapid increases associated with the middle of the 20th century until approximately 1970-80 following which a decline is observed coincident with and resulting from the introduction of air quality regulations (Smol, 2008).

1.5.4 Biological indicators

A wide range of biological indicators can be used in palaeolimnological studies. Remains examined include those derived from within both the lake itself and its catchment. For a biological indicator to be useful in a palaeolimnological context it needs to leave remains in the sediment that are identifiable and robust enough to withstand degradation. A well-developed understanding of species/taxa tolerances is also necessary to establish the ecological implications of the observed communities (Cohen, 2003).

Algae are an important biological indicator used in palaeolimnological studies, particularly diatoms. Whilst, as a group, diatoms are able to tolerate a wide range of freshwater and marine environments, individual species have discernible tolerance ranges, particularly in relation to chemical variables such as pH and total phosphorus (TP). Diatoms are excellent palaeolimnological indicators because they are able to colonise habitats and reproduce rapidly, they are sensitive to shifts in habitat and water chemistry and their silica valves are resistant to degradation meaning they preserve well even in ancient sediments (Battarbee *et al.,* 2001).

Invertebrates in freshwaters represent many different levels within freshwater food webs, and inhabit every possible niche. Common remains examined by palaeolimnologists include Cladocera*,* Ostracods*,* Chironomids and other Diptera well as the chitinous remains of other groups of macroinvertebrate such as Trichopera*,* Ephemeroptera and Coleoptera (Smol *et al.,* 2001). The remains left by these groups can be difficult to identify to species or even genus level and therefore their use as palaeolimnological indicators has developed more slowly than the other indicator groups.

Remains from vertebrates, such as fish are not commonly found in large numbers in sediment cores, primarily due to the relatively small volume of sediment associated with each slice. However recent developments in coring techniques have included the development of wide bore corers (such as Big Ben, Patmore *et al.,* (2014) which enables a greater volume of sediment to be collected in each slice, and fish remains such as scales, teeth and bones have been identified (Sayer *et al.,* 2016).

1.5.5 Applications

The application of palaeolimnological approaches has progressed and become more refined as technologies and methods have been developed. An overview is provided here, with a focus on shallow lakes and waterbird declines.

One of the first and most extensive applications of palaeolimnology focused on the acid rain debate. Problems arising from acid rain were identified as early as the 1950s (Smol, 2008). However, tying down the source of acidification and understanding its extent was problematic without long term environmental monitoring data. Lake sediment records were able to fill this gap in knowledge, palaeolimnological methods were used to establish the timing of acidification, to disentangle the potential causes and to establish how current acidity was placed within long term levels of natural variability. The data from palaeolimnological studies were also able to establish the effects of acidification on lake ecology and assess the effects of emissions reductions (Battarbee and Howells, 1990; Battarbee *et al.,* 2005)

Similarly, the effects of eutrophication, including toxic algal blooms, increased aquatic macrophytes/periphyton biomass, detrimental alterations to water quality and fish kills (resulting from decreased oxygen levels), were of growing concern in the latter part of the 20th century (Smol, 2008). Palaeolimnology used a combination of chemical, physical and biological techniques and transfer functions to track changes caused by eutrophication events, infer past levels of key nutrients and importantly identify the causes of eutrophication (Bennion *et al.,* 1996b).

Palaeolimnology also plays an important role in the implementation of the European WFD, which requires reference conditions to be determined for water bodies, from a range of different trophic states, against which current ecological status can be measured. Palaeolimnology is named specifically as a technique suitable for establishing the reference conditions of lakes, and has been used in a number of studies (Bennion *et al.,* 2010; Bjerring *et al.,* 2008; Dalton *et al.,* 2009).

When the principal aim of a project is to establish the degree of change at a site, fine scale temporal resolution is not always necessary or cost effective. Instead a top-bottom palaeolimnological approach can be employed (Bennion *et al.,* 2004). This involves comparing a slice of sediment from the top of a core (representing present day conditions) with a sample from close to the bottom of the core (to represent historic or pre-industrial conditions). In addition to WFD applications, the top-bottom approach can be useful in studies examining broad scale changes across several sites, and has been successfully applied to examine change in response to metal pollution (Brooks *et al.,* 2005), long term oxygen conditions (Kurek *et al.,* 2012), and eutrophication (Dixit *et al.,* 2011).

Transfer functions have been pivotal to debates such as acid rain and eutrophication. However, in a conservation context the reduction of complex lake processes and relationships can be less informative than a multi-indicator approach (Sayer *et al.,* 2010). By combining ecological knowledge and evidence from multiple palaeolimnological indicators at different trophic levels, the management of shallow lakes can be based on more comprehensive evidence that takes account of both direct and indirect relationships between communities and physical, chemical and temporal processes.

A number of studies have sought to link contemporary research with palaeolimnological datasets (Ayres *et al.,* 2007; Sayer *et al.,* 2012; Sayer *et al.,* 2010). However, this cross-disciplinary field is only developing slowly (Davies and Bunting, 2010; Froyd and Willis, 2008). The advantages of such a holistic, multi-proxy approach used in conjunction with firm autecological understanding have been demonstrated in several studies, and have highlighted the multiple factors that were regulating freshwater systems, emphasising the dynamic and complex nature of these habitats (Sayer *et al.,* 2012).

1.5.5.1 Shallow lakes and conservation management

Much early palaeolimnological work centred around relatively large, deep lakes where the time-depth sequence of sediment deposition was likely to be undisturbed by physical or biological mixing. Whilst it is acknowledged that issues such as sediment mixing are more likely to arise in shallow lakes (Bloesch, 1995), results of poorly dated or disturbed cores have not typically been published, and it is therefore difficult to assess the extent to which shallow lake work is hampered by such processes. There are, however, an increasing number of examples of palaeolimnological studies being successfully carried out in shallow lake and pond systems, particularly in relation to restoration and conservation management (Ayres *et al.,* 2007; Bennion *et al.,* 1996a; Rawcliffe *et al.,* 2010; Sayer *et al.,* 2010).

Despite some studies providing a good basis for further cross disciplinary work there remains little link up between the palaeolimnological and conservation communities. Of the 100 questions of conservation importance identified by Sutherland *et al.,*(2006), Davies and Bunting (2010) identified 54 that could benefit from palaeoecological datasets because they required consideration of long term data, natural variability and/or establishment of baseline conditions. The use of palaeolimnology in conservation management is a slowly growing field despite its applicability being recognised more than 20 years ago (Smol, 1992). Gillson and Marchant, (2014) suggest that the underuse of palaeoecological data in contemporary management is a result of datasets that are “not accessible or amenable". Davies and Bunting (2010) identify a lack of familiarity with the respective fields as another reason preventing collaborative working between palaeoecologists, researchers and practitioners.

1.5.5.2 Waterbird declines

There are relatively few examples of studies that use palaeolimnological techniques to examine species declines to inform conservation management. Studies commonly focus upon community level shifts in taxa that leave remains in the sediment, such as cladocera, macrophytes and invertebrates (Davidson *et al.,* 2011; Langdon *et al.,* 2010; Sayer *et al.,* 2010). Two key examples of the application of palaeolimnological data being used to understand waterbird decline include Allott *et al.,* (1994) and Brooks *et al.,* (2012). Allott *et al.,* (1994) used palaeolimnological techniques to examine water quality changes in lochs occupied by black throated divers (*Gavia arctica)*. They were able to identify sites which had experienced acidification, nutrient enrichment and the effects of local afforestation. This study provided the first evidence of environmental change in Flow Country lochs, however it did not relate this change specifically to changes in black throated diver abundance or distribution. However, a more recent study of the fluctuating Slavonian Grebe (*Podiceps auritus*) population at Loch Ruthven specifically linked ecological change within the loch and changes in grebe breeding success (Brooks *et al.,* 2012). Lake productivity and chironomid abundance were found to have increased over the last 100 years. Grebe productivity had been monitored annually since the 1970s and it was found to fluctuate in a pattern that followed chironomid abundance. The fluctuations in chironomid abundance were shown to be correlated with diatom-inferred total phosphorus concentrations rather than climate variation.

1.6 Overall focus and specific research aims

Species decline is a growing priority for conservationists and therefore identifying anthropogenic pressures and ameliorating their impacts is a key concern for wetland conservation, particularly as the recognition of wetland value increases. The common scoter is a Red Listed breeding species, and is a priority for UK conservation. The decline of common scoter may also be indicative of wider wetland degradation.

The lack of both detailed contemporary limnological data and landscape characterisation mean that it is not currently possible to accurately determine levels of heterogeneity between Flow Country lochs, or determine how this could be influencing current common scoter loch use. The difficulties in disentangling drivers of decline are further compounded by the fact that no historic limnological data exist relating to the period either prior to, or contemporaneous with common scoter decline. To address these key gaps in knowledge, data are needed from a range of spatial and temporal scales. Detailed physical, chemical and biological survey data will improve the understanding of common scoter decline, particularly if subtle influences on the degree of common scoter loch use are operating. Combining detailed limnological survey data with an understanding of how landscape scale features can influence common scoter distribution, will also highlight important links between landscape scale features and within loch processes. In addition to these two spatial scales, data from a range of temporal perspectives have the potential to address current knowledge gaps and inform conservation efforts. With regional climate models failing to reflect current common scoter distributions (Huntley *et al.,* 2007), an investigation into the possible effects of annual climate variation could provide more useful insights into the future persistence of common scoter in Scotland. Assessing the extent and type of environmental change experienced at common scoter lochs over the last 150-200 years has the potential to add to our understanding of current levels of heterogeneity between lochs. No detailed, historic survey data exist for common scoter breeding lochs, so the temporal resolution offered by a palaeolimnological perspective can provide valuable insights that may help identify the most pertinent drivers of decline

The overall aim of this research is to assess the causes of common scoter declines at an internationally important wetland using data from multiple spatial and temporal scales. Common scoter loch-use is examined firstly in the context of local, within-loch characteristics and the heterogeneity of Flow Country lochs established. The associations between common scoter distribution and within-loch features are then examined in relation to landscape scale drivers. The effects of annual climate variability on changes in common scoter numbers in the Flow Country are assessed in relation to both local (breeding ground) and regional (wintering ground) climate.

The second part of this theses adds a temporal perspective to common scoter decline by using a palaeolimnological approach to assess the extent and types of environmental change that have occurred in Flow Country lochs. The value of adding this temporal perspective to species decline research is assessed, and its potential for disentangling spatially correlated hypotheses for decline examined. The intention is that the outcomes of this research will be useful in informing, directing and prioritising both future research addressing species declines, and also conservation efforts for common scoter and the Flow Country wetlands.

Specific aims:

1. Determine levels of heterogeneity in Flow Country lochs;
2. Develop and refine hypotheses for common scoter decline in the Flow Country using within-loch data;
3. Explore the influences of landscape-scale drivers on common scoter distribution in the Flow Country and key within-loch features;
4. Examine the effect of annual climate variation on both common scoter;
5. Determine the suitability of shallow Flow Country lochs for palaeolimnological research;
6. Use a palaeolimnological top-bottom approach to determine the extent and type of environmental change in Flow Country lochs, particularly in relation to levels of current loch use by common scoter;
7. Undertake wide bore, multi-proxy palaeolimnological analyses at four Flow Country lochs to examine recent environmental change at a fine temporal resolution, and explore the implications of recent environmental change for common scoter.

1.7 Structure and outline of thesis, including specific objectives

The structure of this thesis, including an overview of each chapter is provided below; the specific aim (from section 1.6 above) addressed by each chapter is detailed, together with a more detailed list of objectives.

Chapter 2 provides details on the study area generally, site selection and the 18 study lochs more specifically. Information concerning the laboratory and field methods used in this study is also provided.

Objectives:

- To collate existing data concerning the study area and study lochs;
- To describe laboratory and field methodologies in addition to details of site selection

Chapter 3:

To address Aims 1 and 2, Chapter 3 brings together new and existing data to examine the between-loch variability of 18 Flow Country lochs in terms of physical, chemical and biological parameters. This chapter then examines the relationship between loch features and common scoter loch-use to develop and refine hypotheses for decline.

Objectives:

- To generate a scoter loch value for each of the 18 sites, to be used in general linear modelling and data interpretation;
- To use Geographic Information Systems (GIS) to produce bathymetry and percentage macrophyte cover maps of the 18 study sites;
- To use sediment type characterisations to generate a sediment score for each loch;
- To compare water chemistry across sites and examine correlations between water chemistry variables;
- To explore macrophyte, diatom and chironomid species composition across sites;
- To use principal component analysis (PCA) (water chemistry and chironomids) and detrended component analysis (DCA) (macrophytes and diatoms) to explore the heterogeneity between Flow Country lochs;
- To use canonical correspondence analysis (CCA) with forward selection to examine the relationships between communities and environmental variables;

- To use general linear modelling approach to identify the statistically significant variables associated with common scoter loch use.

Chapter 4 addresses aim 3 and 4; a SDM approach is undertaken to explore the association between common scoter presence and landscape scale features. A general linear modelling approach is used to explore the relationship between influential landscape features and within loch characteristics important to scoter. Chapter 4 also assesses the extent to which annual climate variation influences change in common scoter numbers in the Flow Country.

Objectives:

- To use a general linear modelling approach to identify statistically significant relationships between annual climate variables (temperature, rainfall) and changes in common scoter abundance in the Flow Country;
- To use maximum entropy species distribution modelling approach to identify landscape scale features associated with lochs used by common scoter in the Flow Country;
- To use general linear modelling to determine whether there are statistically significant associations between landscape scale features and within loch characteristics.

Chapter 5 focuses on aims 5 and 6; core stratigraphy and ecological change at 18 lochs is examined using a palaeolimnological approach and the relationship to current scoter loch use is assessed.

Objectives:

- To assess the stratigraphic integrity of the cores using LOI, XRF and ^{210}Pb profiles
- To explore the dominant chironomid and diatom taxa in the tops and bottoms of the cores;
- To use DCA to examine associations between sites and dominant species in the tops and bottoms of the cores;

- To use procrustes analysis to ascertain the degree of change in chironomid and diatom communities between the top and bottoms of the cores;
- To use the procrustean randomisation test (PROTEST) to compare top-bottom ordinations for chironomids and diatom communities.

Chapter 6 addresses aim 6 it uses a multiproxy, fine resolution approach to examine recent changes in 4 Flow Country lochs in relation to the hypotheses developed for common scoter decline.

Objectives:

- To assess stratigraphic integrity using LOI, XRF and ^{210}Pb profiles from the cores;
- To determine the extent and type of environmental change at each of the four Flow Country lochs by examining changes in diatom, invertebrate, cladocera and macrophyte communities;
- To use PCA to compare the types of environmental change occurring between lochs;
- To use Constrained Incremental Sums of Squares cluster analysis (CONISS) analysis to identify statistically significant breaks in the stratigraphic data;
- Use palaeolimnological evidence to explore the theories of common scoter decline.

Chapter 7 provides a synthesis and overview of each section of this research. It brings together the findings and the implications for future management, with a particular focus on common scoter and addressing species decline.

CHAPTER 2: STUDY AREA, SITE SELECTION AND METHODS

2.1 Overview

This chapter provides a description of the study area, the Flow Country in Northern Scotland and an overview of the types of open water bodies it contains. Chapter 3 details the abiotic and biotic characteristics of each of the study sites; the current chapter therefore focuses on descriptions of the wider Flow Country area and details how the study sites were selected. Details of the field and laboratory methods used in this thesis are provided; generic numerical methods such, as data manipulation and transformations are included here, whilst details of specific analytical techniques are provided in the methods section of the relevant results chapters.

2.2 Study Area

Peatlands are important habitats that not only support a distinct and increasingly rare flora and fauna, but also provide a range of unique and valuable ecosystem services (Joosten and Clarke, 2002). Freshwater lakes within peatlands are understudied and overlooked, despite these acidic, low nutrient systems being home to a number of rare and priority freshwater species (Baars *et al.,* 2014; Drinan *et al.,* 2013b). Oligotrophic lochs and many of the species inhabiting them are protected and prioritised at both a national (UK BAP priority habitat) and international level (Annex 1 of the EU Habitats Directive 92/43/EEC) making them a priority for conservation management. Despite this there remains a paucity of data characterising these systems making informed management difficult.

2.2.1 The Flow Country

The Flow Country (Figure 2.1) extends across the counties of Caithness and Sutherland in north Scotland; it is a remote landscape in which low temperatures and high rainfall have led to the development of large areas (ca. 440,000 hectares) of blanket bog (Lindsay *et al.,* 1988). The deep (up to 5m) peat, with its high water table is covered by vegetation dominated by species of sphagnum mosses including *Sphagnum fuscum, S. rubellum, S.austinii*, heather (*Calluna vulgaris*) and cotton grasses (*Eriophorum vaginatum*) (Coulson *et al.,* 1995). Palaeoecological studies indicate that the landscape was characterised by open woodlands of birch (*Betula* sp.), juniper (*Juniperus* sp.), hazel (*Corylus* sp.) and willow (*Salix* sp.) during the early to mid-Holocene but with the exception of a brief period of local pine forest growth (4,500-4,000BP) the landscape has been largely treeless since approximately 5,500BP (Charman, 1994). At 400,000 hectares (constituting an estimated 1.5% of global blanket bog extent) the Flow Country is considered one of the largest continuous expanses of this habitat to exist worldwide (Wilson *et al.,* 2014). It is estimated to store approximately 400 million tonnes of carbon; more than twice that of all the UK's forests combined (Scottish Natural Heritage, 2014). The landscape supports a composition of flora and fauna unique in Britain, being more akin to the subarctic habitats of northern Europe. The Flow Country is interspersed with peatland pools and lochs which themselves support a range of rare and specialised wetland species (Coulson *et al.,* 1995; Downie *et al.,* 1998; Drinan *et al.,* 2013a; Lindsay *et al.,* 1988; Stroud *et al.,* 1988). The Flow Country is a designated Ramsar site of international importance and is under consideration for UNESCO World Heritage Site status. Protection also includes a network of Sites of Special Scientific Interest (SSSI), Special Areas of Conservation (SAC) and Special Protection Areas (SPA).

2.2.2 Flow Country lochs

Interspersed throughout the blanket bog of the Flow Country are many stream networks, rivers and lochs. The streams and rivers flow from altitudes of 738m to sea level. Approximately 37% of the lotic systems flow through SSSIs (at the 1:125,000 scale, SNH, 2001). Water passing through the Flow Country is classified as good quality (SNH, 2001), 80% flows through peatland and moorland/peatland habitats, 10% through rough and improved grassland and 7% through coniferous plantation (SNH, 2001). The lochs of this region vary greatly in size (between 1 and 3371 ha) with a mean area of 40ha. In addition, there are a large number of small bog pools and hollows too small to be marked on 1: 50,000 scale maps. The lochs range in altitude between sea level and 543m and 29% of the total standing water in the area occurs within SSSIs (at the scale 1:125,000, (SNH, 2001)).

SNH (2001) used data from the standing waters database and a classification developed by Palmer, (1992) to sub-categorise the loch types found in the Flow

Country based on their vegetation communities (Table 2.1); with the aim of quantifying the number of different loch types. Loch types 2 and 3 dominate the freshwater landscape of the Flow Country, few examples of the other loch types are present (Table 2.1).

Vegetation-based loch classification systems can be transformed into loch trophic categories based on known links between aquatic plant communities and nutrient status. The majority of Flow Country lochs are classified as oligotrophic (82%), followed by dystrophic systems (15%). Less than 2% of Flow Country lochs are classified as mesotrophic or eutrophic (Table 2.2).

Loch Type	Description from Palmer, (1992)	Number of sites in the Flow Country
1	*Species-poor group, characterised by submerged Sphagnum and Juncus bulbosus, often accompanied by Potamogeton polygonifolius. Pools and small lochs on blanket bog in northern Scotland and a few pools on acid substrates in southern Britain are typical of this Type*	*63*
2	*Sites are typified by Juncus bulbosus and Potamogeton polygonifolius, along with Littorella uniflora, Lobelia dortmanna and Potamogeton natans. This Type includes peaty lochs in northern Scotland*	*148*
3	*Type 3 is distinguished from Type 2 by the higher incidence of Myriophyllum alterniflorum, Isoetes lacustris and Fontinalis antipyretica. These sites tend to be larger and rockier than Type 2 sites and occur on base- poor rocks in Scotland.*	*184*
4	*Type 4 contains elements (e.g. Littorella unifora, Potamogeton natans and Myriophyllum alterniflorum) of Type 3, but in addition a number of plants such as Potamogeton filiformis, Potamogeton praelongus, Myriophyllum spicatum and Chara species are common.*	*9*
5b	*The variant 5B consists of species-poor sites dominated by Potamogeton natans and Nymphaea alba*	*1*
7	*Although similar in many ways to Type 4 water bodies, Type 7 sites usually lack a number of species such as Myriophyllum alterniforum and Juncus bulbosus. Lochs with a strong marine influence, on shell sand, limestone and Old Red Sandstone in northern Scotland, are typical of Type 7.*	*1*

Table 2.1 Description and total number of each loch type (based on Palmer *et al.,* (1992) lake classification) in the Flow Country, Scotland, from SNH (2001)

Trophic Category	% lochs in the Flow Country
Dystrophic	15
Oligotrophic	82
Mesotrophic	<1
Eutrophic	<1
Mixed Influences	<2

Table 2.2 Percentage of Flow Country lochs belonging to different trophic categories, from SNH (2001)

2.3 Site Selection

The overall aim of this research was to examine common scoter declines at Flow Country lochs; site selection therefore focused on lochs which currently or historically had records of breeding scoter. The analyses in this thesis are carried out at a number of different temporal and spatial scales, which are illustrated in Table 2.3).

		SPATIAL SCALE		
		Flow Country	18 Lochs	4 Lochs
TEMPORAL SCALE	Present day	Chapter 4 *(Maxent SDM analysis)*	Chapter 3 *(Ordinations and GLMs)* Chapter 4 *(GLMs within-loch and landscape)*	*
	1987 to 2014	Chapter 4 *(GLMs climate analysis)*	-	-
	1850 ***and*** present	-	Chapter 5 *(Top-bottom analysis)*	*
	1850 ***to*** present	-	-	Chapter 6 *(Big Ben analysis)*

**Four lochs included in the 18-loch analysis*

Table 2.3 The temporal and spatial scale of analysis in each thesis chapter

Chapter 3 focuses on contemporary data from 18 Flow Country lochs which were split evenly between the current and historic categories (identified in Table 2.4). Chapter 4 examines scoter loch use at two spatial scales, and two temporal scales. Analysis examining the relationship between annual climate variation and changes in scoter abundance is based on climate data for the whole Flow Country region; dating back to the late 1980s, when surveys of common scoter first began. Species distribution modelling in chapter 4 was based on present day data and covered almost the entire Flow Country (an area of approximately 100km^2). Chapter 4 also examines the links between landscape features and within-loch variables at the 18 lochs for which detailed survey data were available (from chapter 3). The top-bottom analysis in chapter 5 focuses on the 18 lochs at two points in time, firstly the present day (represented by the core tops) and secondly a period ca. 1850 (taken from the bottom of the core). Chapter 6 focuses on fine temporal change at a sub-set of four sites (selected from the original 18, and denoted with a * in Table 2.4

Selection of the 18 study lochs

The RSPB Forsinard reserve has been annually monitoring common scoter at approximately 100 lochs and pool systems since 2002; these data were combined with earlier more sporadic survey data and Rare Breeding Birds Panel (RBBP) records to identify sites used by common scoter. Approximately 40 lochs had been used by scoter either historically or post 1995, and of these very small pool systems were discounted as these were not likely to yield sediment suitable for palaeolimnological analysis. The remaining sites were categorised as either historic (recorded common scoter use prior to 1995) or current (records of scoter since the first surveys in the late 1980s) in terms of scoter use (Table 2.4). An equal number of historic and current breeding sites were selected for use in this study; the final selection of our 18 sites was based on those which i) had some existing environmental data (particularly relating to fish populations), ii) were set in a landscape setting typical of that found in the Flow Country (namely open bog (without forestry), plantation forestry or areas of deforested plantation) and iii) we could gain landowner permission to survey. The 18 sites were spread across an area of 450km^2 (Figure 2.1), including seven different landowners or estates. Seven of the lochs are set in an open bog setting, six are at least partially surrounded by forestry and the remaining five have deforested area within close proximity (Table 2.3). The sites were all included in a recent study (Hancock *et al.,* 2015; Hancock *et al.,* in prep.) and therefore useful additional data were available concerning brown trout frequency.

Selection of the 4 lochs

Selection of the four sites that were the focus of Chapter 6 was primarily based on the lithostratigraphic data from the Glew cores taken in 2013 (chapter 5). Cores that demonstrated a conformable stratigraphy and a coherent XRF profile were prioritised. Secondly sites were also selected with contrasting scoter loch values. FEAR and LEIR are the two highest scoring sites that are frequently used by common scoter. AMHU has a mid-range SLV and TALA has a low SLV score.

Chapter 6 aims to examine two theories for common scoter decline, namely possible changes in fish populations and the effects of plantation forestry. However, the reliability of fish data available at the time of writing was somewhat questionable, as there was evidence that several of the sites identified from rod and line surveys, (methods detailed in section 2.4.1.2) to be fishless were known to support fish (based on estate stocking data and trout fishing literature Hancock pers. comm., Sandison, 2015). Indeed, for all of the lochs in which no fish were caught during rod and line surveys (BEUL, CLAC, DUGE, DUIN, and LOSG) there was evidence from other sources that fish were, in fact, present. Due to the ambiguity of the fish data the site selected had a range of fish densities rather than “no” fish.

The four sites were set in a mixture of landscape settings bog (TALA), primarily bog small amount of forest (AMHU), bog with more substantial amount of forest (FEAR) and bog with areas of deforestation (LEIR).

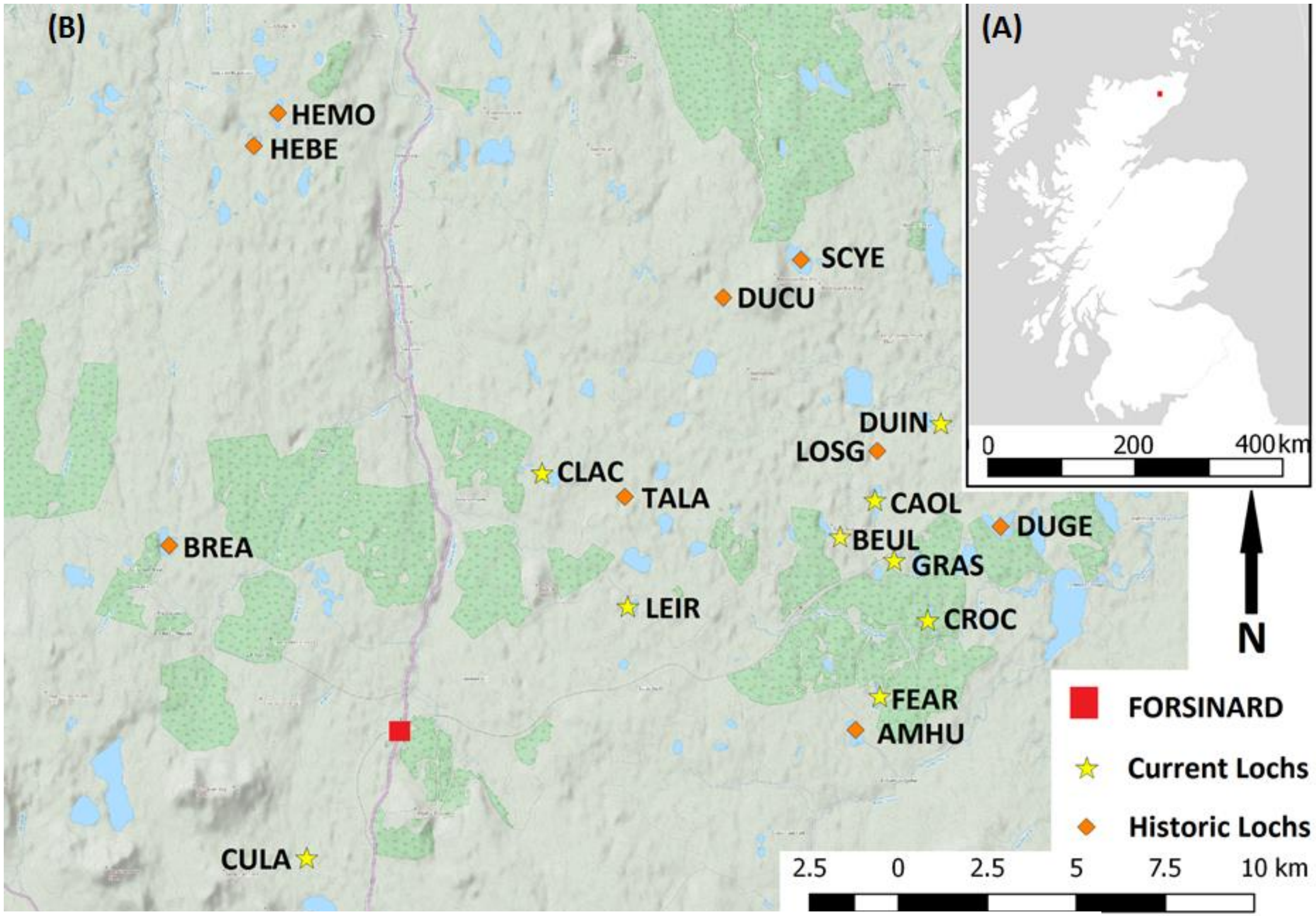


Figure 2.1 Map showing the locations of (A) Forsinard in Scotland and (B) Forsinard and the 18 study lochs

Loch name (Loch code)	**Loch Type**	**Brown Trout abundance (fish per rod hour)**	**Catchment Area (ha)**	**Dominant landcover types$^+$ (percentage of catchment)**
Loch a'Mhuillinn (AMHU)*	*Historic*	2.7	470	Bog (94) Forestry (6)
Lochan Beag Beul na Faire (BEUL)	*Current*	0	6	Bog (100)
Loch nam Breac (BREA)	*Historic*	1.6	942	Bog (86) Forestry (14)
Caol Loch (CAOL)	*Current*	0.4	87	Bog (100)
Loch nan Clach Geala-west (CLAC)	*Current*	0	20	Bog (100)
Lochan Croc nan Lair (CROC)	*Current*	0.1	6	Forestry (53) Bog (47)
Loch Culaidh (CULA)	*Current*	0.5	25	Bog (100)
Lochan Dubh Cul na Beinne (DUCU)	*Historic*	5.2	96	Bog (100)
Lochan Dubh Nan Geodh (DUGE)	*Historic*	0	71	Bog (91) Forestry (9)
Loch an Duine (DUIN)	*Current*	0	30	Bog (100)
Loch nam Fear (FEAR)*	*Current*	0.3	22	Bog (68) Forestry (32)
Grassie Loch (GRAS)	*Current*	0.7	38	Bog (75) Deforested Area (25)
Loch na h-Eaglaise Beag (HEBE)	*Historic*	1.3	155	Bog (100)
Loch na h-Eaglaise Mor (HEMO)	*Historic*	0.8	437	Bog (100)
Loch Leir (LEIR)*	*Current*	2	96	Bog (91) Deforested area (9)
Loch Losgann (LOSG)	*Historic*	0	37	Bog (100)
Loch Scye (SCYE)	*Historic*	0.4	166	Bog (100)
Loch Talaheel (TALA)*	*Historic*	1.6	25	Bog (100)

+ Terrestrial vegetation cover in the catchment based on CEH data Hughes et al. 2004

** denotes sub-sites, chapter 6,*

Table 2.4 The full name and code of each study loch, together with brown trout densities (from rod and line surveys) and dominant landcover types

2.4 Methods

2.4.1 Existing datasets

Existing data on Flow Country lochs is sparse. However, it is the only area in Scotland for which routine and standardised monitoring of common scoter occurs. This thesis uses common scoter survey data, together with the limited amount of existing physico-chemical and biological data that is available. Records of common scoter loch use are vital to be able to understand decline and were provided by RSPB Forsinard reserve. Fish surveys conducted in 2010 and 2011 are particularly pertinent to issues of scoter decline as fish have been implicated as a possible cause of scoter decline both in the Flow Country and other British and Irish sites (Hancock *et al.,*2015, Partridge, 1987). These survey data were provided by RSPB and WWT. Aquatic macrophyte surveys were conducted by SNH at several of the study sites in the 1980s, and are included to provide useful insights into the recent ecological conditions and potential change within the lochs. Data from the Centre for Ecology and Hydrology (CEH) lakes portal was used to characterise the catchments of the study lochs.

2.4.1.1 Common Scoter surveys

The first surveys of Common Scoter in the Flow Country were conducted in the late 1980s and periodically throughout the 1990s predominantly by RSPB staff and volunteers. Although not standardised across many sites, the surveys did indicate a decline in breeding numbers that was confirmed by the national surveys of 1995 and 2007. Annual standardised monitoring of common scoter breeding in the Flow Country has been organised by RSPB since 2002. Around 100 sites including lochs and pool systems in the Flow Country are visited on the same day during two key periods of scoter breeding season. Up to 3 coordinated “early” surveys are carried out between late April and the end of May when the birds are arriving and pairing. Up to three “late” surveys are carried out in July and early August during the brood rearing/fledging period. Each loch is surveyed following the methodology adopted for the national surveys (Underhill *et al.,* 1998), with the entire loch being viewed from different vantage points and the number of males, females and pairs noted and the size of ducklings recorded.

These data are used in Chapter 3 to develop a scoter loch value; a relative measure of scoter use at each of the 18 lochs over the last 20 years. Scoter presence records for the entire RSPB survey area are used in Chapter 4 as part of the Maxent species distribution modelling analysis.

2.4.1.2 Fish surveys 2010 and 2011

No electrofishing data is available for any of the study sites, however, the fish communities of all 18 lochs were surveyed in 2010 and 2011 (between April and August) using standardised rod and line surveys by RSPB and WWT. Each loch was fished by the same individual for a total of five hours, the total length and weight of each fish caught was recorded; fish diet was assessed by examining the stomach contents of a number of the fish caught in 2010. Brown trout abundance per site are expressed as mean number of fish caught per rod hour. These data are presented in Chapter 3 and used in the ordinations of invertebrate and diatom communities and also in the general linear modelling analysis examining associations between scoter loch value and within loch characteristics.

2.4.1.3 Macrophyte surveys 1986-7

Aquatic macrophyte surveys were conducted at eight lochs in between 1986 and 1987 by SNH staff. The surveys involved walking the shore of lochs and recording the presence of submerged, floating and emergent species and their abundance using the DAFOR (dominant, abundant, frequent, occasional and rare) scale. These data are presented in Chapter 3 and are used to examine the extent of recent macrophyte community change in the lochs by comparing them to surveys conducted during this research (methods detailed in 2.4.2.1.3).

2.4.1.4 Catchment characterisation

Data from the CEH lake portal database were used to determine the catchment size and dominant landcover types within the catchment of each study site. In this database catchment size is derived using a 50m resolution digital elevation model (DEM) (Hughes *et al.,*2004). For relatively flat, low gradient landscapes such as the Flow Country it is possible a 50m resolution DEM may not detect subtleties in landscape topography and therefore under or overestimate catchment area. Detailed examination of these data, together with local knowledge and ground truthing, suggest that these data should be treated with some caution for more atypical landscapes such as the Flow Country.

Similarly, landcover classification in the catchments is based upon LCM90 Landcover class (Fuller *et al.,*1994). This classification system attempts to separate out areas of "open dwarf shrub heath" and "bog, deep peat", ground truthing suggests some of these delineations may be inaccurate for parts of the Flow Country, therefore in the current study these two categories are grouped as bog. In addition, areas categorised as "coniferous forestry" by the LCM90 Landcover class are in some instances now areas of deforested plantation, therefore these are renamed as deforested area based on ground truthing observations in the current study.

2.4.2 Data collected in this research

2.4.2.1 Field methods

2.4.2.1.1 Palaeolimnological samples

Short sediment cores were collected from the littoral zone of each of the 18 lochs using a Glew corer (7.4cm internal diameter, (Glew, 1991)), 16 sites were cored in October 2013, due to access constraints the remaining two sites (Loch nam Fear (FEAR) and Loch a'Mhuillinn (AMHU)) were not sampled until August 2014. The cores were sliced in the field at 1cm intervals, each slice was collected into a whirlpack bag and stored in a dark and cool location in the field until cold storage in the laboratory (Table 2.5 for core details). In Chapter 3 the modern, surface samples (1-2cm) from each loch were analysed to examine contemporary communities of diatoms (section 2.4.2.2.5) and chironomids (section 2.4.2.2.6). In Chapter 5 lithostratigraphic (section 2.4.2.2.2) and geochemical analysis (section 2.4.2.2.3) are carried out on each slice along the core. Community change is examined by undertaking a top-bottom approach whereby the community composition is determined for both a surface sample (representing the contemporary communities) and a sample from close to the base of each core (representing historic/pre-1850 conditions).

A wide bore (8cm) piston corer, developed by the Environmental Change Research Centre at UCL and known as Big Ben (Patmore *et al.,* 2014) was used to take cores from four of the study lochs in April 2016. Cores were collected close to the location of the previous Glew cores (coring locations provided in Table 2.6) and were sliced into whirlpak bags on site at 0.5cm intervals. Samples were stored in a dark and cool location until return to the laboratory where they were placed in cold storage.

Core Code	Sampling date	Grid Reference	Water depth (m)	Total core length (cm)
AMHU_1	30/08/2014	ND0193641944	1.9	13
BEUL_1	15/10/2013	ND0146147633	1.2	11
BREA_1	18/10/2013	NC8260047766	2.9	21
CAOL_1	15/10/2014	ND0250748316	1.7	17
CLAC_1	17/10/2013	NC9354449409	1.8	20
CROC_1	15/10/2013	ND0398845401	2.3	11
CULA_1	17/10/2013	NC9322849594	1.3	23
DUCU_1	12/10/2013	NC9845154325	1	10
DUGE_1	13/10/2013	ND0602147731	1.5	16
DUIN_1	14/10/2013	ND0444350747	2.2	21
FEAR_1	30/08/2014	ND0250743151	1.8	11
GRAS_1	13/10/2013	ND0314947050	0.7	15
HEBE_1	16/10/2013	NC8544659030	1	7
HEMO_1	16/10/2013	NC8605959840	1.4	18
LEIR_1	13/10/2013	NC9562445888	1.7	14
LOSG_1	14/10/2013	ND0263749929	1.6	14
SCYE_1	12/10/2013	ND0046455251	3	31
TALA_1	18/10/2013	NC9558848372	1	7

Table 2.5. Details of the 18 cores taken from the study sites in October 2013 and August 2014 (AHMU_1 and FEAR_1)

Core Code	Date	Location	Water Depth (m)	Total Core Length (cm)
AMHU_BB	20/4/15	ND 0183941930	1.7	48
FEAR_BB	23/4/15	ND0251943170	1.8	33
LEIR_BB	21/4/15	NC9566045883	1.6	48
TALA_BB	22/4/15	NC9556448923	0.8	33

Table 2.6. Details of the four Big Ben cores taken in April 2016

2.4.2.1.2 Water Chemistry

Measurements were taken at each site, including pH, conductivity and oxygen saturation along a depth gradient (50cm intervals). These measurements were taken using a Hach HQ40d multiprobe in October 2013.

Water samples were collected for analysis at each of the sites at the same time as sediment cores were collected in October 2013. Water for analysis was collected in the field into two litre acid-washed bottles; upon returning to the field base the sample was sub-sampled into two smaller acid-washed bottles; a filtered and acidified sample (for DOC analysis) and an unfiltered, unacidified sample for anion and, cations analysis. The filter papers from each sample was retained, wrapped in foil and frozen for Chlorophyll A analysis.

2.4.2.1.3 Macrophyte and bathymetry surveys

Aquatic macrophyte surveys were carried out at all 18 study lochs between 17th August and the 5th September 2014. 16 of the lochs were surveyed by boat and the remaining two, Loch an Duine (DUIN) and Loch Losgann (LOSG), which are the smallest and remotest lochs, were surveyed by wading from the shore. Boat surveys covered the lochs by rough transects, with individual survey points being selected at random every 5-20m depending on loch size. Between 30 and 80 points were visited per loch. At each point a double-headed rake was thrown out to a distance of approximately 3 metres and dragged along the bottom of the loch to recover any macrophytes growing on the bottom. At some points, the water was clear and shallow enough to see to the bottom. At these points a bathyscope was also used to survey plants growing on the bottom. For shore based/wading surveys the double-headed rake was thrown out 3 metres into the loch and dragged back along the bottom. A bathyscope was also used where depth and water clarity permitted.

At each sample point a record was made of water depth (using an Echotest 2 depth sounder) and sediment depth (determined by measuring the depth a long metal pole could be inserted into the sediment, at points where sediment depth exceeded the 310cm measurable by our survey pole a depth of 310cm+ was recorded). Sediment types brought up on the end of the pole and/or rake or observed using the using the bathyscope were recorded; sediment was classified based on descriptions provided in Lake Habitat Survey methodology developed by SNIFFER (2008) (Boulder>256mm, Cobble 64-256mm, Gravel 2-64mm, Sand 0.06-2mm, Silt <0.06mm, Peat/organic). The presence of each sediment category was recorded at each point, not just the dominant sediment type. Macrophyte percentage cover and macrophyte species percentage composition was estimated based on material brought up by the rake and viewed through the bathyscope. Plants were identified to genus or species in the field except for charophyte and mosses which were collected for identification using a microscope. Charophyte and aquatic mosses were collected in the field and sent to experts Nick Stewart and Ambroise Baker for identification.

2.4.2.2 Laboratory Analysis

2.4.2.2.1 Water chemistry

Water samples and filter papers collected in 2013 were sent to the University of Nottingham for analysis of anions, cations (by ion chromatography), DOC (spectrophotometric method, following filtration and inorganic carbon removal) and Chlorophyll A (manual colorimetric method).

2.4.2.2.2 Loss-on-ignition and wet density

Dry weight and organic content analysis was performed on every slice of the 18 Glew cores and the four Big Ben cores. Methods followed Dean (1974) and weights were measured to four decimal places. 1-2g of wet sediment was weighed into a crucible, these were then placed in an oven overnight at 105˚C, the next day the samples were reweighed to give a dry weight. The samples were then placed in a furnace at 550˚C for two hours and re-weighed providing the organic content.

Wet density was calculated for every slice of the 18 Glew cores and the four Big Ben cores, the sediment was weighed in a 2cm^3 brass vial to calculate grams of sediment per cubic cm (g/cm^3).

2.4.2.2.3 X-ray florescence

Samples were frozen, freeze dried and ground into a fine powder prior to instrumental analysis. X-ray florescence (XRF) is a type of elemental analysis that allows quantitative determination of the geochemical composition of sediments. Samples of a known weight (between 0.5 and 3 grams) are bombarded with X-rays which effect the electrons present in the atom by displacing electrons from inner orbital shells. This causes movement of electrons from outer to inner shells to fill the gap. This process is known as fluorescence, the amount of energy released by electrons moving in this way is uniquely characteristic and also allows the elemental concentration to be determined (typically Si, Ti, Ca, K, Fe, Mn Cl, S, Nb, Ni, Pb, Rb, Sr, Zn and Zr). Each slice of all 18 Glew cores and the Big Ben core taken from Loch Leir were analysed by a Spectro XLAB2000 X-ray fluorescence (XRF) spectrometer.

The heavy metal profiles from XRF analysis can be used to provide a rough estimate of the timescale covered by recent (1850-present) sediments in the core. Anthropogenic atmospheric pollutants (such as heavy metals Zn, Pb and Cu) deposited at lakes are rapidly taken up by sediments (Smol, 2008); heavy metal analysis of samples along the length of sediment cores can therefore provide a historic record of atmospheric pollution experienced by a lake and its catchment. The profile of heavy metal pollutants in recently deposited lake sediment follows a pattern similar to the schematic profile provided for SCPs in Figure 2.2 (from Rose *et al.,* (1995)). Increases are typically observed from the period of the industrial revolution (c.1850) until pollution legislation was introduced in the 1970s (Rose *et al.,* 1995); following which a reduction in atmospheric metal pollution occurred which can be observed in the profile.

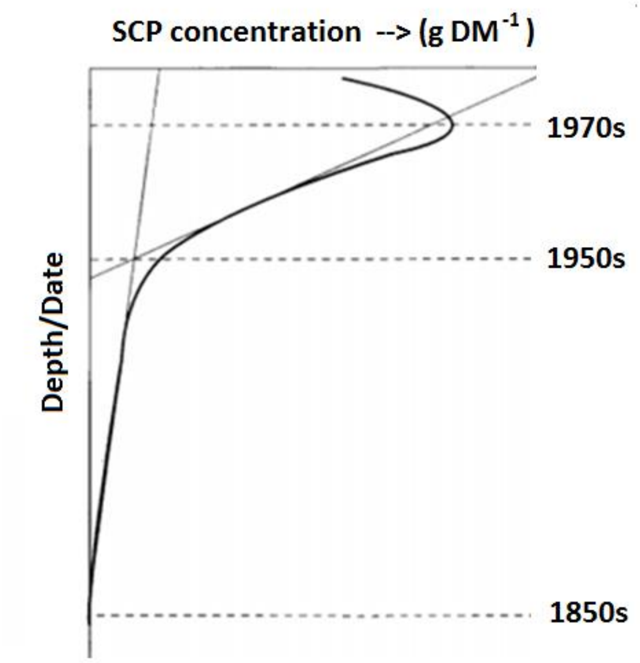


Figure 2.2 Schematic spherical carbonaceous particles (SCPs) profile adapted from (Rose *et al.,* 1995), ‘1850s’ -start of SCP record; ‘1950s’ rapid increase in SCP concentration; and ‘1970-1980’ subsurface peak, after which SCP concentration decreases

2.4.2.2.4 ^{210}Pb Dating

Radiometric dating was carried out on three of the 18 Glew cores (LEIR_1, CAOL_1 and GRAS_1) and three of the four Big Ben cores (AMHU_BB, FEAR_BB, TALA_BB) by the Bloomsbury Environmental Isotope Facility (BEIF) at University College London. The methodology has been extensively used to date lake sediment samples and is based on measuring naturally occurring lead-210 (^{210}Pb) radionuclides in addition to artificially produced Cesium-137 (^{137}Cs) and Americium-241 (^{241}Am) released by nuclear weapons testing and nuclear reactor accidents. The six sediment cores were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay using ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. Lead-210 was determined via its gamma emissions at 46.5keV, and ^{226}Ra by the 295keV and 352keV gamma rays emitted by its daughter isotope ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. Cesium-137 and ^{241}Am were measured by their emissions at 662kev and 59.5kev (Appleby *et al.,* 1986). The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self-absorption of low energy gamma rays within the sample (Appleby *et al.,* 1992).

2.4.2.2.5 Diatom analysis

Diatom analysis was carried out on samples from the top (1-2cm) and the base (between 5 and 27cm) of each Glew core. The four Big Ben cores (sliced at 0.5cm intervals) were analysed for diatoms down to a 10cm depth, as this was shown from radiometric dating to cover the key focus period of this study (1850-present day).

Subsamples of approximately 0.01g (wet weight) were prepared from each slice following Battarbee *et al.,*(2001). Organic matter was removed from the samples by adding 5ml of 30% hydrogen peroxide (H_2O_2) and heating to 80^oC in a water bath; the samples were monitored for several days until all organic material was removed. Any remaining H_2O_2 and any carbonates are eliminated from the sample by adding 1-2 drops of hydrochloric acid (HCl). Samples were centrifuged for 4 minutes at 1200rpm, following which the supernatant liquid was decanted off and the diatoms re-suspended in distilled water; this washing process was repeated four times. The cleaned diatom suspension was then diluted to a suitable concentration, coverslips were arranged on a metal setting out tray, away from sources of dust and air currents. 0.5ml of well mixed diatom suspended was added to each coverslip and allowed to dry. A drop of Naphrax was added to a slide and the dry coverslip inverted over the top; the slides were immediately heated on a hotplate (set to 130^oC) to drive off the toluene and allow the slide to set. A known quantity of microscopic markers (divinylbenzenees microspheres) were added to the samples from the four big Ben cores (just before to slide mounting) to allow quantification of diatom concentration. Slides were examined using a phase-contrast microscope at 1,000x magnification, with identification based on (Camburn and Charles, 2000; Krammer and Lange-Bertalot, 1986)

Percentage abundance of diatom species was determined for the samples from the Glew cores by counting 200 diatom valves on each slide. Diatom accumulation rate could be determined for the Big Ben cores using the microsphere markers and determination of sediment accumulation rate from radiometric dating analysis; 300

valves were counted per slide and reported as valves per gram accumulated sediment (g cm^{-2} yr^{-1})

2.4.2.2.6 Chironomid Analysis

Samples for the top-bottom analysis were taken from the top (1-2cm) of each Glew core. The bottom sample was located several slices up from the bottom of the core (ranging from 5 to 27cm depth depending on core length). The Big Ben cores (sliced at 0.5cm intervals) were analysed down to 10cm depth (as radiometric dating demonstrated 10cm covered the key focus period of this study, 1800-present day), every slice down to 5cm and every other slice between 5-10cm.

The chironomid analysis followed (Brooks *et al.,* 2007), approximately 1-1.5 grams of wet sediment was heated to 70˚C in 10% Potassium hydroxide (KOH) solution for approximately 5 minutes. The sample was then sieved using 212um and 92um sieves. The resulting material from the two sieve fractions was examined by placing a small quantity at a time in a grooved sorting tray under x10 to x40 level magnification. Head capsules were removed using fine forceps into a vial containing 70% ethanol. Slide mounting the head capsules with euparal requires them to be progressively dehydrated from 70% ethanol to 100% ethanol to eurparal essence. Ten small dots of euparal were added to each slide, two head capsules were placed into each, positioned ventral side up, before placing a 6mm coverslip over each blob of euparal. Chironomids were identified to species morphotypes based on Brooks et al (2007), and Anderson et al (2013). A total of at least 50 heads per sample were identified from a known volume of sediment. For the Glew core sample concentrations are expressed as heads per gram of wet sediment, for the Big Ben cores sediment accumulation rate from radiometric dating analysis was used to determine the number of heads per gram of accumulated sediment (g cm^{-2} yr^{-1}).

2.4.2.2.7 Macrofossil Analysis

Macrofossil analysis was carried on the four Big Ben cores, radiometric dating indicated that the top 10cm of the cores covered the period of interest, with much of the most relevant material (1950s-present day) being contained within the top

5cm. Samples were analysed from every slice (0.5cm intervals) down to 5cm depth and every other sample thereafter to a depth of 10cm.

The quantity of sediment analysed was between 22 and 66g wet weight and 25 and 40ml volume. The quantity was calculated by first filling a 100ml measuring cylinder to 50ml with tap water and placing on a tared balance (accurate to 0.001g). Sediment was then added and the final volume and weight of sediment added was noted. The material was then gently washed under the tap through a stack of two sieves (355um and 125um mesh size). The soft, peaty nature of the sediment meant it did not need pre-treating with 10% potassium hydroxide (as in Sayer *et al.,* (2012)). The two resulting size fractions were then examined a small amount at a time in a square petri dish (with 1cm squares marked on the base of the dish to facilitate a methodological search) under a x10 – x45 zoom stereo microscope. An estimate of charcoal remains was determined for the coarse (355um) fraction of all samples; the total number of squares on the petri dish containing charcoal was determined and then the number of charcoal pieces within each square enumerated for at 10 randomly selected squares. The mean number of charcoal remains per square was multiplied by the total number of squares containing charcoal. This was divided by the amount of sediment (grams) analysed to give a comparable estimate of the total charcoal remains present in each sample Plant and macroinvertebrate remains were picked out using fine forceps and stored in glycerol in a 24-section sorting dish. Individual remains were identified by reference to literature (Birks, 2002) and the UCL macrofossil reference collection. Sediment accumulation rates from radiometric dating analysis was used to determine the number of macrofossil remains of accumulated sediment (g cm^{-2} yr^{-1}).

2.4.2.3 Numerical methods

Details of statistical analyses are provided in the methods section of each chapter, preparation of data for use in these analyses is as follows.

Data manipulation

The aquatic macrophyte, water depth and sediment characteristics were recorded at 30-70 points per loch (as detailed in section 2.3.2.1.3); calculations to provide single site scores for each of these metrics were carried out as detailed in Table.2.7.

Variable	Determination
Sediment score *(0-1 scale)*	Sediment types (boulders, cobbles, gravel, sand, silt and peat) recorded at each survey point were given a score between 1-6 (from boulder to peat), according to decreasing in particle size. As more than one sediment type could be recorded at each survey point scores per point were standardised by dividing by the number of sediment types recorded. A loch sediment score was calculated by summing the standardised scores from each point and dividing by the total number of sampling points per loch.
Proportion of loch below 1m depth *(%)*	Bathymetry maps were produced from the water depth data, a contour plugin in QGIS (QGIS Development Team, 2016) was used to interpolate the depths between survey points; from this the proportion of the loch less than 1m in depth could be determined by dividing the area of water less than 1m deep by total loch area
Total area *(ha)*	Established for each site using the area function in QGIS
Mean/max depth (c)	Average and maximum water depths recorded
Percentage vegetation cover *(%)*	Mean percentage cover
Plant height *(cm)*	Mean macrophyte height
Plant volume inhabited (PVI)	$\text{PVI} = \frac{\text{area of macrophyte cover x plant height}}{\text{Water depth}}$

Table 2.7 Description of how the loch metrics were calculated from the macrophyte and bathymetry surveys carried out in 2014

Data transformations

Prior to statistical analysis the normality of each univariate variable was determined using the Shapiro-wilks test in R (R Core Team, 2016) and where necessary data was transformed to provide the closest approximation of a normal distribution (Table. 2.8).

Multivariate community datasets were assessed for normality in Canoco 5 (ter Braak and Smilauer, 2012) and transformation applied as detailed in Table 2.9

Variable	**Min**	**Max**	**Mean**	**Transformation**
Sediment score *(0-1 scale)*	0.52	0.69	0.59	Natural Log
Proportion of loch below 1m depth *(%)*	17	100	60	None
Total area *(hectare)*	3	34	13.3	Log_{10}
Mean depth *(cm)*	74	210	113	Log_{10}
Max depth *(cm)*	100	345	195	Log_{10}
DOC *(ppm)*	4.33	15.11	8.25	Natural Log
pH	5.13	6.80	6.11	None
Conductivity (us/cm^3)	54.30	87.30	68.06	Natural Log
Sodium *(mg/L)*	0.86	12.67	9.02	None
Potassium *(mg/L)*	0.36	2.36	1.10	Square root
Magnesium *(mg/L)*	1.37	2.95	1.95	Natural Log
Calcium *(mg/L)*	5.10	7.67	6.12	Natural Log
Chloride *(mg/L)*	2.35	17.09	11.62	Natural Log
Nitrate *(mg/L)*	0	0.09	0.02	Square root
Sulphate *(mg/L)*	0.47	2.95	1.56	Natural Log
Mean brown trout caught per rod hour	0	5.2	0.98	Square root
Mean brown trout weight per site *(g)*	0	1986	235	Square root
Chlorophyll A *(ug/L)*	0.3	5.0	1.6	None
Mean chironomid head capsules in surface sediments *(head capsules per gram wet weight)*	25	137	70	Square root
PVI	0.08	11.91	3.97	Square root
Percentage vegetation cover *(%)*	1.11	61.77	27.04	None
Plant height *(cm)*	2.77	29.01	12.61	Square root

Table 2.8 Data transformations and minimum, maximum and range of values for each loch univariate variable

Community dataset	**Data type**	**Chapter**	**Transformation**
Aquatic macrophytes and mosses	Factor (present/absence)	3 and 6	none
Chironomid	Abundance (per gram wet sediment	3 and 5	Log (1*Y+1)
	Abundance (g cm yr)	6	Log (1*Y+1)
Diatoms	Percentage	3 and 5	Log (1*Y+1), rare species down-weighted
	Abundance (g cm yr)	6	Log (100*Y+1), rare species down-weighted
Macrofossils	Abundance (g cm yr)	6	Log (100*Y+1)

Table 2.9 Data type and transformation of each multivariate dataset

CHAPTER 3 CHARACTERISATION OF PEATLAND LOCHS AND DEVELOPING HYPOTHESES FOR COMMON SCOTER (MELANITTA NIGRA) DECLINE

3.1 Overview

Chapter 3 is an exploratory data chapter which assesses the heterogeneity of Flow Country lochs by examining newly collected and existing survey data from 18 lochs. Ecological surveys are combined with chemical and physical data to characterise present day conditions within the lochs, and examine heterogeneity between lochs. Constrained ordination analysis is used to examine the factors structuring community composition within Flow Country lochs; analysis focuses on communities at different trophic levels, namely diatoms, macrophytes and invertebrates. The second part of this chapter builds on the initial loch characterisation by using these data to examine associations between within loch characteristics and common scoter loch use. The degree of scoter loch use is determined for each loch using long term, standardised survey data. A general linear modelling approach is used to determine significant associations and formulate hypotheses for common scoter decline.

3.2 Introduction

This chapter firstly aimed to establish current ecological conditions for 18 Flow Country lochs. The analysis was primarily based on newly collected data but also brought together data from other sources to characterise current conditions within Flow Country lochs. The physical structure of the lochs was examined using detailed bathymetry surveys and assessment of sediment composition at between 30-70 survey points. The water chemistry of the lochs was established from field based measurements and laboratory analysis, and was used to establish the chemical characteristics of the lochs. Primarily newly collected data was used to examine the biological communities of the lochs, this was complemented by historic macrophyte data and fish survey data. Communities were assessed at different levels throughout the food chain including primary producers, such as algae and macrophytes, as well as primary and secondary consumers, such as invertebrates and fish. The relationships between the physical, chemical and biological loch properties were explored using multivariate analysis in an attempt to establish the degree of similarity between lochs, and additionally identify the most pertinent drivers of loch ecology.

The exploration of Flow Country loch ecology provides the basis for the second aim of this chapter which was to identify loch characteristics associated with common scoter loch use, to develop and refine hypotheses for decline. Whilst the sites were originally selected based on either current (post 2002) or historic (pre-1995) scoter presence (chapter 2), this chapter quantifies the importance of the lochs to scoter. Detailed survey data, dating back to the 1980s, is used to establish a relative scoter loch value for each of the 18 sites. This measure is based not just on presence or absence but the number of scoters using a site. This robust measure of a lochs importance to scoter allows an in-depth assessment of the associations between the degree of scoter loch use and within loch characteristics. Exploratory multivariate analysis using scoter loch value is formalised by a general linear modelling approach; which was used to identify statistically significant loch characteristics that are associated with common scoter use of Flow Country lochs.

3.3 Methods

3.3.1 Study Area

This chapter focuses on the 18 lochs in the Flow Country, identified in chapter 2, section 2.2.1.

3.3.2 Site selection

The basis for site selection is detailed in Chapter 2, section 2.3. The 18 sites are split into two types, nine are current scoter lochs, with consistent records of breeding since the 1980s, and the remaining nine are historic scoter lochs, which had records of breeding in the late 1980s and 1990s but no records since 2002. The sites are set in a mixture of blanket bog, forestry plantation and deforested plantation. Further information concerning site selection is provided in chapter 2, section 2.3. The full loch names and four letter abbreviated loch codes are provided in Table 2.4. Hereafter this chapter uses the loch codes to denote the study sites.

3.3.3 Existing datasets

All the common scoter data detailed has been collected and provided by RSPB Forsinard reserve. These data include standardised, annual surveys (since 2002) of ca. 100 lochs and pool systems in addition to one-off surveys in 1989, 1991 and 1996 of a smaller number of sites (for survey methodology see 2.4.1.1).

RSPB conducted brown trout surveys at the study lochs between 2009 and 2011. Details of field and laboratory methods for these surveys can be found in chapter 2, section 2.4.1.2.

Historic macrophyte survey data is used to examine recent change in Flow Country lochs; the data used was gathered by SNH surveys conducted in the 1980s, the methods of which are detailed in 2.4.1.3.

CEH data from the lakes portal, based on Hughes et al. 2004 is used to estaimte catchment area and landcover types.

3.3.4 New data

Aquatic macrophyte and bathymetry surveys were carried out in August 2014 (field methodologies detailed in 2.4.2.1.3). Water chemistry was determined both in the field in August 2014 (section 2.4.2.1.2) and by laboratory analysis (section 2.4.2.1). 16 sediment cores were taken from the study lochs in October 2013 and two (from Loch nam Fear and AMHU) in August 2014 (2.4.2.1.1). The present-day community composition of diatoms and chironomids is determined from the analysis of sediments from the surface of these cores (see chapter 2.3.2.1 for field methods and 2.4.2.2.4 and 2.4.2.2.5 laboratory procedures).

3.3.5 Statistical analysis and data presentation

3.3.5.1 The characterisation of 18 peatland lochs in the Flow Country

Unconstrained or indirect ordination analysis is an effective method for exploring and visualising patterns in multivariate datasets (Gardener, 2014). In this chapter, ordinations are used to explore between-loch variations in communities of macrophytes, diatoms and chironomids as well as chemical and physical parameters. Principal component analysis (PCA) was used to investigate patterns in water chemistry and macroinvertebrate and chironomid communities; detrended correspondence analysis (DCA) was used for diatom and aquatic macrophyte communities. A preliminary DCA (detrending by segments and non-linear rescaling) of each dataset was carried out in Canoco v.5 (ter Braak and Smilauer, 2012) to provide an estimate of the underlying gradient length or number of "standard deviation units" (SD). The choice of PCA or DCA was based upon the gradient length, narrow lengths (<2.5) are more appropriately analysed with PCA whilst assemblages whose variation covers a larger range (>2.5) are more effectively dealt with using DCA (Braak and Prentice, 1988). PCA ordinations were constructed based on a Euclidean distance matrix and DCA included detrending by segments.

Unconstrained ordinations were also used to establish the extent and type of change in macrophyte communities in eight of the lochs for which historic data was available. The presence-absence data from the 18 surveys carried out in 2014 was first ordinated (DCA was selected based upon gradient lengths determined in Canoco v.5) and the historic survey data plotted passively onto the same ordination space. Historic and present-day data points were joined by a line, in this way patterns in the extent and direction of community change could be examined and compared for each site, and the relative position the current communities (which lacked historic data) could be determined.

Constrained or direct ordination techniques such as redundancy analysis (RDA) and canonical correspondence analysis (CCA) are robust techniques for examining the structure of community datasets in relation to environmental variables (Legendre and Legrendre, 2012). The aim of these analysis in this chapter was to identify environmental variables that were exerting statistically significant influence on community composition. Environmental variables included in the constrained analyses were determined using a forward selection procedure, which used partial Monte Carlo permutation tests to identify the minimum adequate predictor variables that explain assemblage variation. Variables were included up to a p-value of 0.1. Gradient lengths were again used to determine whether linear (RDA) or unimodal (CCA) was the most appropriate choice of constrained ordination. In community datasets, rare species can exert a disproportional influence on the axis scores, and therefore rare species were down weighted to counter this. Community datasets were transformed as detailed in Table 2.8. All ordination analyses were carried out in Canoco v.5 (ter Braak and Smilauer, 2012).

The degree of association between water chemistry variables was explored using a correlation matrix (produced using the corrplot package in R (R Core Team, 2016). Chironomid and diatom communities and macrophyte percentage cover at depths are illustrated using the software package C2 (Juggins, 2007) .

3.3.5.2 Developing hypotheses for common scoter decline using general linear models

General linear models (GLMS) were used to examine the loch characteristics associated with common scoter loch use. GLMs are tools which can be used to assess the relationships between a single response variable (common scoter loch use) and a number of potentially significant explanatory variables (environmental/habitat characteristics). General linear modelling was carried out in R core software and related figures produced using ggplot package (Wickham, 2009). Details of how the response and explanatory variables were formulated are detailed below.

Response variable (common scoter loch value)

Females are the most appropriate measure of a population’s reproductive potential and therefore were chosen for scoter loch value determination. Deriving an unbiased response variable for GLMs can be difficult. Simple site averages will be confounded by between-year declines and incomplete site coverage across years. The behaviour of females in the Flow Country between April and August each year falls in three distinct periods. Firstly, there is the period between arrival in April/May and ca. mid-June when females are highly visible, spending much of their time in larger groups and later in pairs, courting and mating. The second phase takes place between June and July when the females become much less visible, as they spend the majority of the time nesting and incubating. In the final stage between the middle of July and late August only females who have incubated successfully can be observed with broods on the lochs. During the incubation period females spend much less time on the lochs and are likely to be undercounted. During the brood rearing period only successful females will remain and their loch use will be somewhat constrained by the mobility of their ducklings. The period when the females first arrive and are pairing/mating was therefore considered the most suitable measure of loch value, as birds are unlikely to go uncounted and are able to spend time at the most profitable sites. Counts of females during this period of the year, for years between 1989 and 2014 were used to provide a relative measure of common scoter loch use since declines are thought to have begun in the 1980s. The scoter loch value (SLV) does not represent the degree of change a site during this time. This is because it is difficult to confidently attach a value for overall change to a site where the total bird number is so consistently low (commonly 1-2 birds per site per year, maximum 4-6 birds at ca. three sites) and where birds are known to move between sites during the year. The current and historic classification used in Hancock *et al.,*2015 was used to ensure that the study sites were equally split between those with continuing use and those which had been abandoned. However, in relation to interpreting the findings of the present study a relative measure of SLV was considered more appropriate than either the current or historic classification or a less robust indictor of change. By using SLV this study is able to establish a relative measure of a lochs importance to scoter, this can then be considered in relation to both contemporary conditions (Chapter 3) and recent environmental change (Chapters 5 and 6). These data can then be used to explore why particular lochs are associated with consistent use by a large number of birds while others are occupied less frequently.

The maximum count of female common scoter during the period between April 1st and 15th June for each of the 18 study lochs was determined each year between 1988 and 2014 from data provided by RSPB Forsinard reserve. Years in which more than 4 out of 18 sites had missing values were removed. The years 2009-2011 were also excluded as the data for this period additionally included multiple uncoordinated visits that were not readily separable from the coordinated count data and therefore the likelihood of birds being double counted (if they moved between sites on different days) increased. 11 years of count data was included in the scoter loch value calculation; missing counts for the 18 sites (n=23 out of 304 site-year combinations) were imputed using TRIM 3.53 software (Pannekoek and Strien, 2001), with a time-effects log-linear model, accounting for serial autocorrelation and over-dispersion, and converted into integers (Table.3.1).

To derive an overall value of each loch for scoters, a general linear mixed model was run with the annual maximum scoter counts by loch as response variable, no explanatory variables, and loch as a random intercept, assuming a Poisson distribution and log-link function. The site random intercepts were then extracted to be used as the scoter loch value. This approach was preferable to simply taking the mean count (which assumes a normal distribution), because the scoter data are a Poisson distributed sample of counts from an effectively random selection of years.

Site code	**1988**	**1991**	**1995**	**1996**	**2003**	**2004**	**2005**	**2007**	**2012**	**2013**	**2014**	**SLV**
FEAR	1	2	2	4	0	2	2	2	3	1	1	**1**
CROC	2	5	2	0	3	3	3	1	3	4	2	**0.99**
GRAS	1	3	2	6	3	1	5	3	2	4	2	**0.97**
BEUL	2	6	4	0	2	4	3	4	2	2	2	**0.96**
LEIR	**1**$^+$	3	6	2	3	1	1	1	2	2	2	**0.95**
CLAC	1	0	2	2	2	1	1	2	1	1	0	**0.87**
CULA	**1**$^+$	3	4	0	1	0	0	6	**1**$^+$	0	**0**$^+$	**0.83**
LOSG	2	0	0	0	0	0	2	0	0	1	1	**0.53**
AMHU	1	0	0	0	0	1	1	0	0	0	0	**0.5**
CAOL	1	0	2	0	0	0	0	0	0	0	0	**0.47**
DUGE	0	1	1	0	0	0	0	0	0	0	0	**0.47**
DUIN	0	0	0	0	0	0	0	1	1	0	0	**0.42**
HEBE	3	1	0	0	0	0	0	0	0	0	0	**0.38**
SCYE	0	2	0	0	0	0	0	0	**0**$^+$	0	**0**$^+$	**0.32**
TALA	1	0	0	0	0	0	0	0	**0**$^+$	0	**0**$^+$	**0.24**
HEMO	1	0	0	0	0	0	0	0	0	0	0	**0.14**
BREA	0	0	0	0	0	0	0	0	**0**$^+$	0	**0**$^+$	**0**
DUCU	0	0	0	0	0	0	0	0	0	0	0	**0**
Total females	18	26	25	14	14	13	18	20	15	15	10	
Total sites	13	9	9	4	6	7	8	8	8	7	6	

Table 3.1 The maximum number of female common scoter recorded at each loch prior to the 15th June for selected years used in the scoter loch value (SLV) calculation. Strength of colour based on number of females present. Bold highlight with $^+$ indicates an imputed value from TRIM analysis.

Explanatory variables (physical, chemical and biological within loch characteristics)

The explanatory variables used in the GLM related to the characteristics of the lochs and were initially categorised as physical, chemical or biological. A correlation matrix was used to identify collinearity (Pearson's R > ±0.4) between each category of variables. When collinearity occurred the most biologically relevant variable were retained.

General linear model refinement

Following removal of collinear variables as described above, the number of potential explanatory variables was still high (11) when compared to the number of observations (N = 18 sites) (Zuur *et al.,* 2009). Therefore, three sub-models were used, focusing on chemical, physical and biological explanatory variables. Each of these models was simplified using step wise deletion of the least significant variable (determined using the drop1 function in R). Non-significant interactions were deleted first and any variables included in a significant interaction were retained even if the variable was non-significant as a main effect. A final minimum adequate sub-model was reached when all remaining interactions and main effects were significant. Overly stringent sub-model refinement could have resulted in significant interactions being overlooked in the final model, therefore sub-models retained variables significant at <0.1. Two-way interactions were permitted but not higher-level interactions (due to the difficulty posed in ecological interpretation). The significant interactions and main effects from each sub-model were carried forward into the final model, which followed the format Table 3.2(a). This final model was refined in the same way, using drop1 and F-ratio, to identify the minimum adequate model Table 3.2(b). The final model retained variables significant at <0.01.

(a) Scoter site value ~ DOC+ Percentage cover + Fish abundance +sediment score: proportion of the loch below 1m+Percentage cover: abundance of chironomid head capsules
(b) Scoter site value ~ DOC + sediment score: proportion of the loch below 1m

Table 3.2 The structure of the overall model produced from the three sub-models (a) and the final minimum adequate model following refinement (b)

3.4 Results

3.4.1 The characterisation of 18 peatland lochs in the Flow Country

3.4.1.1 Sites overview

The 18 study sites are all located in upland blanket bog; altitude ranges from 110 to 190m asl. The catchments include a mixture of open bog, plantation forest and cleared forest. The surface area of the lochs ranges from 3 to 34 hectares and depth from 1 to 3.8 metres. The underlying geology of the sites includes sandstone and igneous rock types (Table 3.3). The geographic location and description of each loch is provided in Figures 3.1 to 3.18.

Loch Name	Loch Code	Grid Reference	Surface Area (ha)	Max Depth (cm)	Altitude (m asl)	Geology
Loch a'Mhuillinn	AMHU	ND018422	22	230	140	Sandstone[1]
Lochan Beag Beul na faire	BEUL	ND015476	3	140	190	Sandstone[1]
Loch nam Breac	BREA	NC827479	29	345	180	Sandstone[2]
Caol Loch	CAOL	ND025486	17	320	150	Sandstone[1]
Loch nan Clach Geala	CLAC	NC932496	4	180	190	Sandstone[2]
Lochan Croc nan Lair	CROC	ND039452	12.5	255	140	Sandstone[1]
Loch Culaidh	CULA	NC863390	11	190	130	Sandstone[2]
Lochan Dubh Cul na Beinne	DUCU	NC984544	7	110	180	Igneous[3]
Lochan Dubh Nan Geodh	DUGE	ND060478	34	190	130	Sandstone[1]
Loch an Duine	DUIN	ND044507	4	110	110	Sandstone[1]
Loch nam Fear	FEAR	ND025431	9.5	180	170	Sandstone[1]
Grassie Loch	GRAS	ND030469	7	100	150	Sandstone[1]
Loch na h-Eaglaise Beag	HEBE	NC854590	11	130	140	Sandstone[2]
Loch na h-Eaglaise Mor	HEMO	NC861599	15	220	140	Sandstone[2]
Loch Leir	LEIR	NC955458	9.4	175	170	Igneous[3]
Loch Losgann	LOSG	ND026500	3	140	140	Igneous[3]
Loch Scye	SCYE	ND006554	35	380	160	Igneous[3]
Loch Talaheel	TALA	NC955489	6	120	180	Igneous[3]

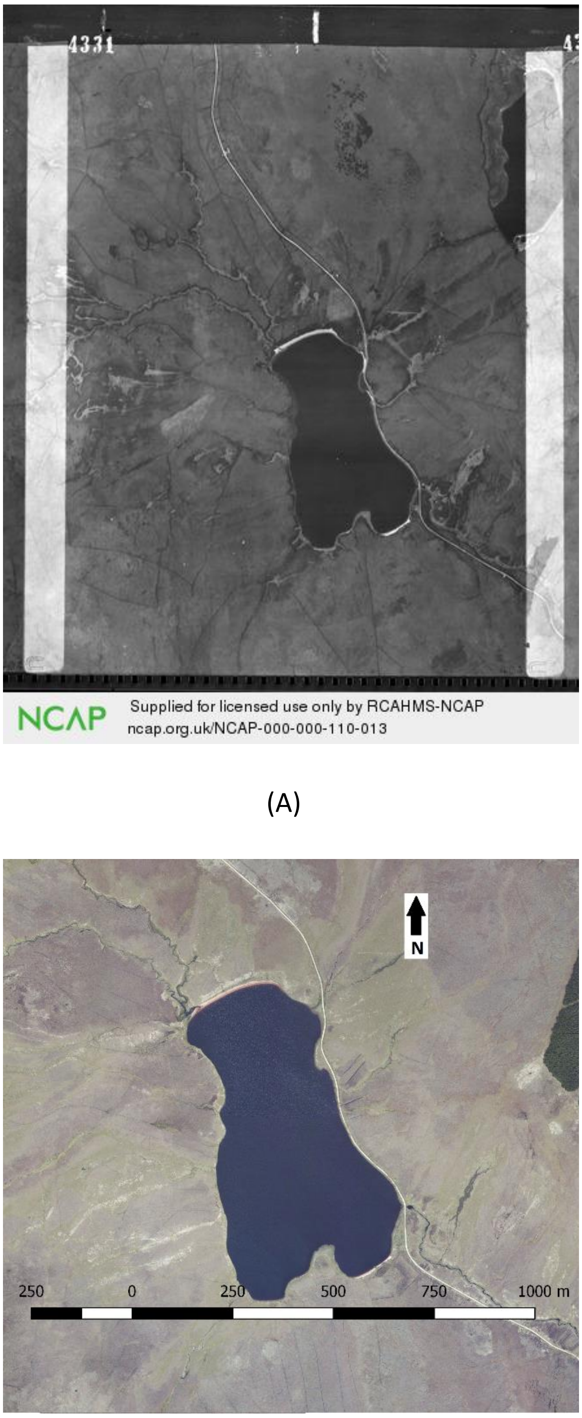
1. Lower old red sandstone-conglomerate sandstone, siltstone and mudstone, 2. Middle old red sandstone-conglomerate sandstone, siltstone and mudstone, 3. Igneous (felsic rock) extrusion

Table 3.3 Location and physical characteristics of the 18 study lochs in the Flow Country

Loch a'Mhuillinn (AMHU),

ND018422

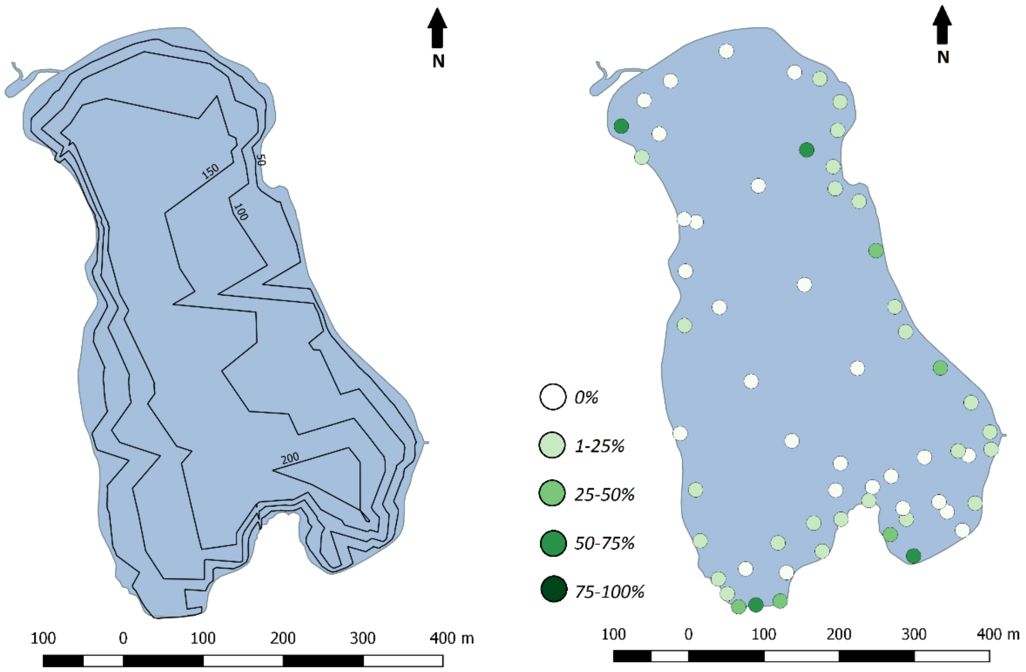
Loch AMHU is owned by the Dalnawillin estate and covers an area of 22 hectares. It reaches a maximum depth of 2.3m; 30% of the loch is less than 1.5m deep (Figure 3.2(A)). Its shoreline morphology includes sandy bays at both its north and south ends (Figure 3.1). The sediment of this loch is a mixture of boulders, cobbles, sand and silt but is predominantly sandy (Figure 3.34). The mean percent cover of aquatic macrophytes and mosses is 11.5% (Figure 3.2(B)). The loch is also notable for *Oreodytes alpinus* a rare and protected species of water beetle, last recorded at this loch in 2010. The land surrounding AMHU is predominantly open bog, the loch has a track running along is eastern edge. Examination of aerial imagery from both the 1950s and more recent google earth images indicates drainage ditches being a common feature of land to the west of AMHU



(A)

(B)

Figure 3.1 Loch a'Mhuillinn (AMHU), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

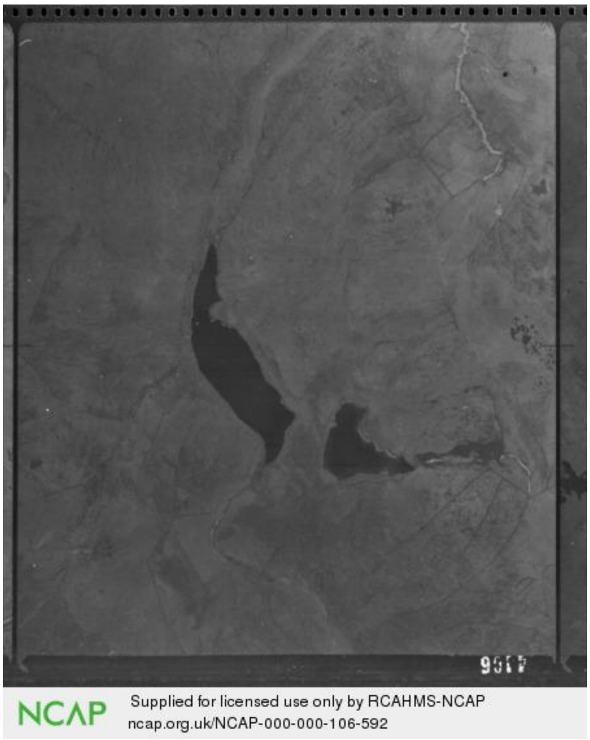


(A) (B)

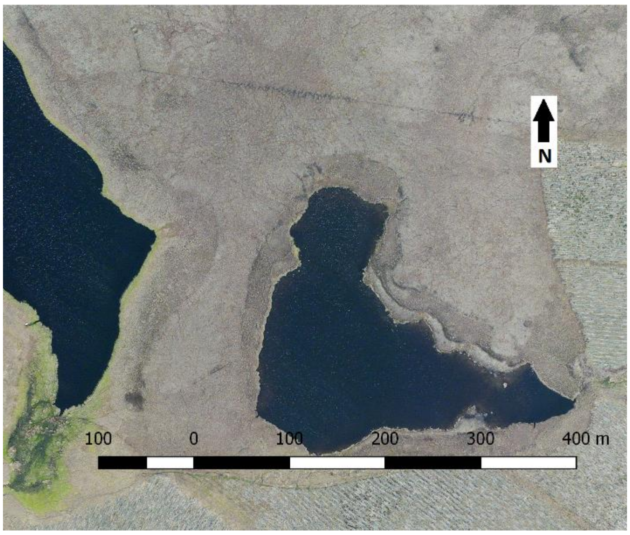
Figure 3.2 Loch a'Mhuillinn (AMHU) (A) Loch bathymetry, 2015 (contours in cm) and (B) Percentage macrophyte cover, 2015

Lochan Beag Beul na Faire (BEUL), ND015476

Lochan Beag Beul na Faire is a small (3 hectares) and shallow (maximum 1.4m) loch (Figures 3.3 and 3.4). It is located on the RSPBs Forsinard reserve, to the east of the larger Skyline loch. Coniferous forestry was planted close to the east and south shores of Lochan Beag Beul na Faire in the 1985 but was later felled in 2003. The sediment of this loch is predominantly sand, silt and peat (Figure 3.34), mean percentage macrophyte cover is 45% (Figure 3.4(B)).

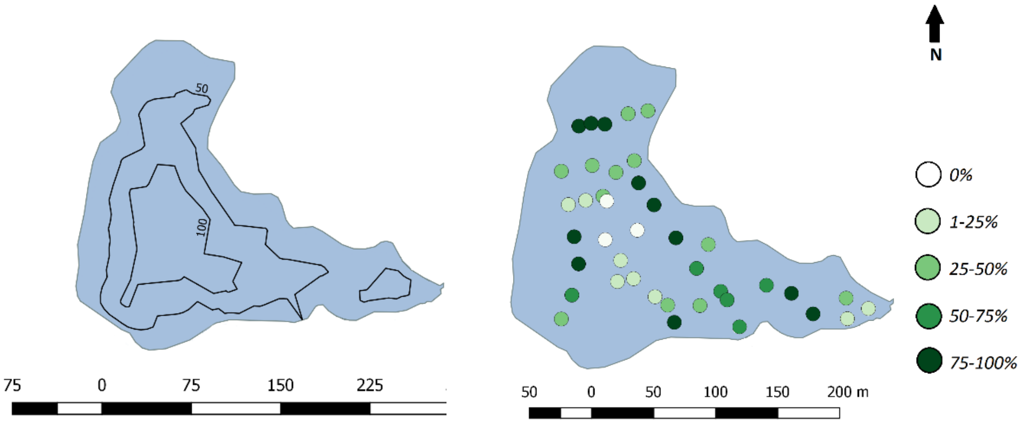


(A)



(B)

Figure 3.3 Lochan Beag Beul na Faire (BEUL), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)



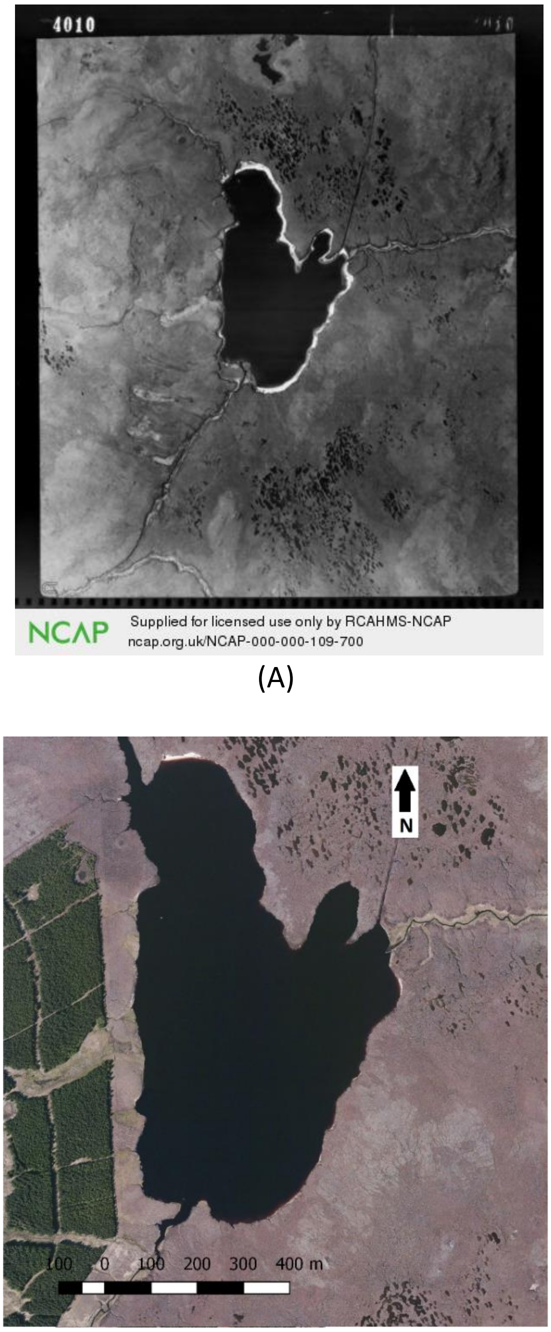
(A)

(B)

Figure 3.4 Lochan Beag Beul na Faire (BEUL), (A) Loch bathymetry, 2015 (contours in cm) and (B) Percentage macrophyte cover, 2015

Loch nam Breac (BREA), NC827479

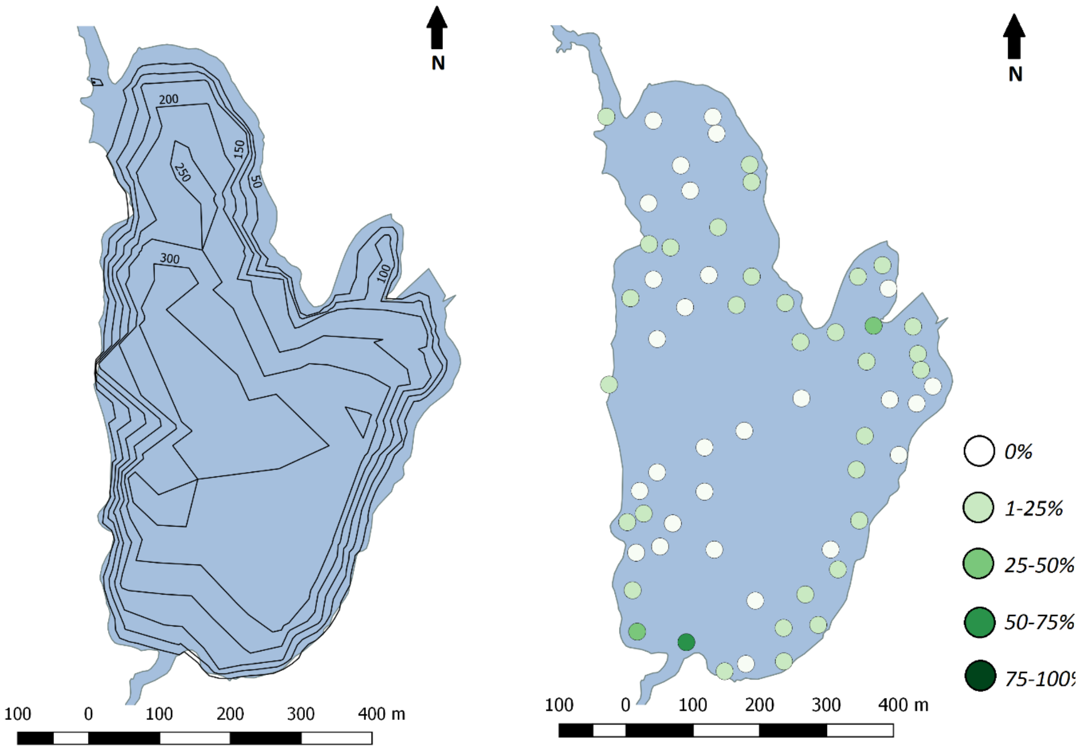
Loch nam Breac is a large deep loch on the west side of the RSPB Forsinard reserve. It covers an area of 29 hectares and reaches 3.45m in depth (Figure 3.6 (A)). The outflow of this loch (on the north east corner) has a weir controlling its outflow. Much of the west side of Loch nam Breac was planted with coniferous forestry in the 1986 and remained present at the time of the present study (Figure 3.5). The dominant sediment types in this loch were hard cobbles, boulders and gravel (Figure 3.34); mosses were more commonly recorded at this site than macrophytes with *Fontinalis squamosa* being the most commonly recorded moss (Table 3.8). The mean percent cover per sample point for this loch was just 6%, considerably lower than at other sites surveyed during this study.



(A)

(B)

Figure 3.5 Loch nam Breac (BREA),, (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)



(A)

(B)

Figure 3.6 Loch nam Breac (BREA), (A) Loch bathymetry, 2015 (contours in cm) and (B) Percentage macrophyte cover, 2015

Caol Loch (CAOL), ND025486

The Gaelic word Caol means long/thin, which aptly describes the shape of Caol Loch (Figure 3.7). It covers an area of 17h and reaches a maximum depth of 3.2m (Figure 3.8). Caol loch, is part of the RSPB Forsinard Flows reserve and to the north is a large expanse of open and unmanaged blanket bog. The land cover to the south includes areas of deforestation, remaining plantation and other waterbodies located to the south of the railway line. Caol Loch had the most diverse macrophyte community of the 18 sites (Table 3.7). At the south end of this loch before the outflow, the loch becomes very shallow and is dominated by *Juncus* and *Equisetum* species. There is evidence of historic fishing at the loch with two small fisherman's lodges close to the south end of the loch.

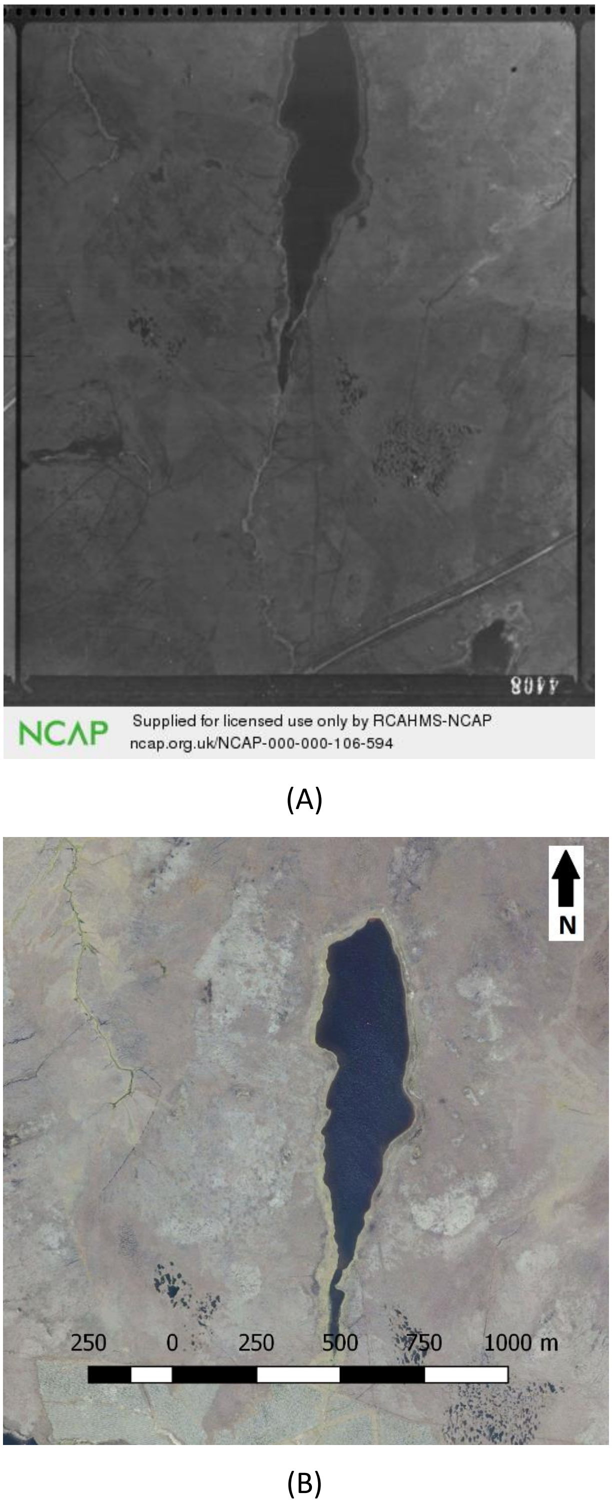
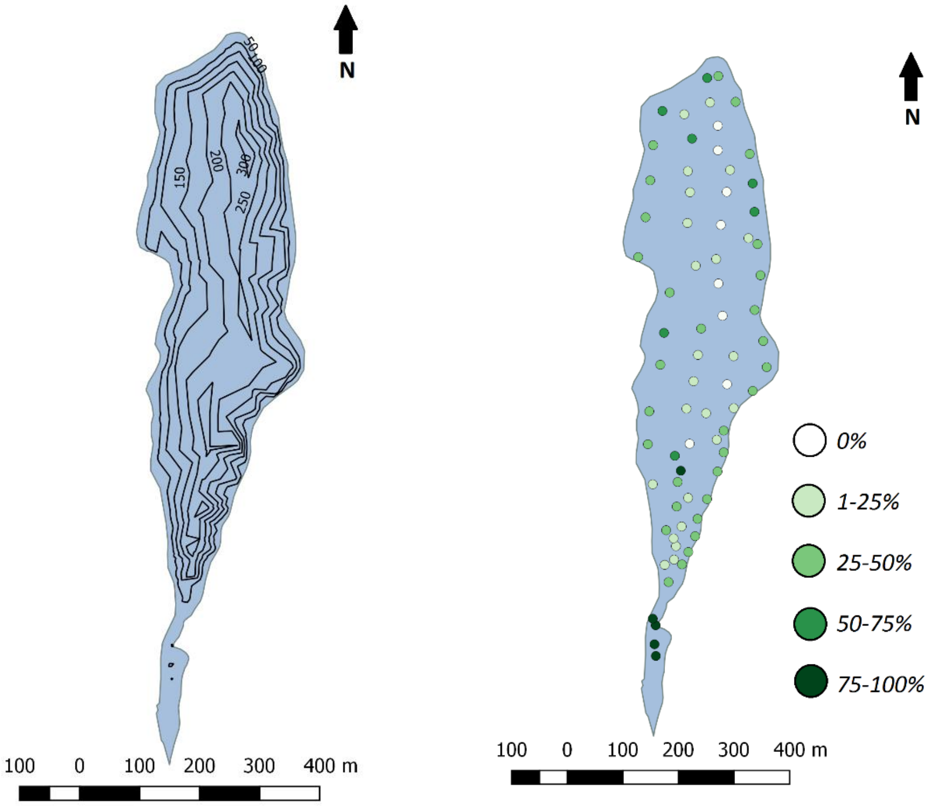


Figure 3.7 Caol Loch (CAOL), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

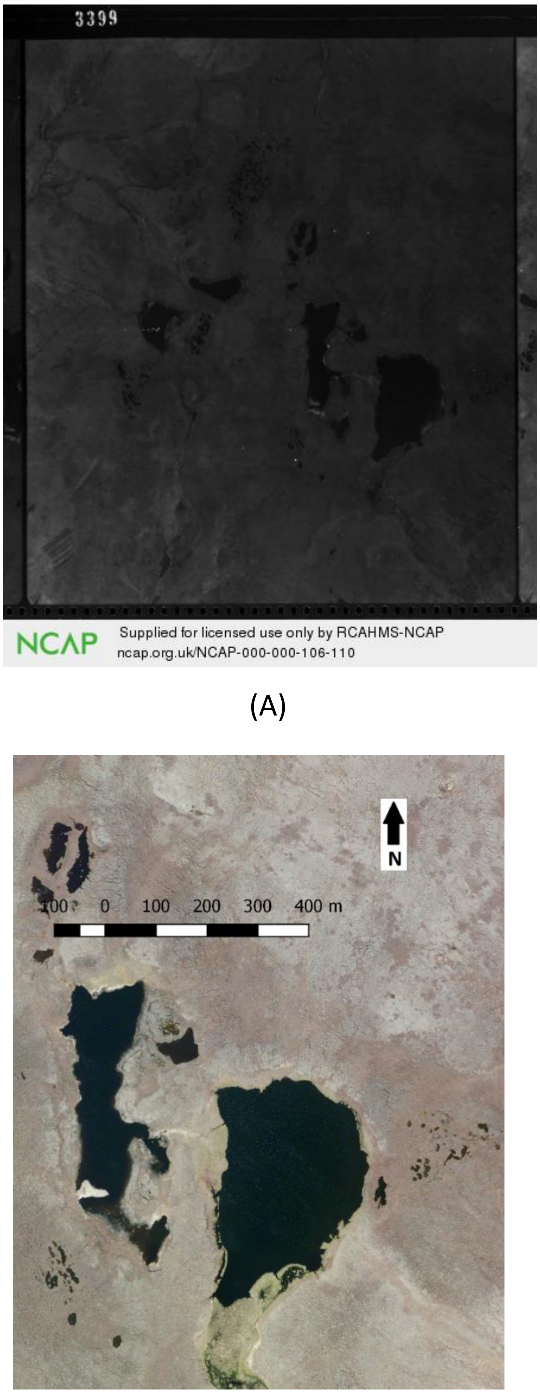


(A) (B)

Figure 3.8 Caol Loch (CAOL), (A) Loch bathymetry, 2015 (contours in cm) and (B) Percentage macrophyte cover, 2015

Loch nan Clach Geala-west (CLAC), NC932496

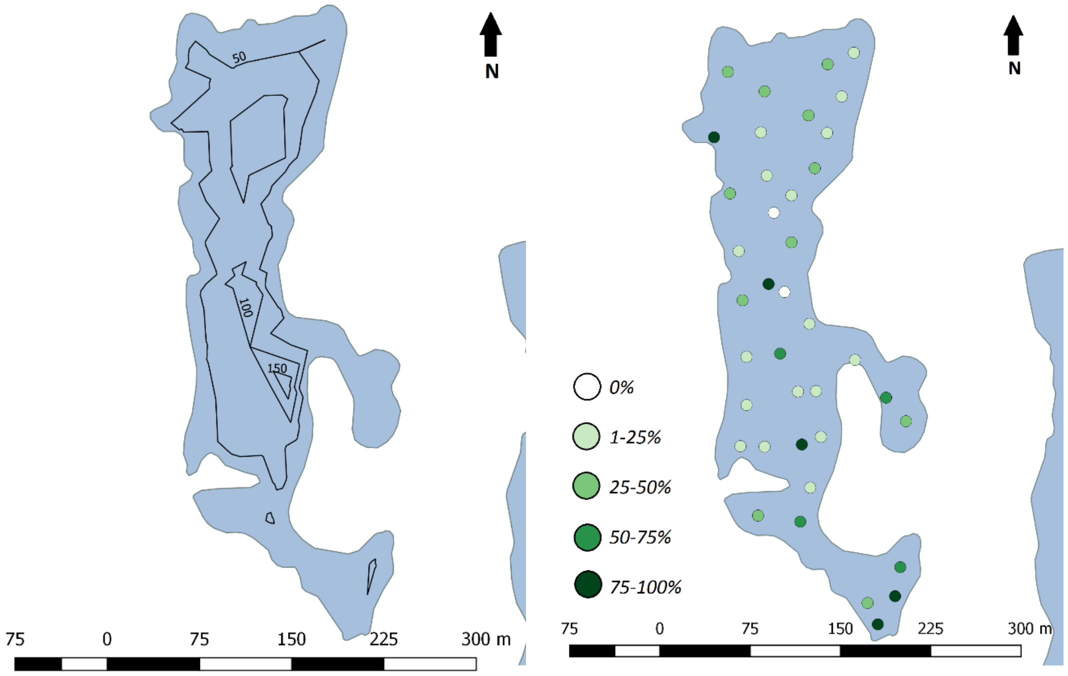
This long, shallow loch is located between a larger deeper loch to the east and several smaller lochs and pool complexes to the west and north (Figure 3.9). The deepest point of this loch is at 1.8m and is 4 hectares in size. There was an area of forestry plantation to the west of this loch. As part of the RSPB reserve this loch has restored bog to its west. Mean percentage cover at Loch nan Clach Geala-west was 36% (Figure 3.10) common macrophytes included *Juncus bulbosus* and *Lobelia dortmanna* (Table 3.7)



(A)

(B)

Figure 3.9 Loch nan Clach Geala-west (CLAC), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

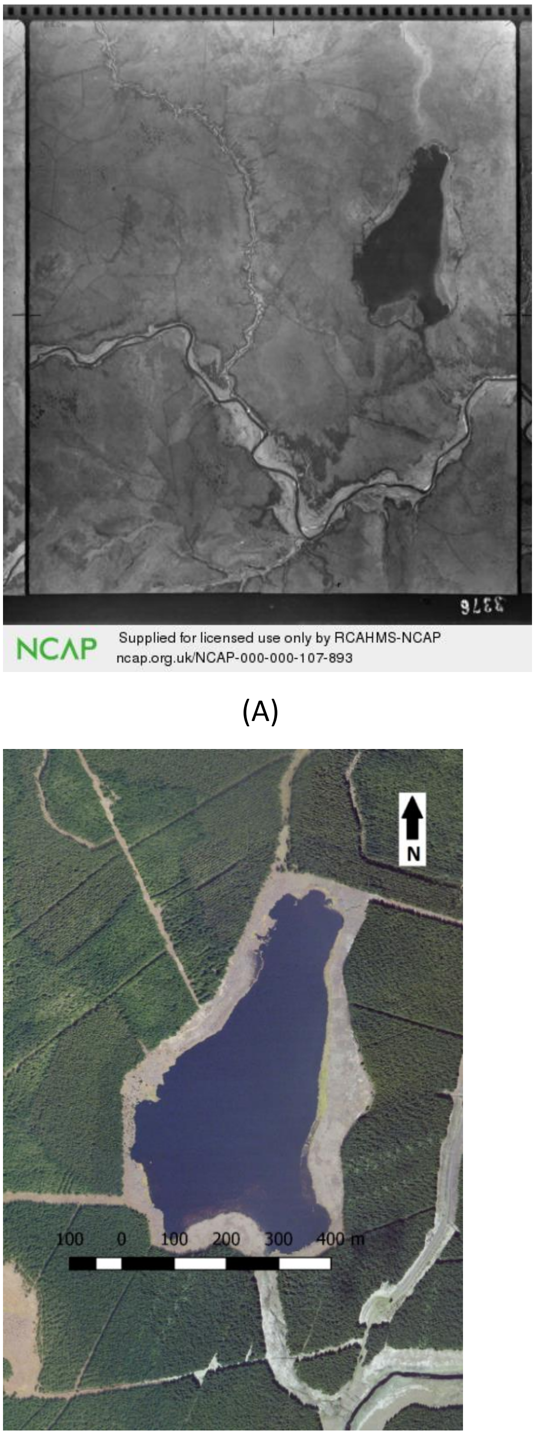


(A) (B)

Figure 3.10 Loch nan Clach Geala-west (CLAC), (A) Loch bathymetry, 2015 (contours in cm) and (B) Percentage macrophyte cover, 2015

Lochan Croc nan Lair (CROC), ND039452

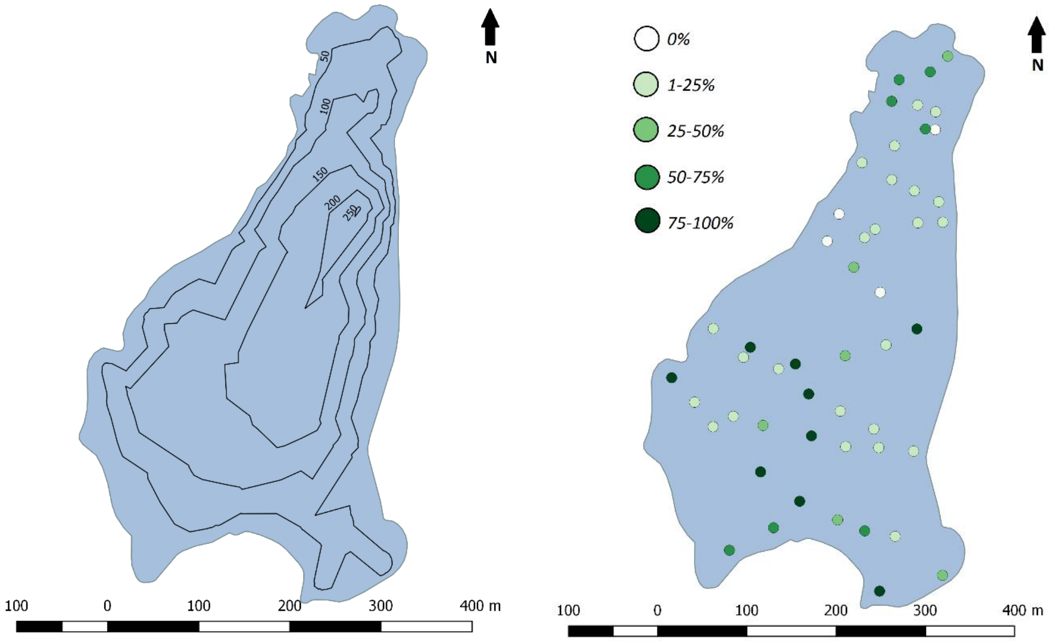
The land surrounding Lochan Croc nan Lair has changed most dramatically out of the 18 study lochs, being now totally enclosed by coniferous forestry plantations 1985 (Figure 3.11). The loch is owned by the Summerleaze estate who stocked the loch with 5,000 Trout in 2005 (M. Hancock pers. comm.). The dominant vegetation in this loch is aquatic mosses, including *Sphagnum denticulatum, Sphagnum squarrosum and Warnstorfia fluitans* (Table 3.6). the mean percentage cover was 37% (Figure 3.12 (B)). The sediment in this loch is predominantly sand, silt and peat (Figure 3.34) and reaches a maximum depth of 2.56m (Figure 3.12 (A))



(A)

(B)

Figure 3.11 Lochan Croc nan Lair (CROC), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

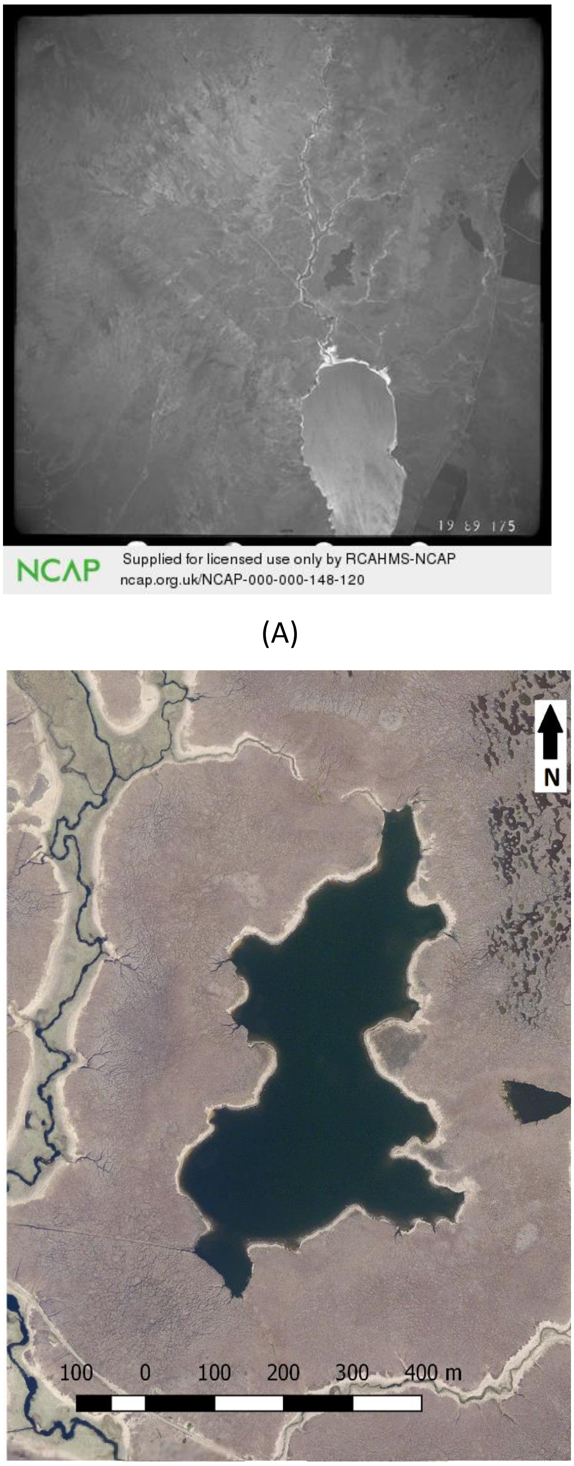


(A) (B)

Figure 3.12 Lochan Croc nan Lair (CROC), (A) Loch bathymetry, 2015 (contours in cm) and (B) Percentage macrophyte cover, 2015

Loch Culaidh (CULA), NC863390

Lying less than 1km to the north of the considerably larger loch Ruthvan, Loch Culaidh is the most southerly situated loch in our study (Figure 3.13). Owned by the Achentoul estate, the loch has a history of fishing; 5 trout were caught during the 2010-2011 surveys. The loch has a complex undulating shoreline shape, having a number of sandy bays, predominant aquatic macrophytes include Isoetids in shallow shoreline areas and large areas of floating *Sparganium* sp. in the centre (Table 3.7). The loch reaches a maximum depth of 1.7m with 55% being less the 1m deep (Figure3.14 (A)). The mean percentage cover recorded at Loch Culaidh was 50%, range 5-90% (Figure 3.14(B).



(A)

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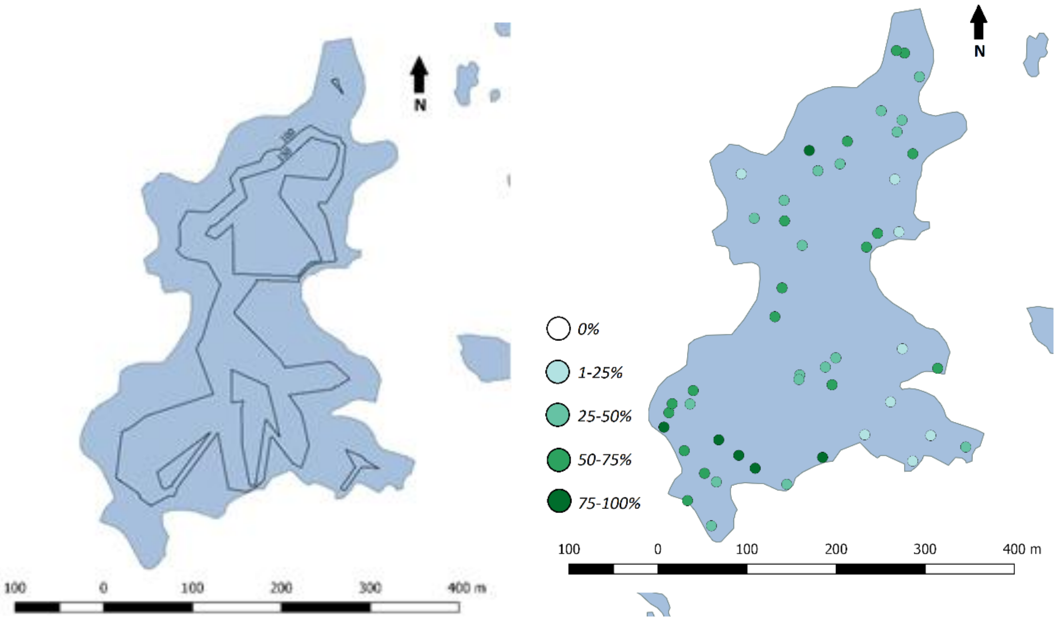
Figure 3.13 Loch Culaidh (CULA), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

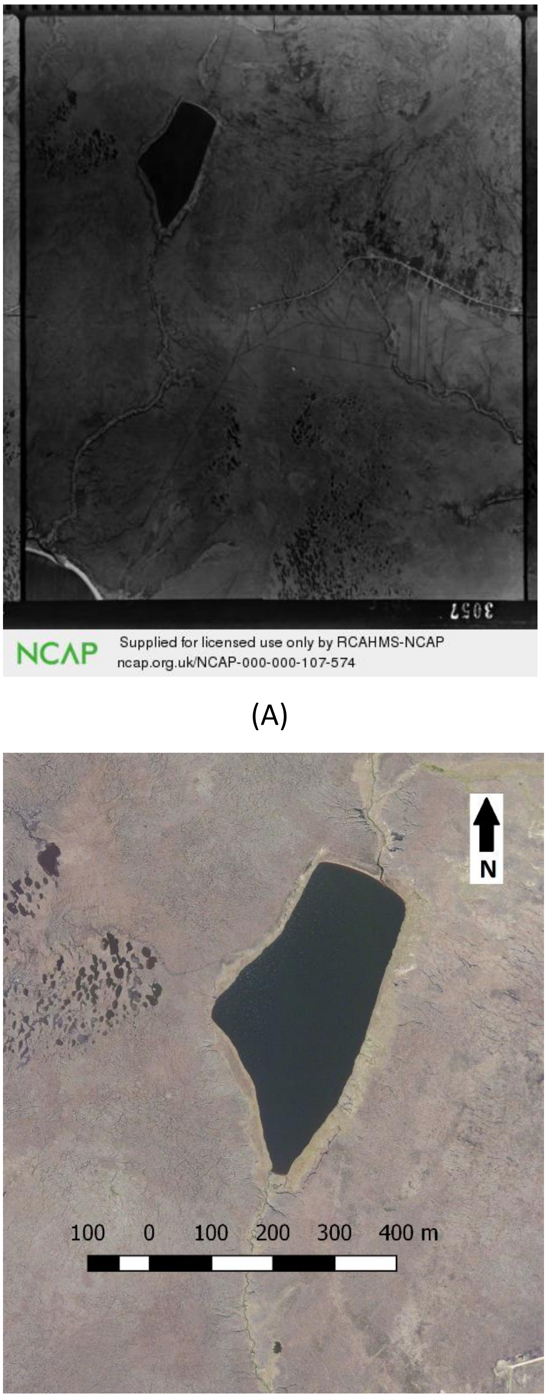


(A) (B)

Figure 3.14 Loch Culaidh (CULA), (A) Loch bathymetry, 2015 (contours in cm) and (B) Percentage macrophyte cover, 2015

Lochan Dubh Cul na Beinne (DUCU), NC984544

Lochan Dubh Cul na Beinne is one of two study lochs owned by the Shurrery estate, considerably smaller and shallower than neighbouring lochs Scye and Calium, Lochan Dubh Cul na Beinne has a simple shape and bathymetry (Figure 3.16). The loch itself is situated within a shallow depression in the landscape and has the remnants of a weir at its outlet, perhaps suggesting it had been deeper (Figure 3.15). 26 trout were caught at this loch in 5 rod hours in 2011, the highest recorded from any of the study sites. Typical macrophytes at Lochan Dubh Cul na Beinne included *Isoetes lacustris, Littorella uniflora and Myriophyllum alterniflorum.* Two species of Charophyte were recorded at the loch *Chara virgate* and *Nitella flexilis agg.* (Table 3.7) mean percentage cover at Lochan Dubh Cul na Beinne was 22% (Figure 3.16)



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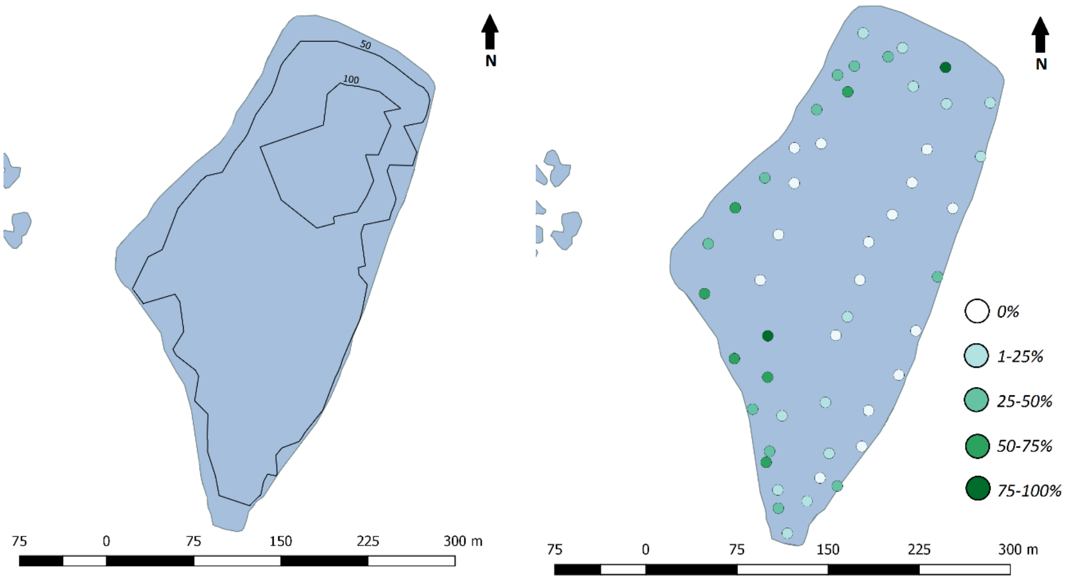
(A)

(B)

Figure 3.15 Lochan Dubh Cul na Beinne (DUCU), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

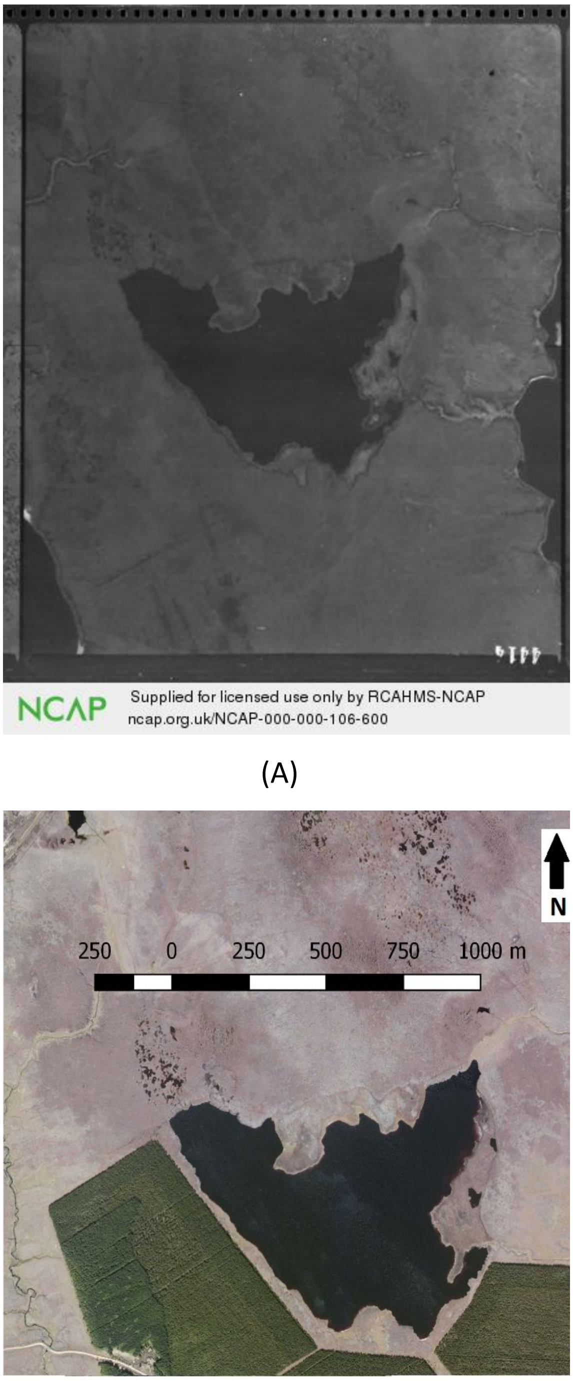


(A) (B)

Figure 3.16 Lochan Dubh Cul na Beinne (DUCU), (A) Loch bathymetry, 2015 (contours in cm) and (B) Percentage macrophyte cover, 2015

Lochan Dubh Nan Geodh (DUGE), ND060478

Lochan Dubh Nan Geodh is a large (34h) and fairly deep (1.9m) loch on the eastern edge of the study area, the south shore of this loch is planted with coniferous forestry plantations (Figure 3.17). Mean percentage cover at this loch was particularly low (Figure 3.18), only 3.3%, with most common species recorded species being mosses (Table 3.8). 52% of the loch is less than 1m deep (Figure 3.18) and approximately 45% of sediment recorded was soft, sand, silt and peat (Figure 3.34).



(A)

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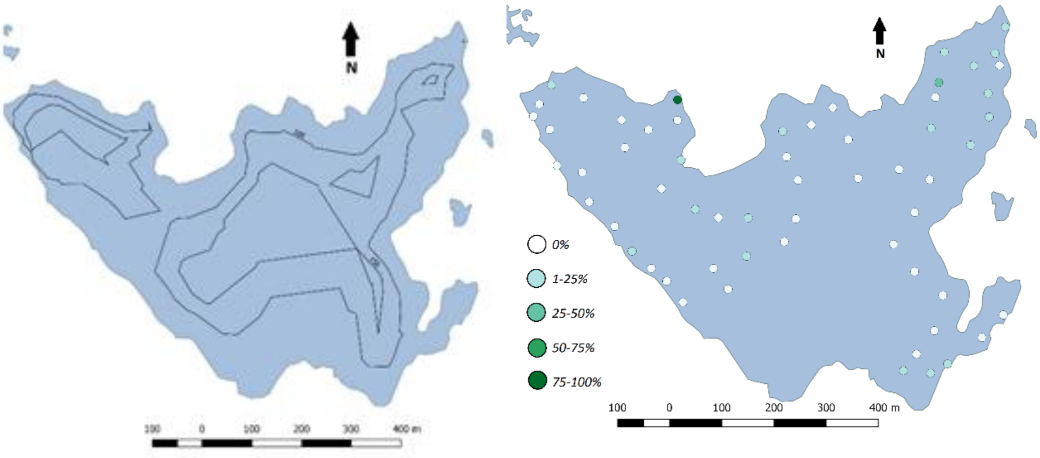
Figure 3.17 Lochan Dubh Nan Geodh (DUGE), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

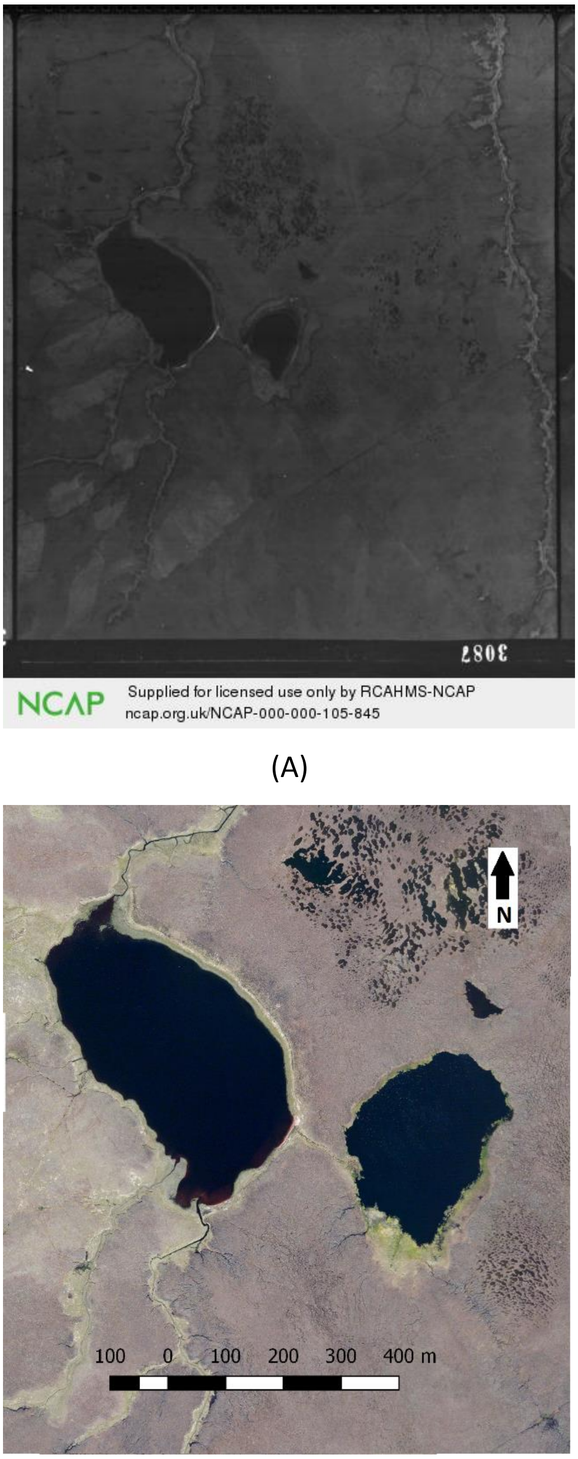


(C) (D)

Figure 3.18 Lochan Dubh Nan Geodh (DUGE), (A) Loch bathymetry, 2015 (contours in cm) and (D) Percentage macrophyte cover, 2015

Loch an Duine (DUIN)

Loch an Duine is located on some the most pristine bog in the Flow Country, towards the centre of the SSSI, it is a small and peat dominated loch located to the east of the larger loch a’Chiteadh (Figure 3.10). *Juncus bulbousus* was the most frequently recorded macrophyte at this site (Table 3.7); the majority of the vegetation was *Sphagnum* mosses (Table 3.8). Shore based survey conducted at Loch an Duine in 2015, therefore no bathymetry or macrophyte cover maps were produced for this loch



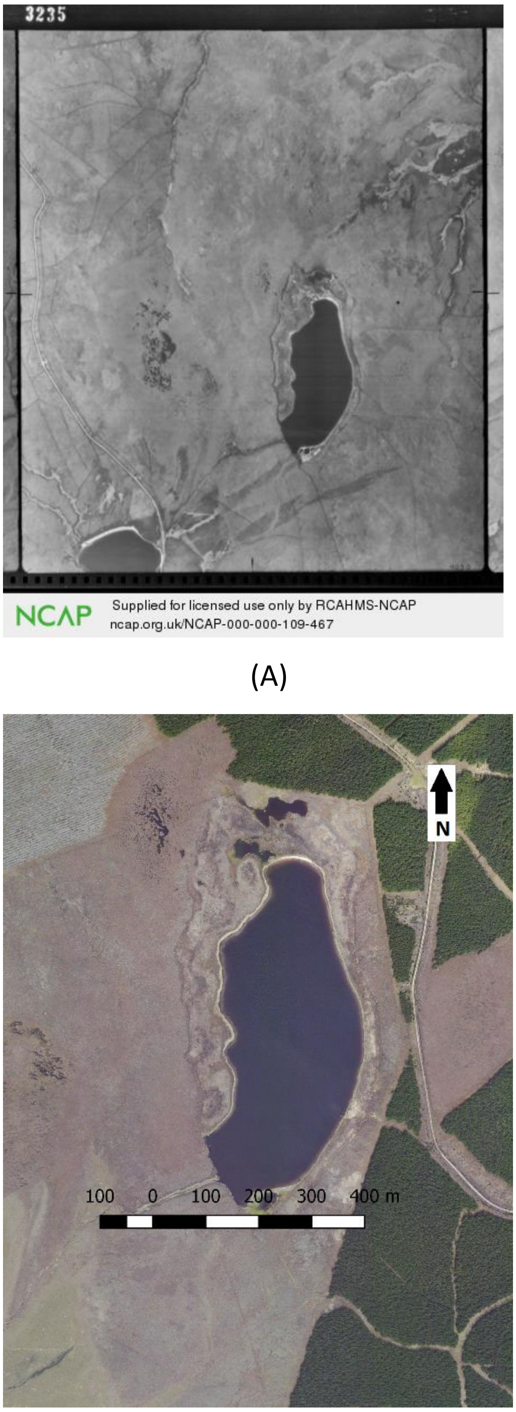
(A)

(B)

Figure 3.10 Loch an Duine (DUIN), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

Loch nam Fear (FEAR), ND025431

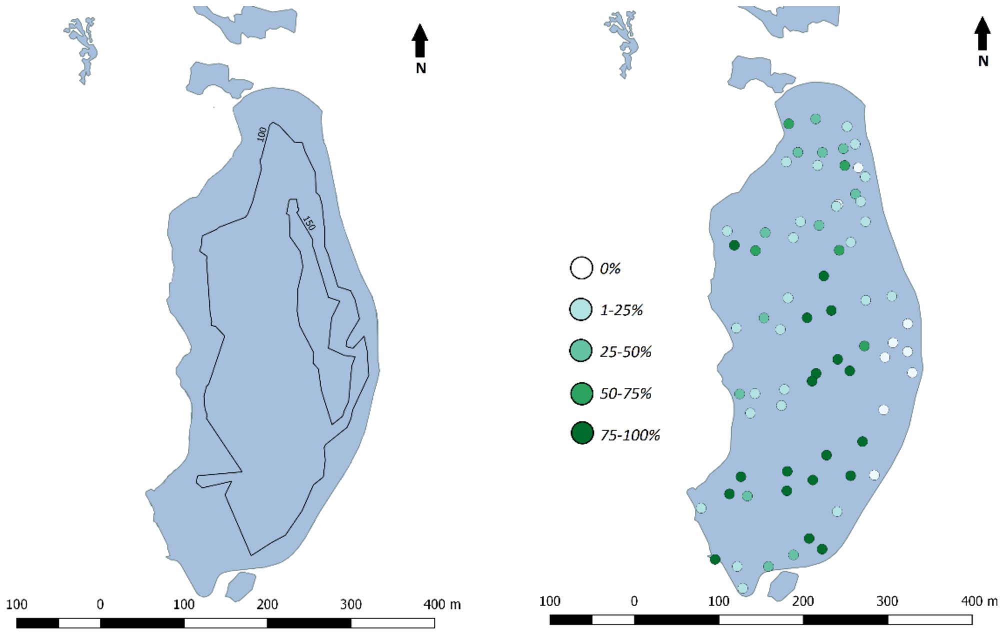
Loch nam Fear is the most productive loch for breeding common scoter in the Flow Country. The aquatic macrophytes of Loch nam Fear are dominated by *Nitella flexilis agg.* and the mean percentage cover was 42% (Figure 3.20). The loch is now surrounded by forestry to the north and east (Figure 3.19). Loch nam Fear reaches a depth of 1.8m, 44% of the loch is less than 1m deep. The outlet of this loch is located in the south west corner, with water levels controlled by a weir which has in recent times become broken, no longer performing its original purpose. Fish in this loch include brown trout and stickleback (RSPB data)



(A)

(B)

Figure 3.19 Loch nam Fear (FEAR), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

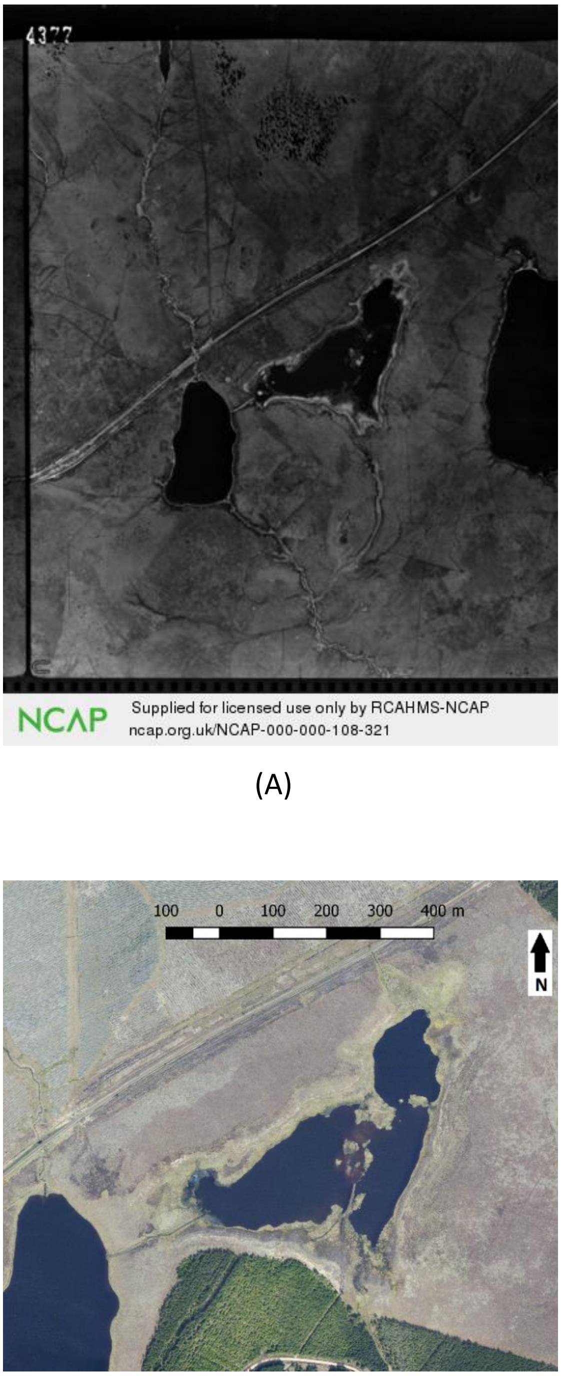


(A) (B)

Figure 3.20 Loch nam Fear (FEAR), (A) Loch bathymetry, 2015 (contours in cm) and (B) Percentage macrophyte cover, 2015

Grassie Loch (GRAS), ND030469

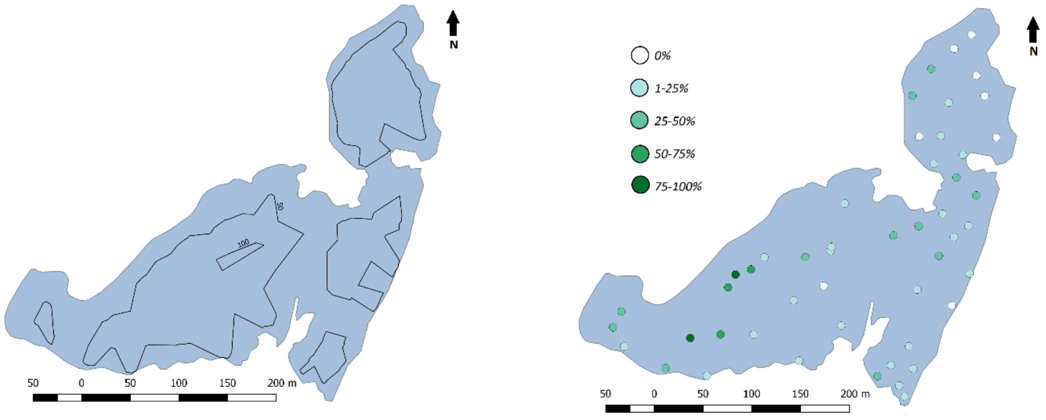
Grassie Loch is a very shallow loch, with 100% of its area below 1m on depth (Figure 3.22). It lies between two larger and deeper lochs Garbh and Caise to the east and west and has the railway line running to the north (Figure 3.21). The three lochs are enclosed the south by plantation forestry. Grassie Loch has a number of small islands present in its centre on which gulls nest. The sediment of Grassie Loch is predominantly silt (Figure 3.34). Macrophyte species include *Littorella uniflora, Lobelia dortmanna, Myriophyllum alterniflorum* and mean percentage cover is 20% (Table 3.7).



(A)

(B)

Figure 3.21 Grassie Loch (GRAS), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

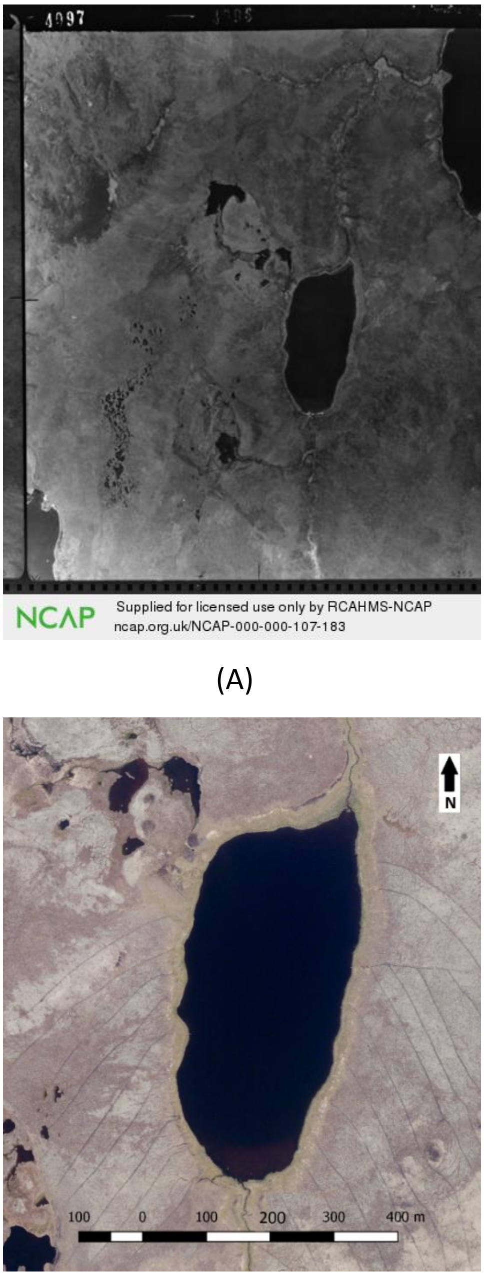


(C) (D)

Figure 3.22 Grassie Loch (GRAS), (A) Loch bathymetry, 2015 (contours in cm) and (D) Percentage macrophyte cover, 2015

Loch na h-Eaglaise Beag (HEBE), NC854590

Loch na h-Eaglaise Beag and Loch na h-Eaglaise Mor are located in the north westerly quadrant of our study area, 5km from the nearest track. Similar to Loch Losgann and Loch an Duine these are considered to be amongst the least impacted sites in the Flow Country. Loch na h-Eaglaise Beag, is located 500m south west of Loch na h-Eaglaise Mor, and is smaller than its neighbour (Figure 3.23). It has a substrate more dominated by hard cobbles and gravel than silt and peat (Figure 3.34). The loch is shallow with a maximum depth of 130 and proportion below 1m depth of 85% (Figure 3.24). From aerial imagery of the site a significant number of drainage ditches can be observed around Loch na h-Eaglaise Beag, indicating that despite its remote location it has been impacted by anthropogenic land use activities. Percentage cover at Loch na h-Eaglaise Beag was low (mean 1%), most commonly recorded species was *Potamogeton natans* and *Fontinalis antipyretica* (Tables 3.7 and 3.8).



(A)

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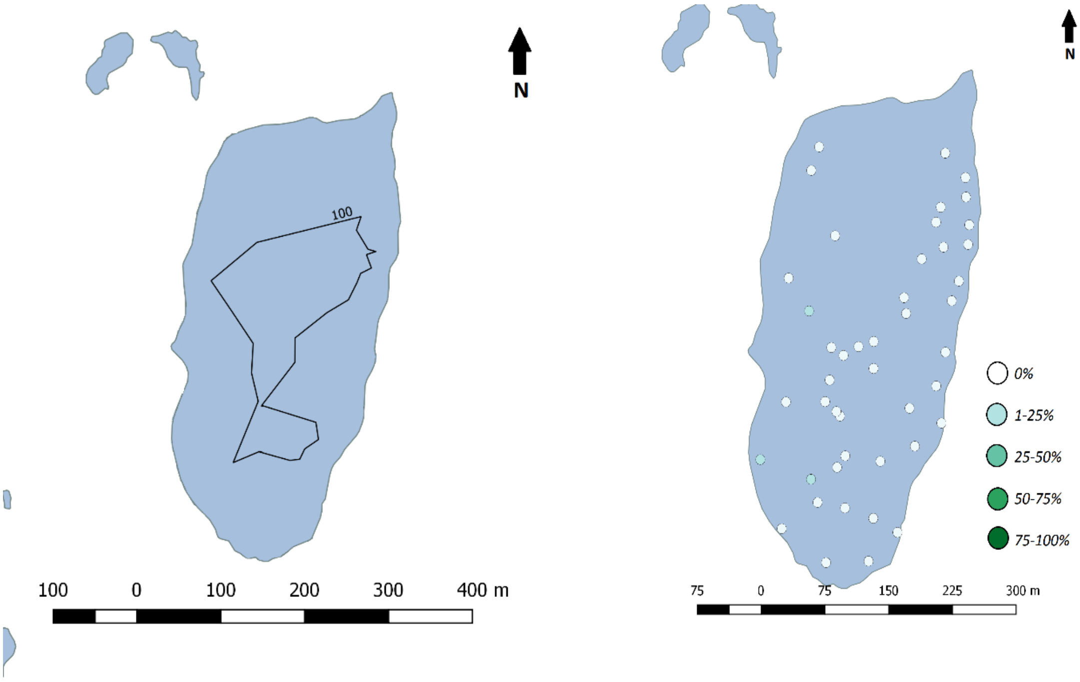
Figure 3.23 Loch na h-Eaglaise Beag (HEBE), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

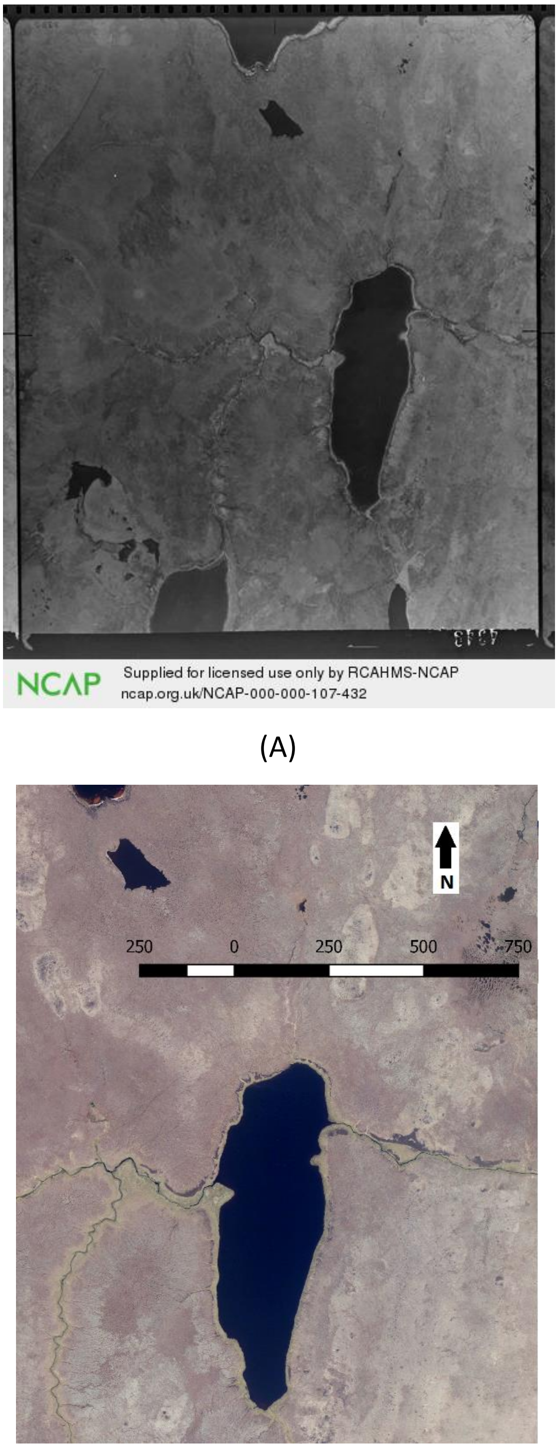


(A) (B)

Figure 3.24 Loch na h-Eaglaise Beag (HEBE), (A) Loch bathymetry, 2015 (contours in cm) and (D) Percentage macrophyte cover, 2015

Loch na h-Eaglaise Mor (HEMO), NC861599

Loch na h-Eaglaise Mor is one of a pair of lochs located on the north-west extent of the scoters Flow Country range; Loch na h-Eaglaise Mor is the most northerly study site and is the closest site to the sea (Figure 3.25). Loch na h-Eaglaise Mor is deeper and larger than Loch na h-Eaglaise Beag, with only 28% of the total area below 1m in depth (Figure 3.26). The most frequently occurring macrophyte was *Myriophyllum alterniflorum* (Table 3.7), with a mean percentage cover of 9%. The DOC concentrations at Loch na h-Eaglaise Mor and Loch na h-Eaglaise Beag were amongst the highest recorded at any of the study sites (Table 3.5).



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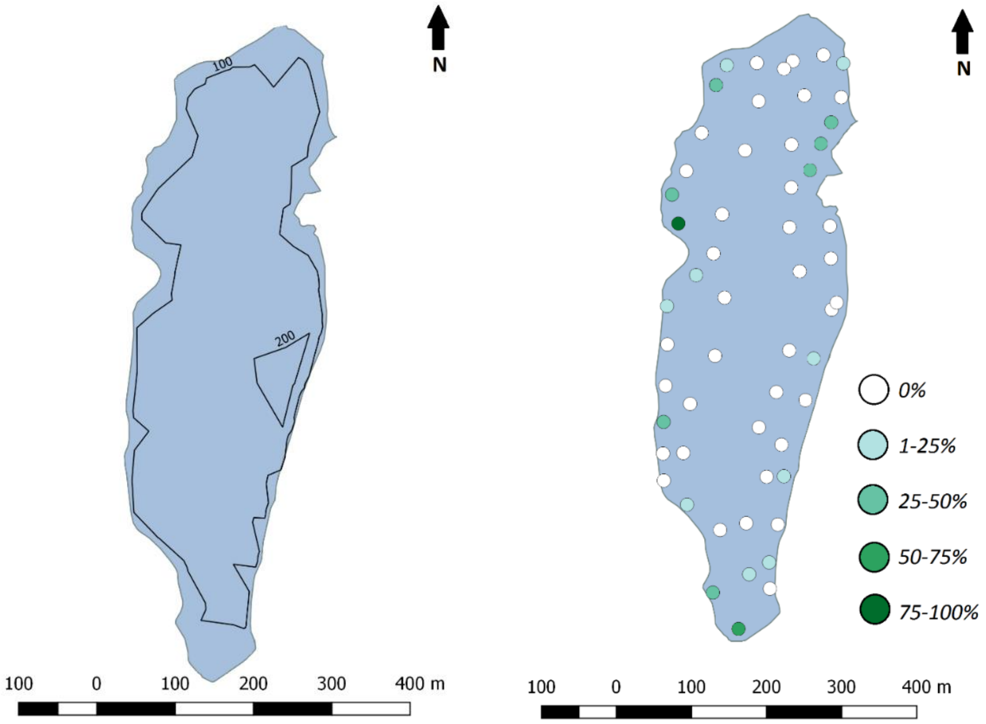
(A)

(B)

Figure 3.25 Loch na h-Eaglaise Mor (HEMO), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

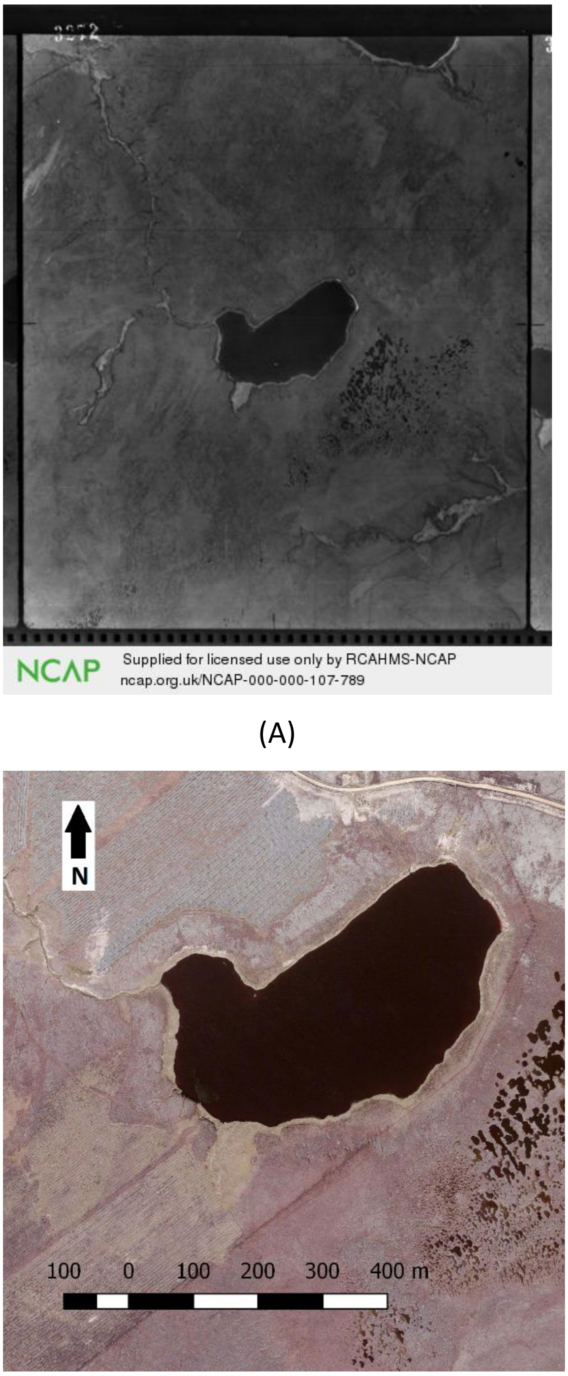


(A) (B)

Figure 3.26 Loch na h-Eaglaise Mor (HEMO), (A) Loch bathymetry, 2015 (contours in cm) and (D) Percentage macrophyte cover, 2015

Loch Leir (LEIR), NC955458

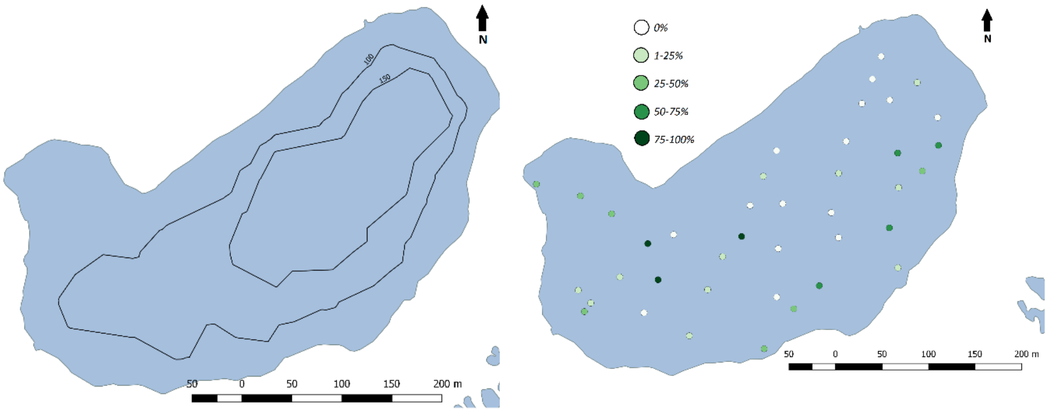
Loch Leir is located on the RSPB Forsinard flows reserve; the remains of the forestry plantations can be seen on the recent Google Earth image to the north and west of the loch (Figure 3.27). To the south east is a bog pool complex. The forestry was planted in 1985 and was amongst the first to be felled in 2003. Loch Leir reaches a depth of 1.7m with 48% below 1m (Figure 3.28). Aquatic macrophytes in this loch are *Isoetes lacustris, Littorella uniflora* and *Lobelia dortmanna* together with *Subularia aquatica* a species less common in Flow Country lochs. Mean percentage cover was 22%.



(A)

(B)

Figure 3.27 Loch Leir (LEIR), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

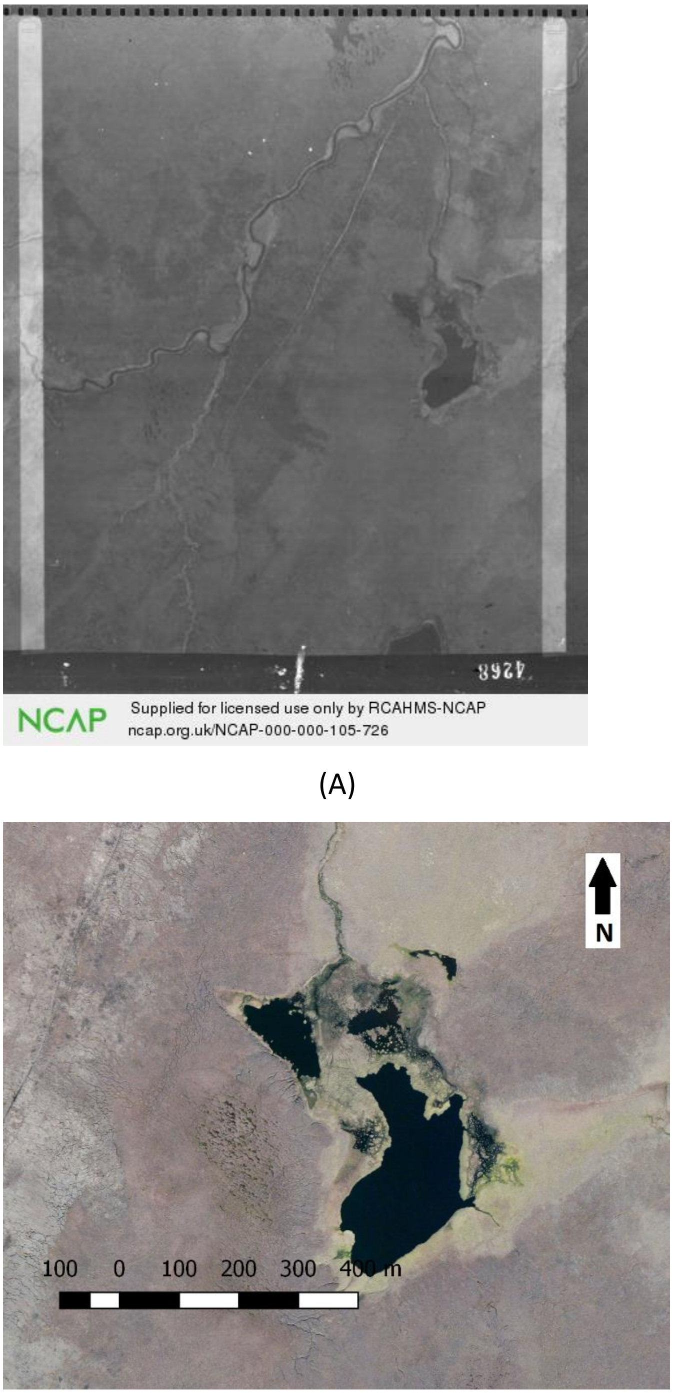


(A) (B)

Figure 3.28 Loch Leir (LEIR), (A) Loch bathymetry, 2015 (contours in cm) and (D) Percentage macrophyte cover, 2015

Loch Losgann (LOSG), ND026500

Located to the west of loch an Duine, Loch Losgann is slightly larger but also located in some of the most pristine blanket bog in the Flow Country, and surrounded by networks of small pools and lochans (Figure 3.29). LOSG has a similar sediment composition and aquatic macrophyte community to loch DUIN and has two species of moss not recorded at the other sites *Riccardia chamedryfolia, Scapania undulata* (Table 3.8). A shore based survey was conducted at Loch Losgann in 2015, therefore no bathymetry or macrophyte cover maps were produced for this loch



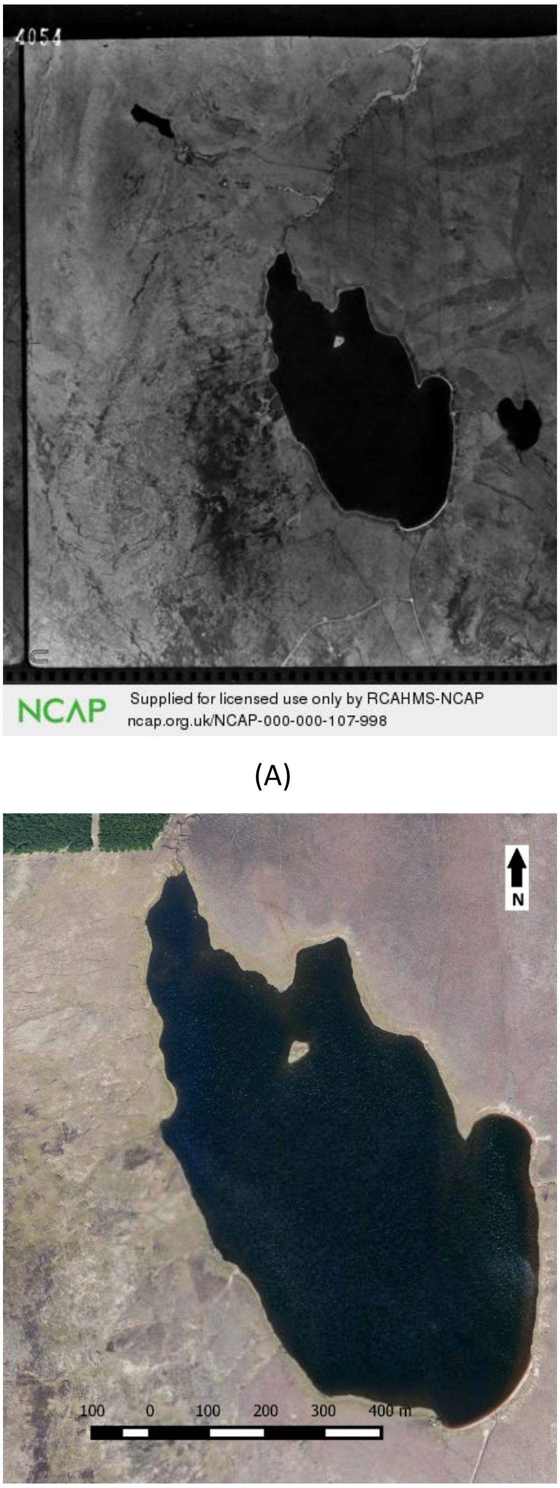
(A)

(B)

Figure 3.29 Loch Losgann (LOSG), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

Loch Scye (SCYE), ND006554

Loch Scye is the largest (35h) and deepest (3.8m) study loch, located in the north-west area of Flows and owned by the Shurrery estate. It has large sandy bays located on its south and north west shores (Figure 3.30). Its inlet, located towards the northern end of the loch, flows through coniferous forestry plantations before entering Loch Scye. Fish at Loch Scye include brown trout and stickleback. It has a small fishing hut on its south shore and otters are also known to visit this loch as evidence by their spraints. Mean percentage cover at Loch Scye was 24, and 34% is less than 1.5m deep (Figure 3.31).



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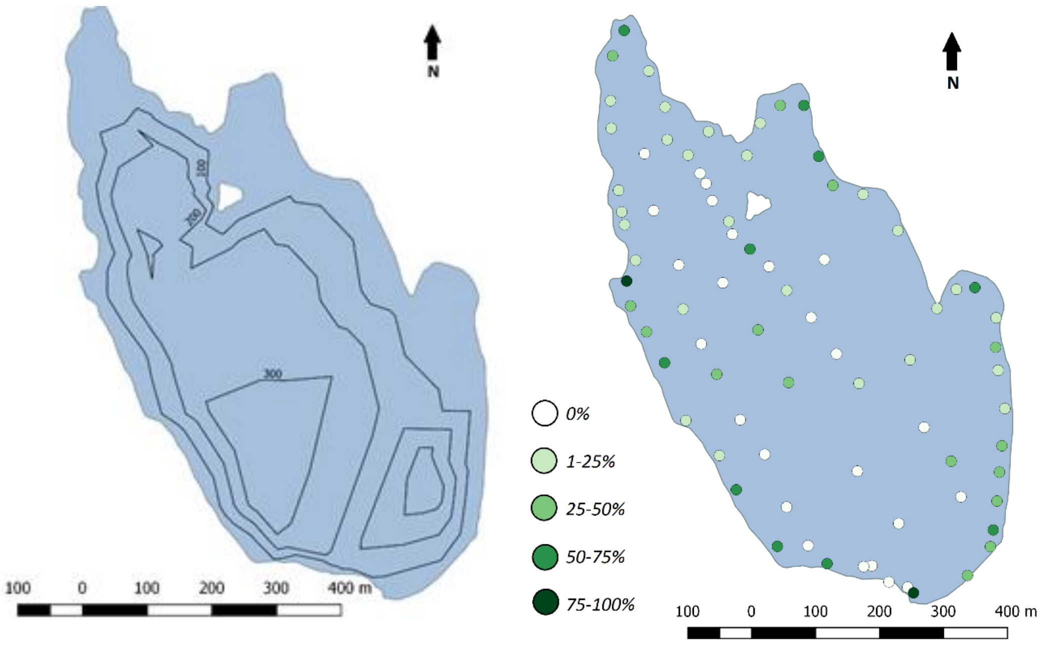
(A)

(B)

Figure 3.30 Loch Scye (SCYE), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)

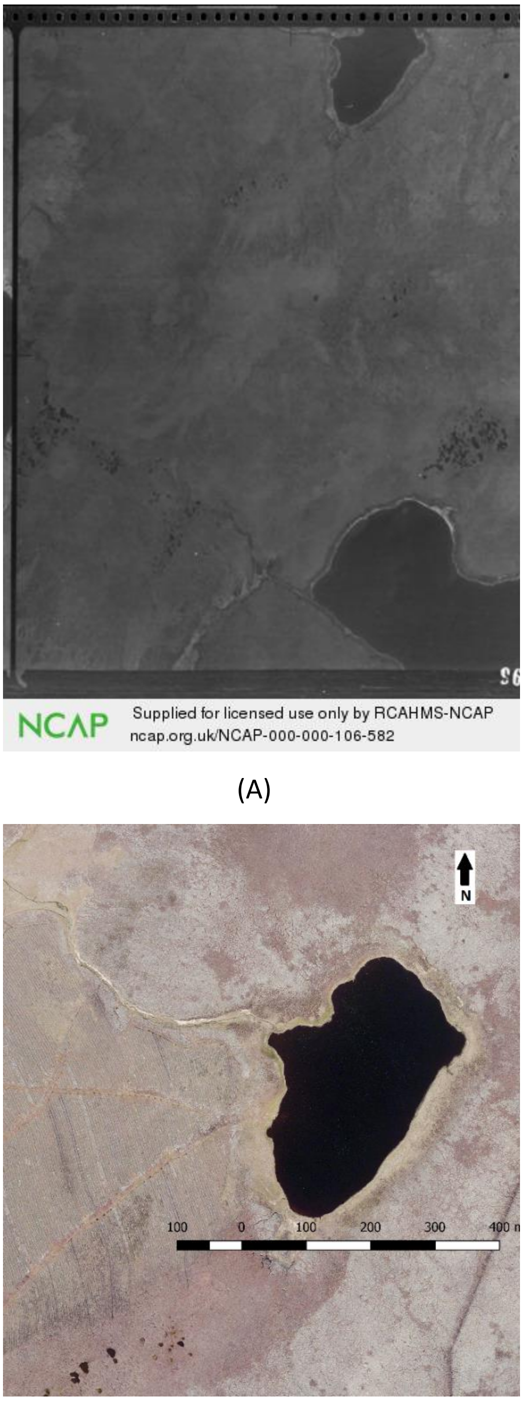


(A) (B)

Figure 3.31 Loch Scye (SCYE), (A) Loch bathymetry, 2015 (contours in cm) and (B) Percentage macrophyte cover, 2015

Loch Talaheel (TALA), NC955489

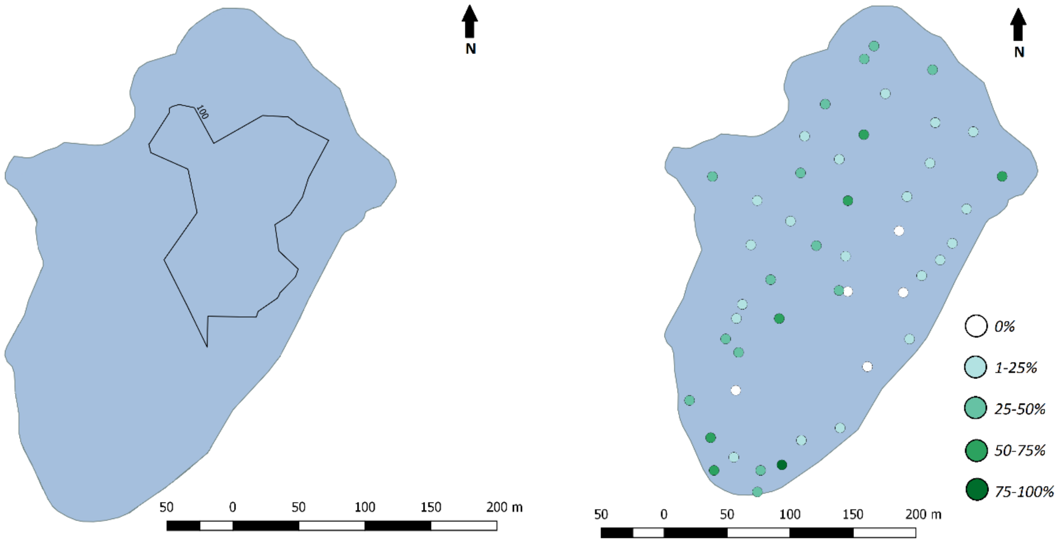
Loch Talaheel is located on part of the Forsinard Flows nature reserve to the north of Loch Sletill (Figure 3.32). It is a small (4h), shallow (1.3m deep) loch which was 1985 surrounded by plantation forestry. The forestry was felled in 1999 and was amongst the first to be removed by RSPB. The loch an inlet on its north-west side and an outlet to the south. Its sediment composition is dominated by sand, aquatic macrophytes include *Isoetes lacustris, Juncus bulbosus, Littorella uniflora, Lobelia dortmanna* and *Myriophyllum alterniflorum* (Table 3.7), mean percentage cover is 27% (Figure 3.33).



(A)

(B)

Figure 3.32 Loch Talaheel (TALA), (A) 1940s aerial photograph (National Collection of Aerial Photography (NCAP), 1940), (B) Present day aerial image (Bing Aerial, 2017)



(C) (D)

Figure 3.33 Loch Talaheel (TALA), (A) Loch bathymetry, 2015 (contours in cm) and (D) Percentage macrophyte cover, 2015

3.4.1.2 Physico-chemistry

Bathymetry

Overall the loch shorelines are characterised by steep sided steps down from the surrounding peat into shallow (<50cm) water and more gently sloping areas of shallow wave washed shores consisting of either sand or peat and small cobbles. The lochs are all shallow (only three reaching more than ca. 2.5m in depth). The bathymetry is typically gently sloping towards the centre or towards one end. The deepest loch is SCYE and the shallowest GRAS (Figure 3.34)

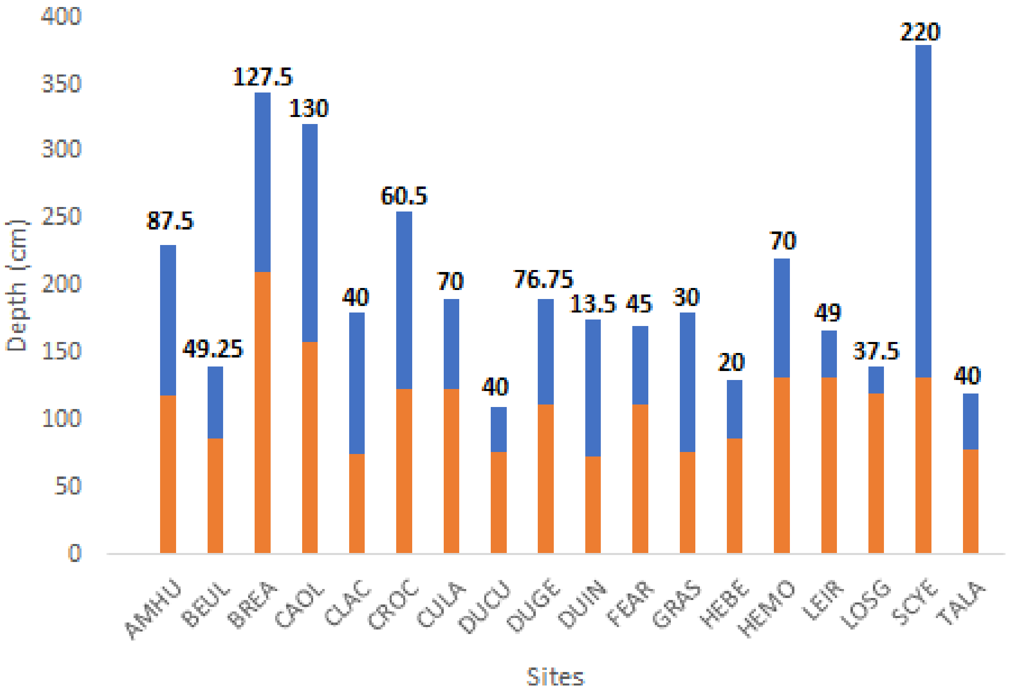


Figure .3.34 Maximum (blue bar), mean (orange bar) and interquartile range (text) of water depths recorded in the surveys of the 18 study lochs in 2015

Sediment composition

All six sediment types were identified in the study sites; sand and cobbles were present at all the sites as was peat and/or silt. Gravel and boulders were found at seven and nine of the 18 sites respectively. Sediment depth ranged from 0 to in excess of 310cm; sediment score gives an indication of the predominant sediment type recorded in the loch, the sediment composition of sites with low sediment scores are characterised by substrates with a larger particle sizes (boulders, cobbles and gravel) whereas sites with high scores are dominated by finer particle sediments (sand, silt and peat). Loch DUIN had the highest sediment score, followed by Lochs FEAR, CULA, and CROC; the largest and deepest sites (SCYE and DUGE) had the lowest sediment scores (Figure 3.35).

Site	MSD	SS
AMHU	63.61	0.18
BEUL	26.83	0.22
BREA	66.57	0.22
CAOL	114.32	0.40
CLAC	18.59	0.35
CROC	44.44	0.58
CULA	113.90	0.60
DUCU	39.27	0.56
DUGE	36.33	0.11
DUIN	23.65	1.00
FEAR	146.24	0.60
GRAS	28.63	0.30
HEBE	52.78	0.45
HEMO	81.07	0.43
LEIR	108.27	0.54
LOSG	6.73	0.45
SCYE	53.48	0.00
TALA	26.04	0.18

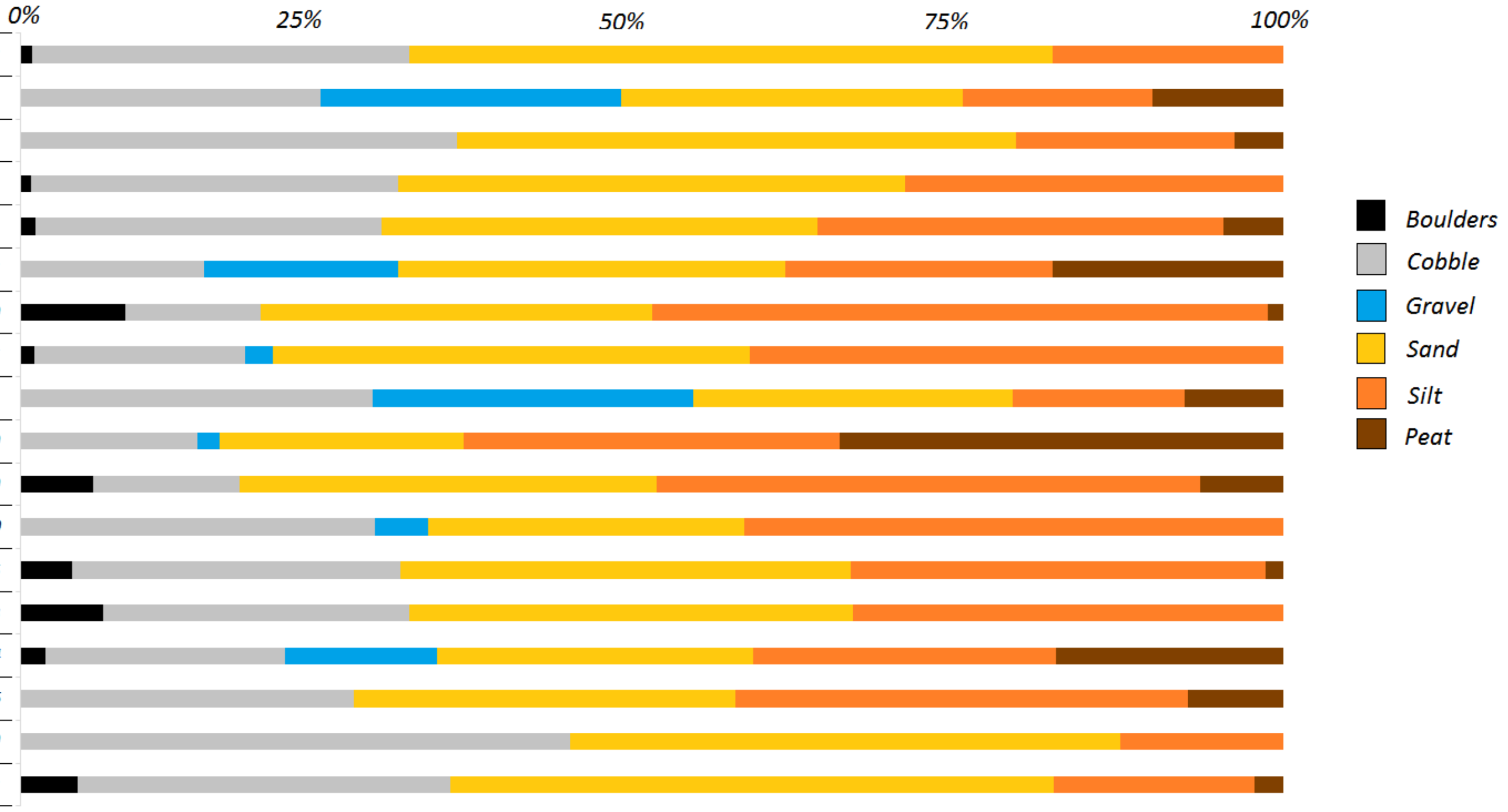


Figure.3.35 percentage composition of different sediment types recorded at each of the 18 study lochs, MSD= Mean sediment depth (cm), SS=Sediment score

Water chemistry

The pH range in August 2014 was pH 5.13-6.82 (Table 3.5) which is within the range for small, predominantly northern dystrophic peat pools dominated by *Sphagnum* species (categorised as type A by Duigan *et al.,*(2006)). The lochs with the lowest pH (DUIN and DUGE) also had the highest organic content in the surface sediments (measured as loss on ignition (LOI)). Conductivity range is 54.8 – 87.3 *uS*cm^{-1} below the mean value for this lake type (120.10 *uS*cm^{-1}), but within the range (12.10 – 530*uS*cm^{-1}, Duigan *et al.,*(2006)). The chlorophyll A range was predominantly below the mean value recorded for oligotrophic lakes, with the exception of GRAS (2.598 ug/L) and LEIR (4.980 ug/L), both of which were below the maximum value for oligotrophic loch types (OCED, 1982). Dissolved organic carbon (DOC) ranged from 4.33ppm to 14.72ppm with a mean of 8.30ppm. Dissolved oxygen (DO) ranged from 12.44 – 13.21 mg/L; when measured at 50cm depth intervals during October 2013, the lochs were not stratified.

Nitrate in the lochs was low (Table 3.6, 0.0-0.1 mg/L) as is typical of oligotrophic, acidic systems (Rydin and Jeglum, 2013).

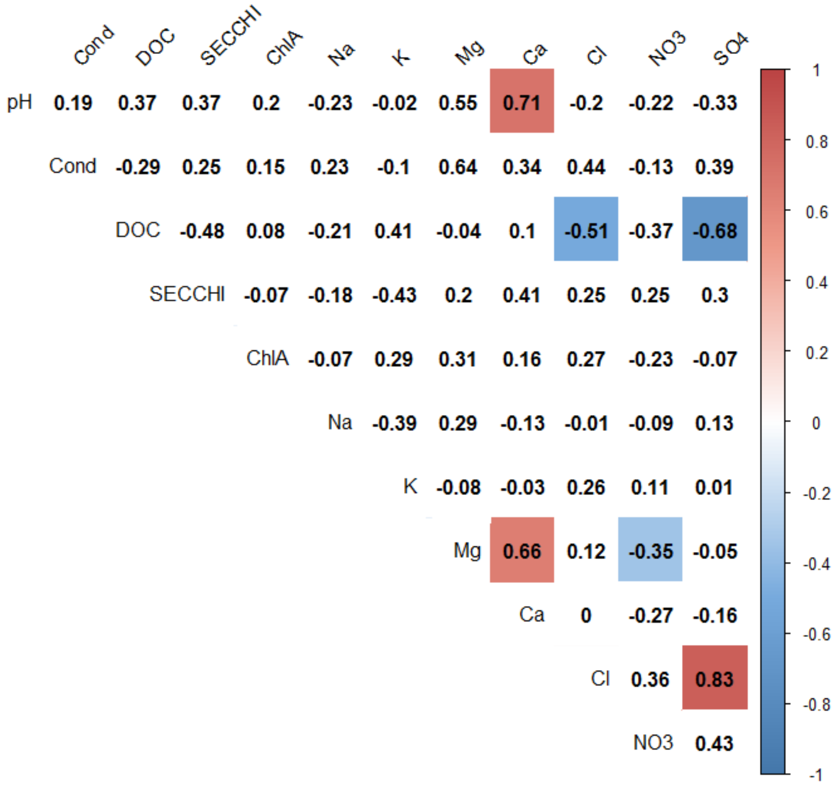
Site Code	pH	Conductivity (us/cm^3)	DOC ppm	DO (mg/L)	LOI surface (%)	Chlorophyll A (mg/L)
AMHU	5.53	54.3	6.52	11.79	44.1	1.77
BEUL	5.56	61.7	5.33	12.79	69.2	1.27
BREA	6.1	59.1	10.78	11.56	76.5	1.62
CAOL	6.7	77.8	6.20	12.68	35.0	0.62
CLAC	5.8	56	4.33	12.86	53.9	1.04
CROC	5.4	76.2	4.97	12.75	23.2	0.34
CULA	6.8	69.5	4.57	12.54	56.7	1.89
DUCU	6.8	57.6	15.11	12.84	15.8	1.14
DUGE	5.2	87.2	5.10	12.75	86.6	2.23
DUIN	6.8	82.2	6.89	12.65	83.7	1.03
FEAR	5.13	72.3	6.38	11.63	56.4	0.37
GRAS	6.8	87.3	9.41	13.21	39.2	2.60
HEBE	6.4	64.4	14.72	12.51	16.0	0.64
HEMO	6.58	71.9	14.10	11.69	38.3	1.97
LEIR	6.2	62.2	9.37	11.71	41.0	4.98
LOSG	5.4	56.5	8.87	12.54	33.8	1.64
SCYE	6.7	73.7	5.99	12.53	33.0	2.08
TALA	6.17	55.2	9.97	11.89	6.6	1.40
Min.	5.13	54.3	4.33	*11.56*	6.6	0.34
Max.	6.8	87.3	15.11	*13.21*	86.6	4.98
Mean	6.115	68.1	8.30	*12.38*	45.0	1.59

Table 3.4 Water chemistry recorded at the 18 study lochs in April 2015

Site Code	Sodium mg/L	Potassium mg/L	Magnesium mg/L	Calcium mg/L	Chloride mg/L	Nitrate mg/L	Sulphide mg/L
AMHU	9.5	1.2	1.9	5.8	11.3	0.01	1.4
BREA	9.1	1.4	1.9	7.2	9.6	0	1
BEUL	9.2	1.3	1.4	5.1	15.5	0.1	2.4
CAOL	11.1	0.6	2.2	6.5	13.9	0.03	2.1
CLAC	8.6	0.4	1.5	5.2	8	0.01	1.4
CROC	11.4	1.2	2	6.2	15.8	0.02	2.7
CULA	10.3	0.4	2	6.3	13.1	0.02	2.1
DUCU	9.8	1.5	1.7	6.8	10	0.02	1.2
DUGE	12.7	1.4	2	5.2	17.1	0.02	2.9
DUIN	9.7	0.7	1.5	5.4	10.2	0.01	1.2
FEAR	11.7	0.9	3	7.4	10.1	0.03	1.2
GRAS	11.6	0.8	2.5	6.2	11.7	0.01	1.4
HEBE	12.1	0.6	1.9	5.5	2.4	0	0.5
HEMO	0.9	1.8	1.9	5.9	13.3	0	1.2
LEIR	11.1	1.7	2.6	7	13.3	0	1.2
LOSG	10.5	1	1.5	5.1	11.3	0.04	1.1
SCYE	1.6	0.6	2	7.7	12.3	0.03	1.7
TALA	1.7	2.4	1.6	5.7	10.4	0.04	1.5
Min.	*0.9*	*0.4*	*1.5*	*5.1*	*2.4*	*0.0*	*0.5*
Max.	*12.7*	*2.4*	*3.0*	*7.7*	*17.1*	*0.1*	*2.9*
Mean	*9.03*	*1.11*	*1.95*	*6.12*	*11.63*	*0.02*	*1.57*

Table. 3.5 Water chemistry, anion and cation analysis of water from the 18 study lochs

A correlation matrix of water chemistry variables from the study lochs is shown in Figure 3.36, significant (<0.01) correlations are highlighted. Strong positive correlations can be seen between calcium and both magnesium and pH. Sulphate and chloride show a strong negative correlation with DOC and are themselves correlated. There is also a significant negative correlation between nitrate levels and magnesium.



	Cond	DOC	SECCHI	ChlA	Na	K	Mg	Ca	Cl	NO3	SO4
pH	0.19	0.37	0.37	0.2	-0.23	-0.02	0.55	0.71	-0.2	-0.22	-0.33
Cond		-0.29	0.25	0.15	0.23	-0.1	0.64	0.34	0.44	-0.13	0.39
DOC			-0.48	0.08	-0.21	0.41	-0.04	0.1	-0.51	-0.37	-0.68
SECCHI				-0.07	-0.18	-0.43	0.2	0.41	0.25	0.25	0.3
ChlA					-0.07	0.29	0.31	0.16	0.27	-0.23	-0.07
Na						-0.39	0.29	-0.13	-0.01	-0.09	0.13
K							-0.08	-0.03	0.26	0.11	0.01
Mg								0.66	0.12	-0.35	-0.05
Ca									0	-0.27	-0.16
Cl										0.36	0.83
NO3											0.43

Figure 3.36 Correlation matrix of water chemistry variables, significant positive (red) and negative (blue) statistically significant correlations are highlighted, the strength of the correlation is indicated by the strength of colour (scale on the right).

Principle component analysis (PCA) was used to examine variation in the water chemistry at the 18 study sites. Closely positioned sites on the PCA have a similar water chemistry; PCA also highlights relationships between the variables, a small angle between variables indicates a strong correlation (Braak and Prentice, 1988). Figure 3.37 shows axes 1 and 2 of the PCA, Cl and SO_4 are strongly correlated with one another and both are negatively correlated with DOC. Na and conductivity appear correlated, although the correlation matrix (Figure 3.36) shows not significantly so. PCA analysis of the sites water chemistry reveals four distinct groupings (Figure 3.37). DUIN, HEBE, HEMO, DUCU and BREA are all positioned along the increasing DOC gradient. On the opposite side of the ordination space DUGE and CROC are located at low DOC concentration and high sulphate and chloride concentrations. LOSG, TALA, CLAC and AMHU have high potassium concentrations but are low in pH, conductivity, sodium, magnesium and calcium. BEUL is a slight outlier in this group demonstrating some nitrate influence. The remaining sites CULA, CAOL, FEAR, LEIR, SCYE and GRAS are grouped together with high scores for pH, conductivity and associated ions.

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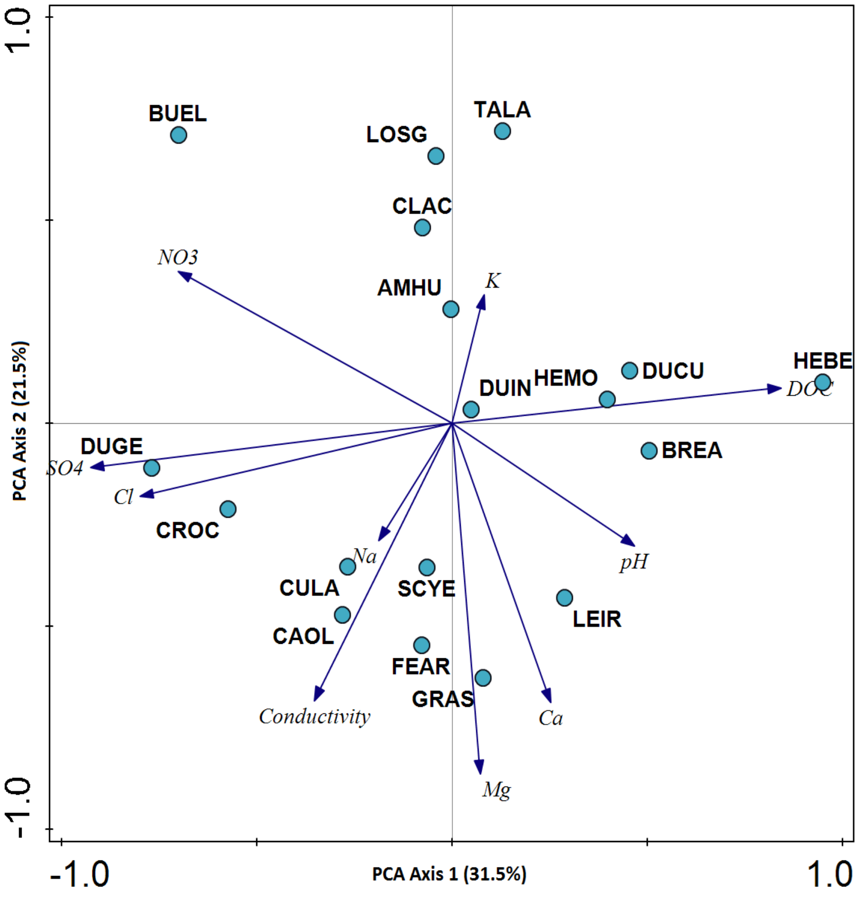


Figure 3.37 Axis 1 and 2 of a PCA of sites by water chemistry, potassium (K), dissolved organic carbon (DOC), pH, calcium (Ca), magnesium (Mg), conductivity, sodium (Na), chloride (Cl), sulphate (SO4) and nitrate (NO3)

3.4.1.3 Aquatic macrophytes

Percentage cover

Mean percentage cover at the sites ranges from <5 to 60% (Figure 3.38). Two of the largest, deepest lochs DUGE and BREA are amongst those with the lowest mean percentage cover; together with the two most northerly sites lochs HEMO and HEBE. The sites with the highest mean percentage cover (BEUL, CULA, FEAR and LOSG) are set in a mixture of landscape setting and have contrasting positions in the PCA of water chemistry characteristics. LOSG and BEUL are associated with lower pH, conductivity and higher NO_3 and K, and FEAR and CULA with higher pH, conductivity and Mg, Ca and Na.

Mean percentage macrophyte cover at different water depths is shown in Figure 3.39. Sites with the highest macrophyte cover across all depth intervals are BEUL, CULA, FEAR and LOSG. Whilst AMHU, BREA, DUGE, and HEBE have the lowest mean percentage cover of less than 20% over all depth intervals. Although HEMO has one of the lowest overall mean percentage cover scores, examination of the different depth intervals reveals that at water depths between 0 and 0.5m mean percentage cover is approximately 60%. At eight sites (AMHU, BEUL, CAOL, BREA, CROC, FEAR and Loch LEIR) macrophytes are able to colonise the deepest parts of the lochs. At remaining 10 sites aquatic macrophytes are not able to colonise the deepest points in the lochs. Maximum macrophyte colonisation depth does not appear to be related to either loch area, maximum depth or landscape setting. Several of the largest and deepest lochs are able to support benthic macrophyte communities at their deepest points whilst in a number of small, shallow lochs macrophyte colonisation does not exceed 1-1.5m

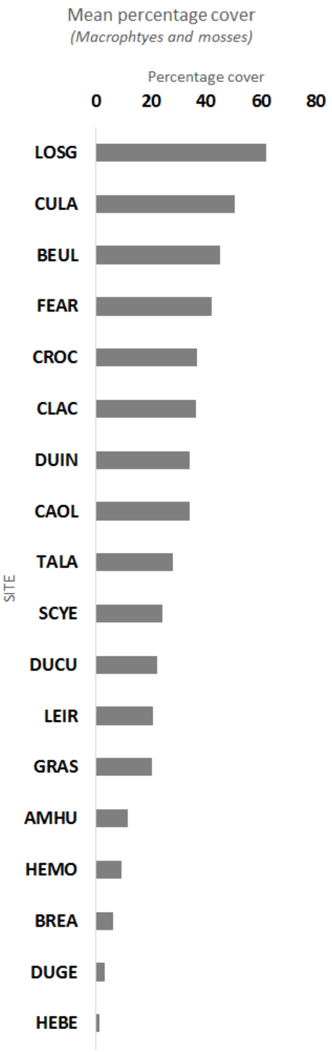


Figure 3.38 Mean percentage cover recorded at each of the 18 lochs

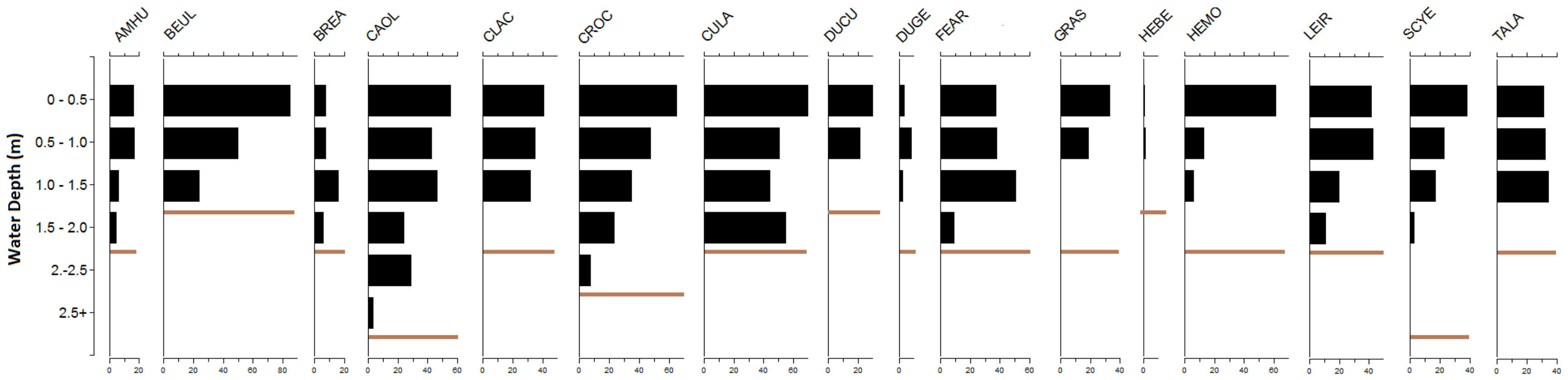


Figure 3.39 Mean percentage vegetation cover at 0.5m depth intervals at the 16 study lochs that were surveyed by boat, the brown line indicates the lochs maximum depth (Loch an Duine (DUIN) and Loch Losgann (LOSG) omitted as shore based macrophyte surveys were conducted at these sites)

Community Composition

Species frequently occurring in the study lochs included *Lobelia dortmanna, Littorella uniflora, Isoetes lacustris, Myriophyllum alterniflorum* and *Juncus bulbosus*. Potamogeton species included *P. natans, P. perfoliatus* and *P polygonifolius.* Two charophyte species *Chara virgata* and *Nitella flexilis* agg. were also recorded in BREA, FEAR, and DUCU. FEAR was dominated by *N. flexilis* agg.; it was recorded at 59 out of 70 survey points, with a mean percentage cover of 48%. (mode 100%) The most diverse aquatic macrophyte communities were at CAOL, CULA, and GRAS, whilst HEMO and HEBE had the lowest species diversity (Table 3.7). The macrophyte communities of CROC, LOSG and DUIN are typical of species poor, acidic pools and small lochs, dominated by Sphagnum and *J. bulbosus* and categorised by Palmer *et al.,* (1992) as type 1. AMHU, BEUL, CAOL, CLAC, CULA, GRAS and TALA type 2 sites, peaty lochs with species of *L. uniflora, L. dortmanna* and *P. natans*. BREA, DUGE, HEBE, HEMO and SCYE have a higher occurrence of *M. alternaflorum*, *I. lacustris* and the moss *F. antipyretica*, they are larger and rockier and classified as type 3 by Palmer *et al.,* (1992). SNH, (2001) identify a limited number of type 4 lochs in the Flow Country (9 out of 406 lochs), FEAR and DUCU belong to this group having a higher occurrence of Chara species, particularly Loch nam Fear which was dominated by *N. flexilis agg*.

The macrophyte communities of CROC, DUGE and LOSG were dominated by aquatic mosses (Table 3.8). The most frequently recorded moss species were *Sphagnum denticulatum* (8 sites), *Fontinalis antipyretica* (7 sites) and *Fontinalis squamosa* (6 sites). Two moss species were only recorded at a single site S*phagnum squarrosum* (GRAS) and *Rhytidiadelphus squarrosus* (SCYE). BREA and LOSG contained four species of moss that were not recorded at any other sites *Hygrohypnum luridum, Hypnum jutlandicum* (BREA) and *Riccardia chamedryfolia, Scapania undulata* (LOSG). Similarities in macrophyte communities between lochs was explored using detrended correspondence analysis (DCA), axis 1 and 2 account for 69.3% of the variation community composition. With the exception of the outliers, HEBE (low macrophyte diversity), LOSG (moss dominated) and FEAR (dominated by *N. flexilis*), the 18 sites are difficult to differentiate, mostly being positioned towards the centre of the ordination space, indicating much similarity in the types of macrophyte communities present at the lochs.

	AMHU	BREA	BUEL	CAOL	CLAC	CROC	CULA	DU CU	DU GE	DU IN	FEAR	GRAS	HEBE	HEM O	LEIR	LOS G	SCYE	TALA
Chara virgata								*										
Glyceria fluitans	*													*				
Isoetes lacustris	*			*			*	*	*					*	*	*	*	*
Juncus bulbosus	*	**	*	*	**	**	*		**	**		*				*	**	*
Littorella uniflora	**			**			*	**				*		*	*	*	*	*
Lobelia dortmanna	*		**	*	*		*				*	*			*			*
Myriophyllum alterniflorum	*			*			*	*		*	*	**		**	**	**	*	**
Nitella flexilis agg.		*						*			**							
Potamogeton natans	*			*								*	**					
Potamogeton perfoliatus				*											*		*	
Potamogeton polygonifolius																*		
Sparganium sp.	*	*	*	*	*	*	**	*	*	*	*	*		*				*
Subularia aquatica				*											*			
Total	**8**	**4**	**3**	**9**	**3**	**2**	**6**	**6**	**3**	**3**	**4**	**6**	**1**	**5**	**6**	**5**	**5**	**6**

*** Present** **** Most abundant macrophyte**

Table 3.6 Aquatic macrophyte species recorded in each loch in August 2015, * denotes presence, **denotes the most frequently recorded species

	AMHU	BREA	BUEL	CAOL	CLAC	CROC	CULA	DU CU	DU GE	DU IN	FEAR	GRAS	HEBE	HEMO	LEIR	LOSG	SCYE	TALA
Calliergon cordifolium				*									*					
Calliergonella cuspidata				*			*											
Cladopodiella fluitans			**		*													
Fontinalis antipyretica	**						*	**				*	**	**	**			
Fontinalis squamosa		**							**			*					**	**
Hygrohypnum luridum		*																
Hypnum jutlandicum		*																
Jungermannia sp.									*									*
Rhytidiadelphus squarrosus																	*	
Riccardia chamedryfolia																*		
Scapania undulata																**		
Sphagnum sp.					**		*			*								
Sphagnum cuspidatum						*				*								
Sphagnum denticulatum		*	*			**			*	**		**				*		*
Sphagnum squarrosum												*						
Warnstorfia exannulata				**			**			*								
Warnstorfia fluitans					*	*						*						
Total	**1**	**4**	**2**	**3**	**3**	**3**	**4**	**1**	**3**	**4**	**0**	**5**	**2**	**1**	**1**	**3**	**2**	**3**

*** Present** **** Most abundant moss**

Table 3.7 Aquatic moss species recorded in each loch in August 2015, * denotes presence, **denotes the most frequently recorded species

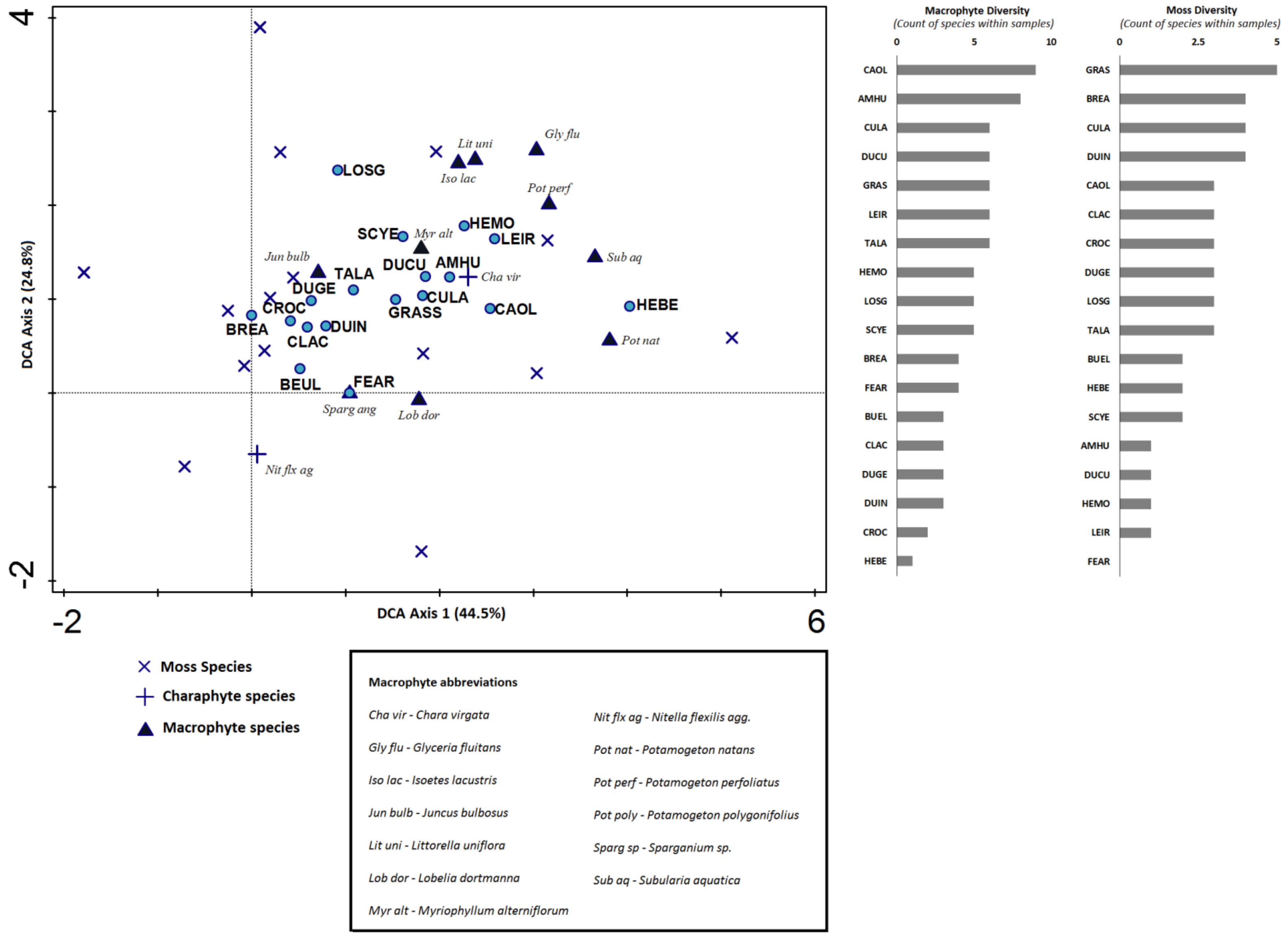
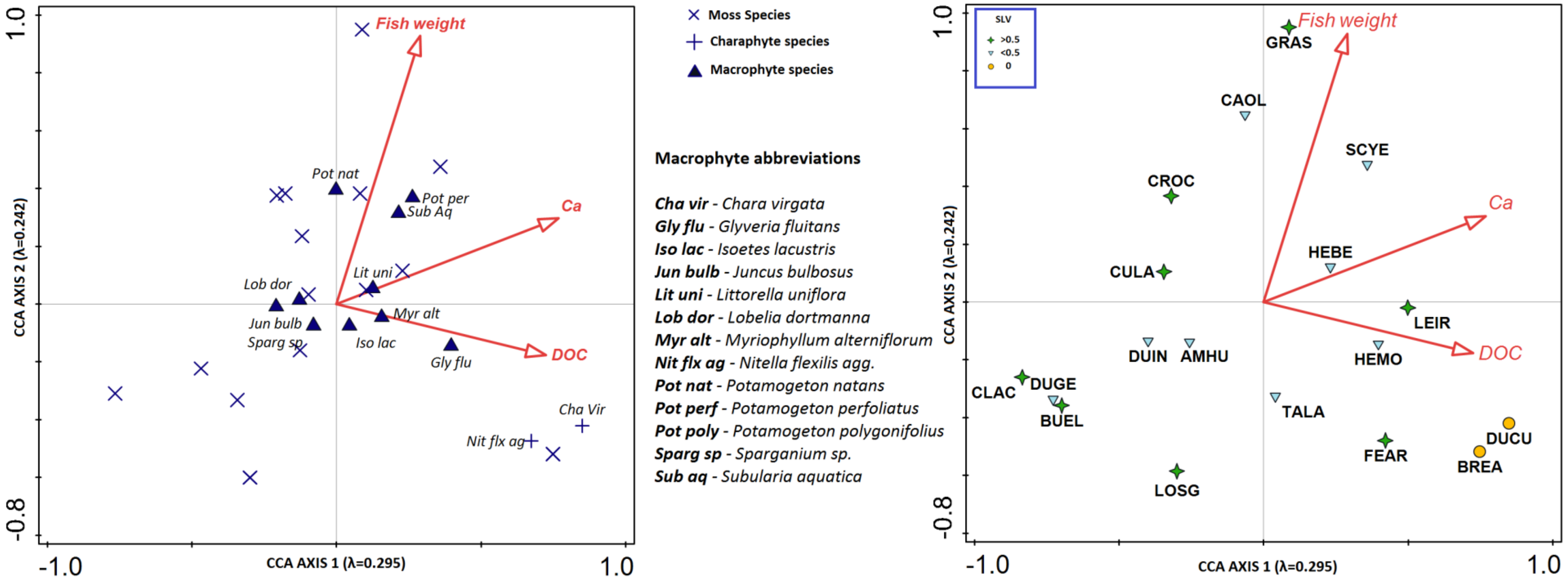


Figure 3.40 Axis 1 and 2 of DCA showing the relationship between aquatic macrophytes and mosses and the 18 study lochs

Factors structuring macrophyte communities

Canconical correspondence analysis was used to examine the relationships between the lochs macrophyte communities and environmental variables. Forward selection procedure (section 3.3.5.1) identified mean fish weight, Ca and DOC as significant explanatory variables, accounting for a total of 24.8% of the variation observed in the macrophyte community.

Charophytes *Chara virgata* and *Nitella flexilis agg*. are both associated with high DOC. The majority of the moss species are positioned on the left-hand side of CCA axis 1 indicating they are associated with low Ca, DOC and fish weight. Two clear exceptions to this are *Hygrohypnum luridum* and *Hypnum jutlandicum* mosses associated with high DOC and *Sphagnum squarrosum* a species associated with high fish weight. *Potamogeton* species are associated with sites where fish weight is high. As a genus commonly associated with mesotrophic conditions, high fish weight and *Potamogeton* presence could indicate sites with higher nutrient levels and consequently productivity. The small growing species of Isoetids, *Lobelia dortmanna, Isoetes lacustris* and *Litterella uniflora* are also associated with low DOC which could be related to more light attenuation at these sites.



Macrophyte abbreviations

Cha vir *- Chara virgata*
Gly flu *- Glyveria fluitans*
Iso lac *- Isoetes lacustris*
Jun bulb *- Juncus bulbosus*
Lit uni *- Littorella uniflora*
Lob dor *- Lobelia dortmanna*
Myr alt *- Myriophyllum alterniflorum*
Nit flx ag *- Nitella flexilis agg.*
Pot nat *- Potamogeton natans*
Pot perf *- Potamogeton perfoliatus*
Pot poly *- Potamogeton polygonifolius*
Sparg sp *- Sparganium sp.*
Sub aq *- Subularia aquatica*

Name	Explains %	pseudo-F	P
Calcium	8.8	1.5	0.016
DOC	7.9	1.4	0.08
Fish weight	8.1	1.5	0.052

Figure.3.41 Axis 1 and 2 of a CCA showing the relationship between (LEFT) aquatic macrophytes (▲), charophytes (+) and mosses (×)and forward selected environmental variables (calcium (Ca), fish weight and dissolved organic carbon (DOC)), and (RIGHT) the study lochs and forward selected environmental variables (calcium (Ca), fish weight and dissolved organic carbon (DOC))

Recent change in macrophyte communities using historic data

There is very little historic environmental data for the Flow Country lochs; in the late 1980s Scottish Natural Heritage (SNH) conducted aquatic macrophyte surveys at 8 of the 18 study sites. Table 3.9 indicates changes in macrophyte species between 1987-90 and 2014 surveys. The four sites with a scoter loch value (SLV) >0.5 have a mean of 6.75 species in the 1980s and a small decline to a mean of 5.75 species by 2014. Conversely in the low scoring scoter lochs (with SLV<0.5) an increase in mean number of species occurs between the 1980s survey and 2014, from 3.25 (1980s) to 5.25 (2014). Species lost from lochs with high scoter value are *P. natans*, *P. perfoliatus* and *P. Polygonifolius, J. bulbosus, Sparganium* sp. *and G. fluitans.* Of the low scoring scoter sites, CAOL (SLV 0.47) saw the largest increase in species from four to nine, new species recorded in 2014 were *S. aquatica, Sparganium* sp., *P. perfoliatus, P. natans* and *G. fluitans.* This increase in species could suggest an increase in nutrient availability at CAOL.

A DCA of macrophyte communities is shown in Figure 3.42, axes 1 and 2 account for a total of 42% of the variation in macrophyte community composition in 2014. Lochs with a low SLV are all moving in the same direction along axis 1 of the DCA whilst lochs with a higher SLV move in contrasting direction within the ordination space. CLAC and DUGE have undergone the smallest amount of change, both move along axis 1 but in opposite directions. The macrophyte communities of LOSG and CAOL have undergone the most change.

LOCH CODE	***SCOTER LOCH VALUE***	***YEAR***	***TOTAL***	*Subularia aquatica*	*Sparganium sp*	*Potamogeton polygonifolius*	*Potamogeton perfoliatus*	*Potamogeton natans*	*Myriophyllum alterniflorum*	*Lobelia dortmanna*	*Littorella uniflora*	*Juncus bulbosus*	*Isoetes lacustris*	*Glyceria fluitans*
CLAC	✦	1980s	6		+					+	+	+	+	+
		2014	**4**		✓					✓	✓	✓		
CULA	✦	1980s	8		+	+		+	+	+	+	+	+	
		2014	**6**		✓				✓	✓	✓	✓	✓	
LEIR	✦	1980s	8	+		+	+		+	+	+	+	+	
		2014	***8***	✓			✓		✓	✓	✓	✓	✓	
LOSG	✦	1980s	**5**		+		+		+			+	+	
		2014	**5**			✓			✓	✓	✓		✓	
CAOL	▽	1980s	**4**						+	+	+	+		
		2014	***9***	✓	✓		✓	✓	✓	✓	✓	✓	✓	
DUGE	▽	1980s	**2**		+							+		
		2014	**3**		✓							✓	✓	
DUIN	▽	1980s	**3**		+	+							+	
		2014	**3**		✓				✓				✓	
SCYE	▽	1980s	**4**						+		+	+	+	
		2014	**6**				✓		✓	✓	✓	✓	✓	

Table 3.8 Presence of macrophyte species recorded for 8 sites at which survey were carried out in both the 1980s and in 2014, sites with low scoter loch value (≤0.5) are denoted by a blue triangle, sites with high scoter value (>0.5) are represented by a green star. (**+**) indicates species presence in 1987-90 surveys and (✓) presence in 2014 surveys

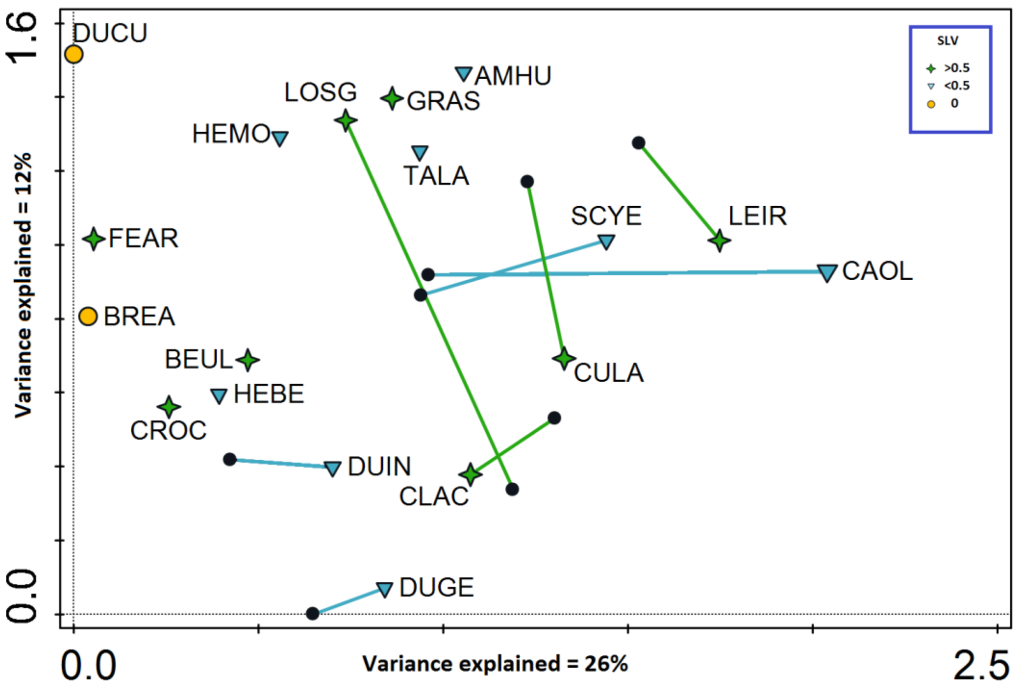


Figure 3.42 Axis 1 and 2 of a DCA ordination of macrophyte communities in 18 Flow Country lochs. 2014 survey data represented by coloured symbols, for the 8 sites where historic survey data was available the 1980s survey data has been plotted passively, the position of historic community composition is represented by the black circles

3.4.1.4 Diatom communities

Community composition

Surface sediment samples from the 18 lochs were analysed for diatom remains. Whilst surface sediments may not represent a complete record of species present at the time of sampling (Battarbee *et al.,* 2001) they represent a standardised approach which enables rapid comparisons between systems. Species that exploit different habitat niches will be represented as remains in surface sediments, using surface sediments is therefore an efficient way to compare communities across multiple sites. Diatoms form a key part of the trophic structure in lakes and are sensitive to habitat structure and water chemistry. Examining diatom communities can also provide useful insights into the physical and chemical characteristics of the lochs.

A total of 94 diatom species were recorded in the surface sediment samples from the 18 lochs, with an average of 24 species per loch (range 19-34). The 20 most frequently recorded diatom species are illustrated in Figure 3.43. *Fragilaria sensu lato* dominate the diatom assemblages; species of *Fragilaria exigua* and *Staurosira construens var venter* were particularly abundant. Benthic species of *Eunotia* were also abundant in several sites (BEUL, CAOL CROC, DUGE, DUIN, LOSG and TALA). Planktonic species of *Aulacoseria* were absent from a number of the lochs (BEUL, LEIR and LOSG), and when present did not form a large proportion of the diatom community (typically making up <20% of the species).

Patterns in diatom community assemblages between lochs were investigated using DCA. To clarify visualisation only the 16 most frequently occurring species are illustrated in Figure 3.44, axes 1 and 2 account for 86.4% of the total variation. Lochs HEBE and AMHU are somewhat separate from the other sites, both having 21 species recorded and are characterised by *Fragilaria exigua*. Similarly, lochs CAOL and SCYE are also separate, but with lower DCA axis 2 scores and are characterised by *Achnanthe*s species and *Pseudistaurosira. elliptica.* BEUL, CLAC, CROC, DUGE, DUIN and LOSG form a distinct group and are characterised by *Eunotia* species, including *E. incisa, E. rhomboidea* and *E. exigua*. Diversity at these sites ranges from 22-28 species. The remaining eight sites are somewhat difficult to separate, suggesting the diatom communities at these sites is relatively similar characterised by *S. contruens var venter, Staurosirella pinnata, Gyrosigma* sp.*, T. flocculosa, A. saxonica* and *Cavinula cocconeiformis*.

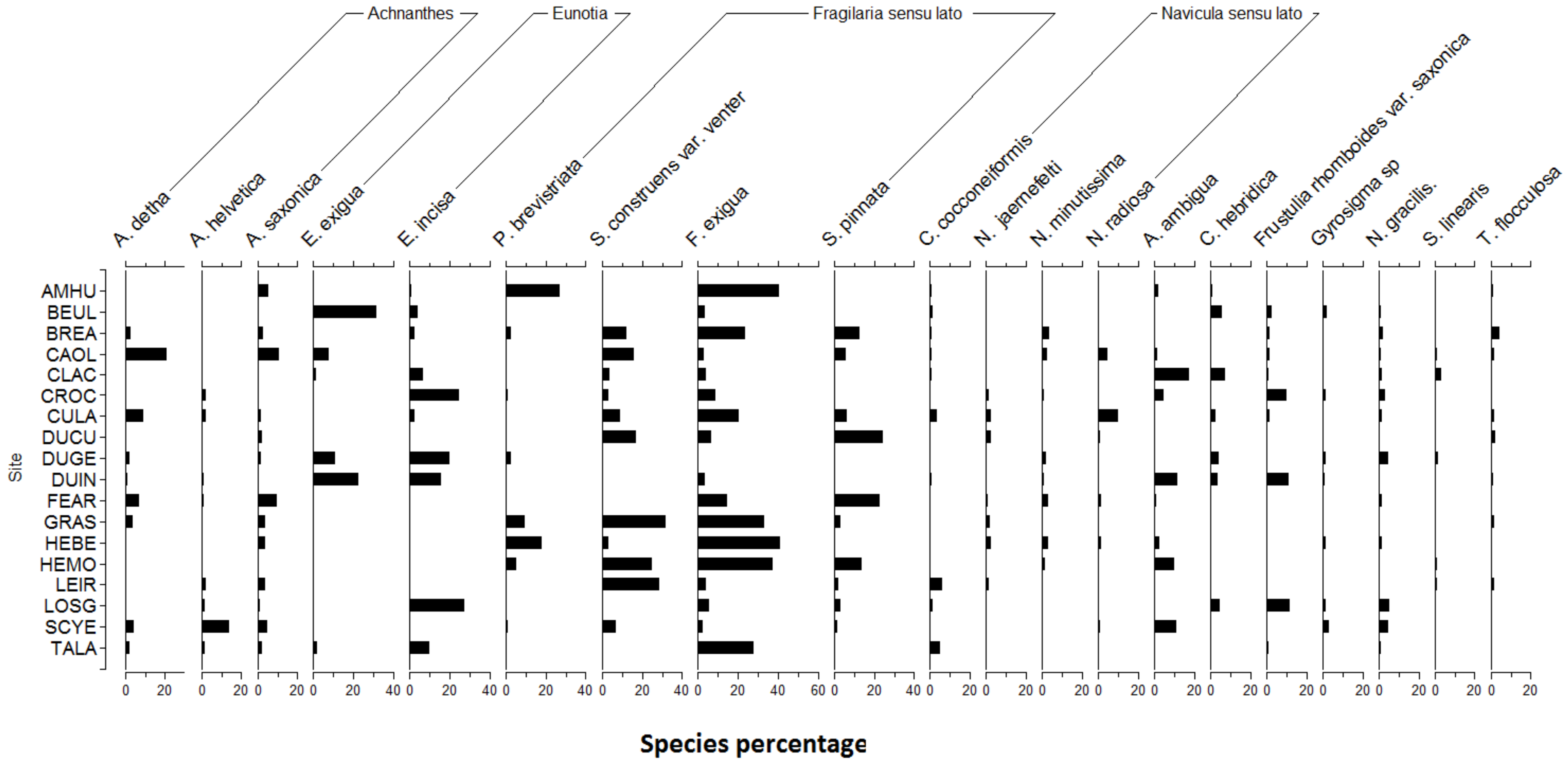


Figure.3.43 Percentage abundance of the 20 most frequently occurring diatom species recorded in the tops of the sediment cores taken in October 2013

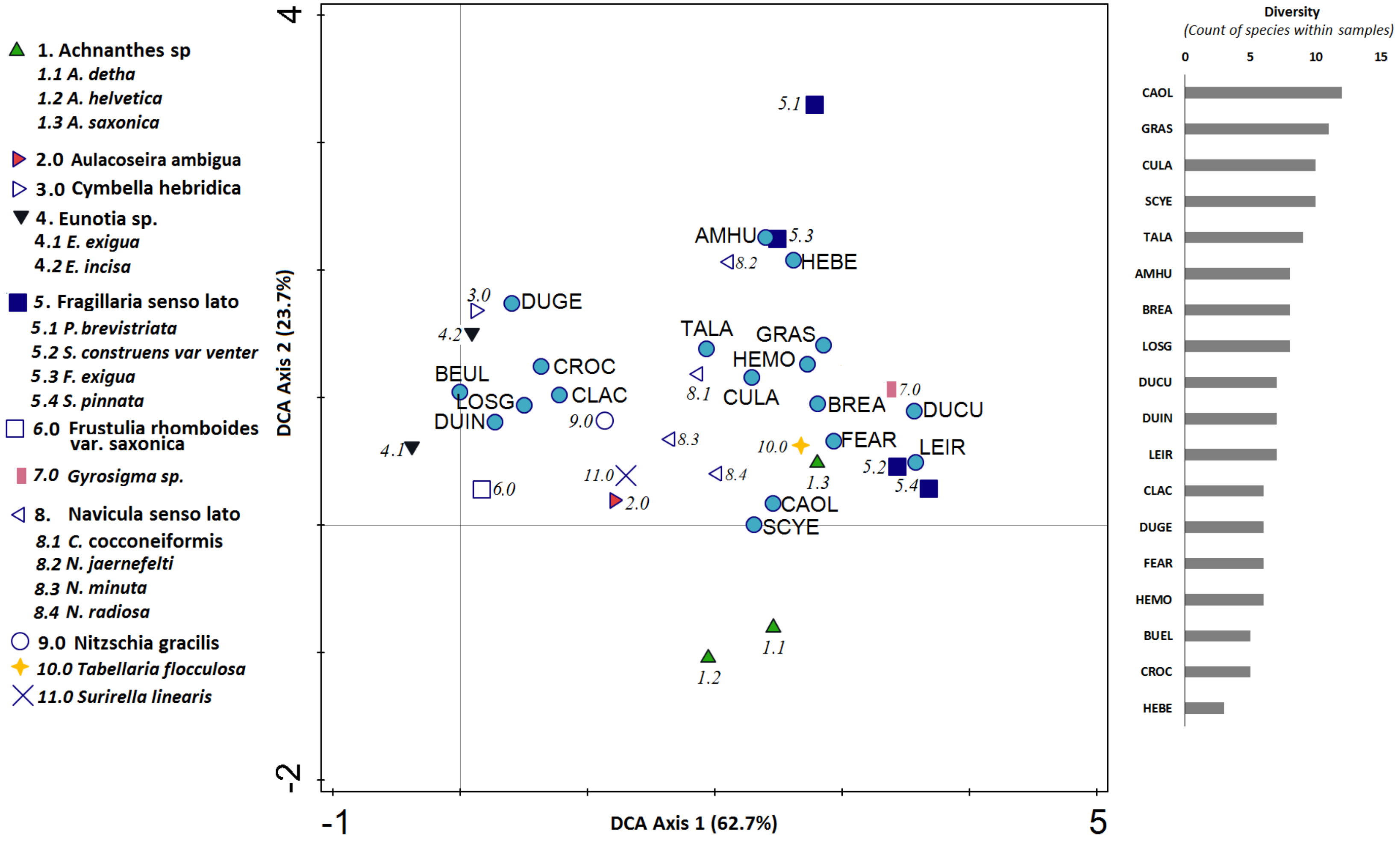
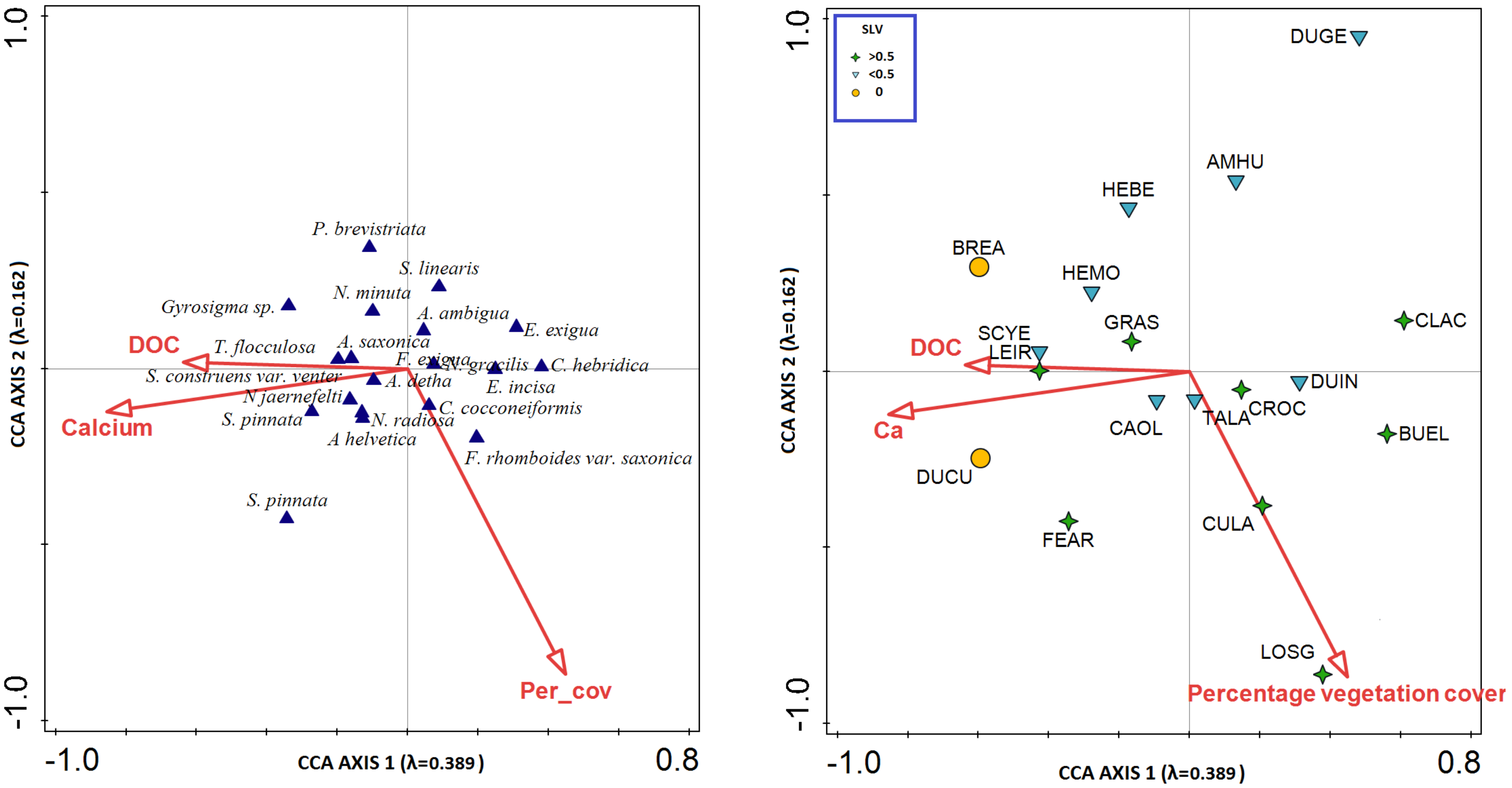


Figure.3.44 Axis 1 and 2 of a DCA showing the relationship between the 20 most frequently occurring species of diatom and the study lochs, total number of species recorded at each site is shown to the right of the plot

Factors structuring diatom communities

Canconical correspondence analysis (CCA) was used to examine the relationship between diatom communities and (forward selected) environmental variables with the aim of highlighting important determinants of community structure. Ca, DOC and percentage cover are all identified as significant explanatory variables accounting for 13.4, 7.9, 6.9% of the variation respectively.



Name	Explains %	pseudo-F	P
Calcium	13.4	2.5	0.002
DOC	7.9	1.5	0.012
Per cover	6.9	1.3	0.058

Figure.3.45 Axis 1 and 2 of a CCA showing the relationship between (LEFT) diatoms and forward selected environmental variables (calcium (Ca), percentage macrophyte cover and dissolved organic carbon (DOC)), and (RIGHT) the study lochs and forward selected environmental variables (calcium (Ca), percentage macrophyte cover and dissolved organic carbon (DOC))

3.4.1.5 Chironomid communities

Surface sediments from the 18 lochs were examined for chironomid head capsules, remains in these surface sediments represent the species inhabiting the loch at the time of sampling. This highly standardised methodology allows the abundance of chironomids and the community assemblages to be accurately compared across sites. Chironomids form an important link in the food chain with species acting as both grazers and predators. As a group, they are themselves a key prey items for a number of vertebrates including fish and waterbirds; chironomids are also sensitive to changes in habitat quality and water chemistry. Identifying patterns in chironomid abundance and community composition can therefore provide useful data for loch characterisation.

Chironomid abundance

Abundance of chironomid head capsules per gram of wet sediment is shown for each of the sites in Figure 3.46. The sites with highest abundance in their surface sediments are HEBE, CLAC, and CAOL. Ordinations from other variables indicate these sites are not particularly similar in terms of their physical or chemical characteristics, or their diatom of macrophyte communities. Similarly, no clear pattern is evident for the four sites with the lowest chironomid abundance (BREA, CROC, DUCU and LOSG) although the sites are amongst those with the lowest pH and highest fish abundance.

Chironomid community composition

A total of 72 chironomid morphotypes were identified. The 20 most frequently occurring chironomid morphotypes are shown in Figure 3.47. *Psectrocladius sordidellus,* a species typically associated with less eutrophic, acidic conditions (Pillot, 2014) and the eurytopic morphotype *Tanytarsus mendax* were found at all 18 sites. *Polypedilum nebeculosum*, *Ablabesmyia*, *Heterotanytarsus* and *Microtendipes pediullus* were found at 14-16 of the 18 sites. *Polypedilum nebeculosum* are common in benthic sediments and sometimes amongst plants in less acidic and more mesotrophic conditions (Pillot, 2009). *Orthocladius*, *Parakiefferiella* and *Cripotopus* were rare, being found at only 1 or 2 sites.

PCA was used to explore patterns in chironomid community composition, to facilitate visualisation only the 20 most frequently occurring taxa are displayed in Figure .3.48; PCA axis 1 and 2 explain 45% of the variation in the chironomid communities. BEUL and CLAC are positioned somewhat separately in the ordination space, indicating a community composition at these sites that is distinct from the other 16 sites. The remaining sites are distributed across the ordination space, with no clearly distinct groups, indicating there is variation between lochs but no distinctly similar groups of chironomid communities

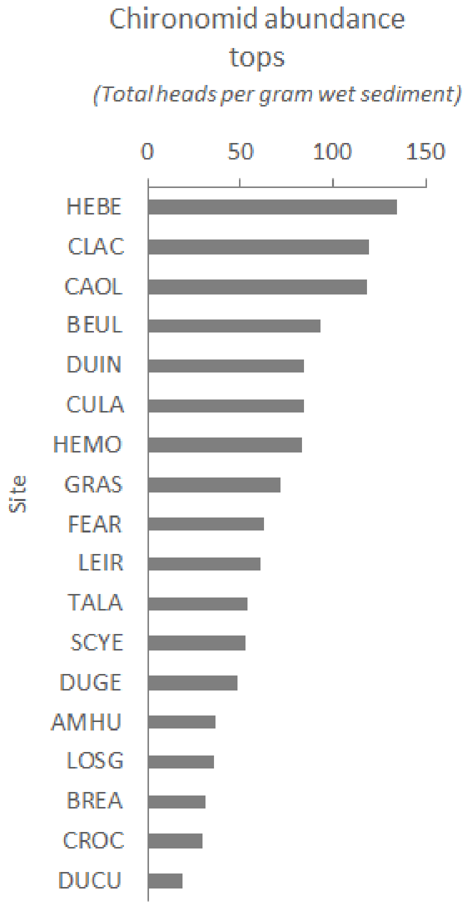


Figure 3.46 Mean chironomid head capsule abundance in the surface sediment of the 18 lochs

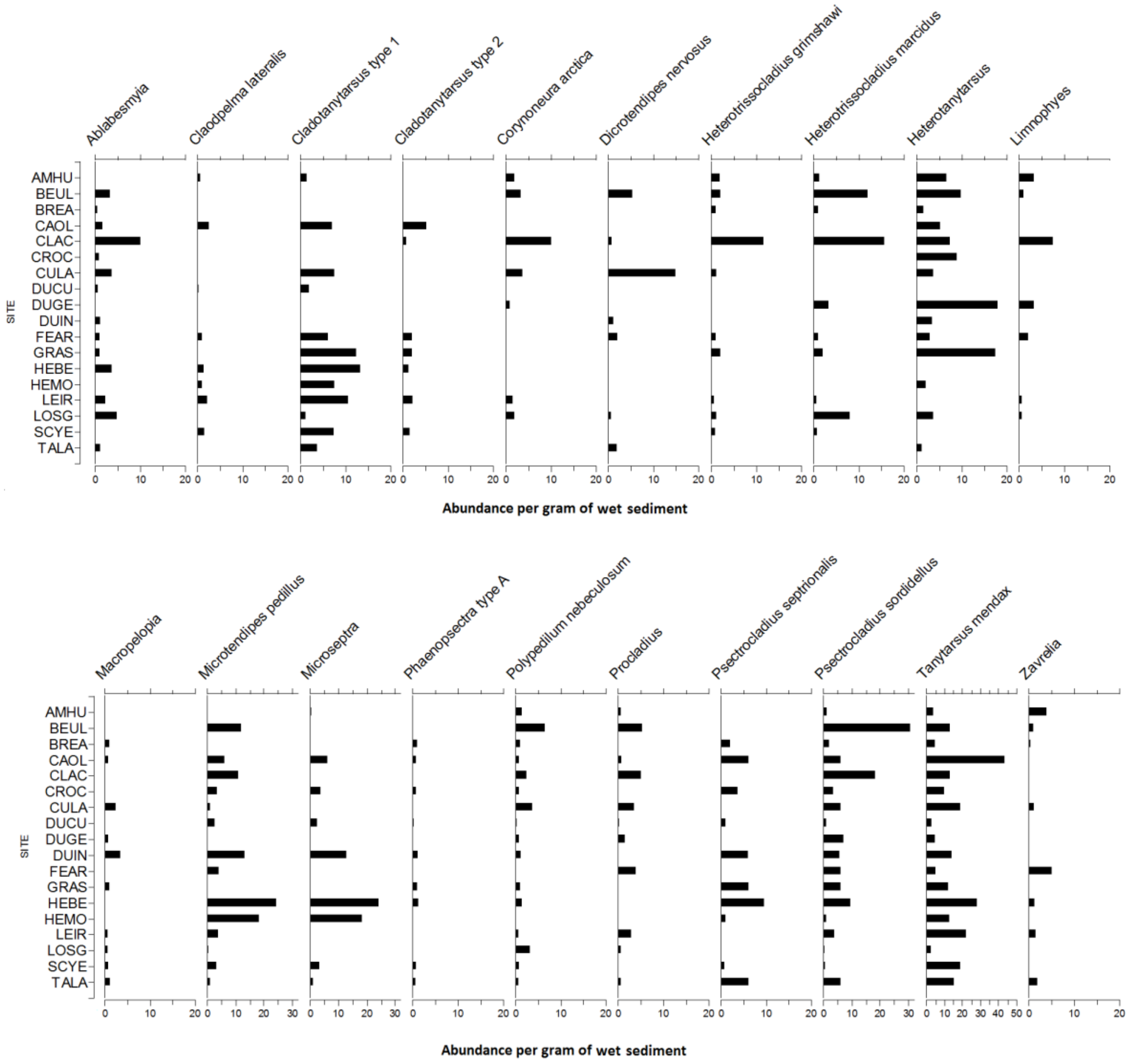


Figure 3.47 Abundance per gram wet sediment of the 20 most frequently occurring chironomid species recorded in the tops of the sediment cores taken in October 2013

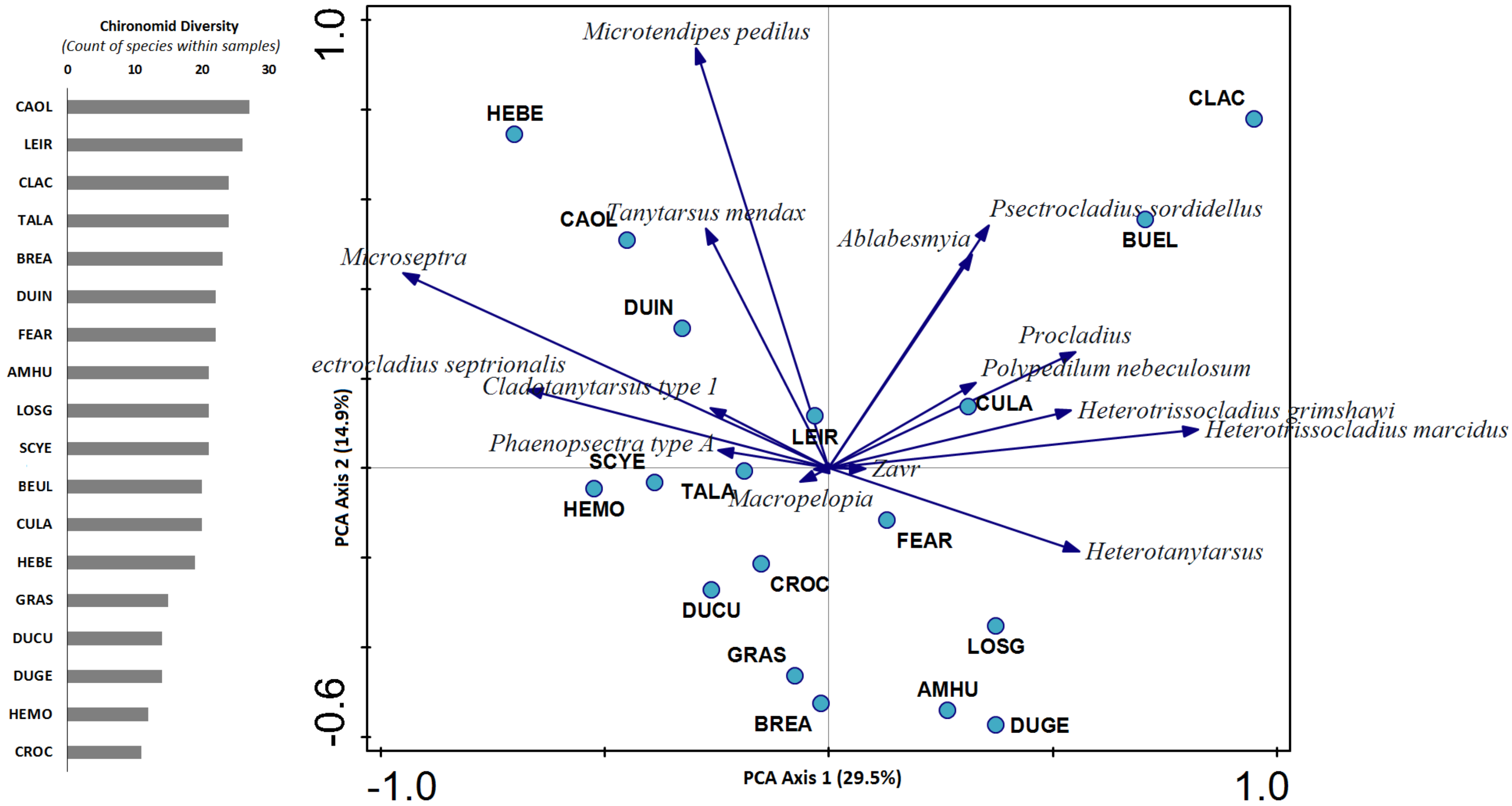
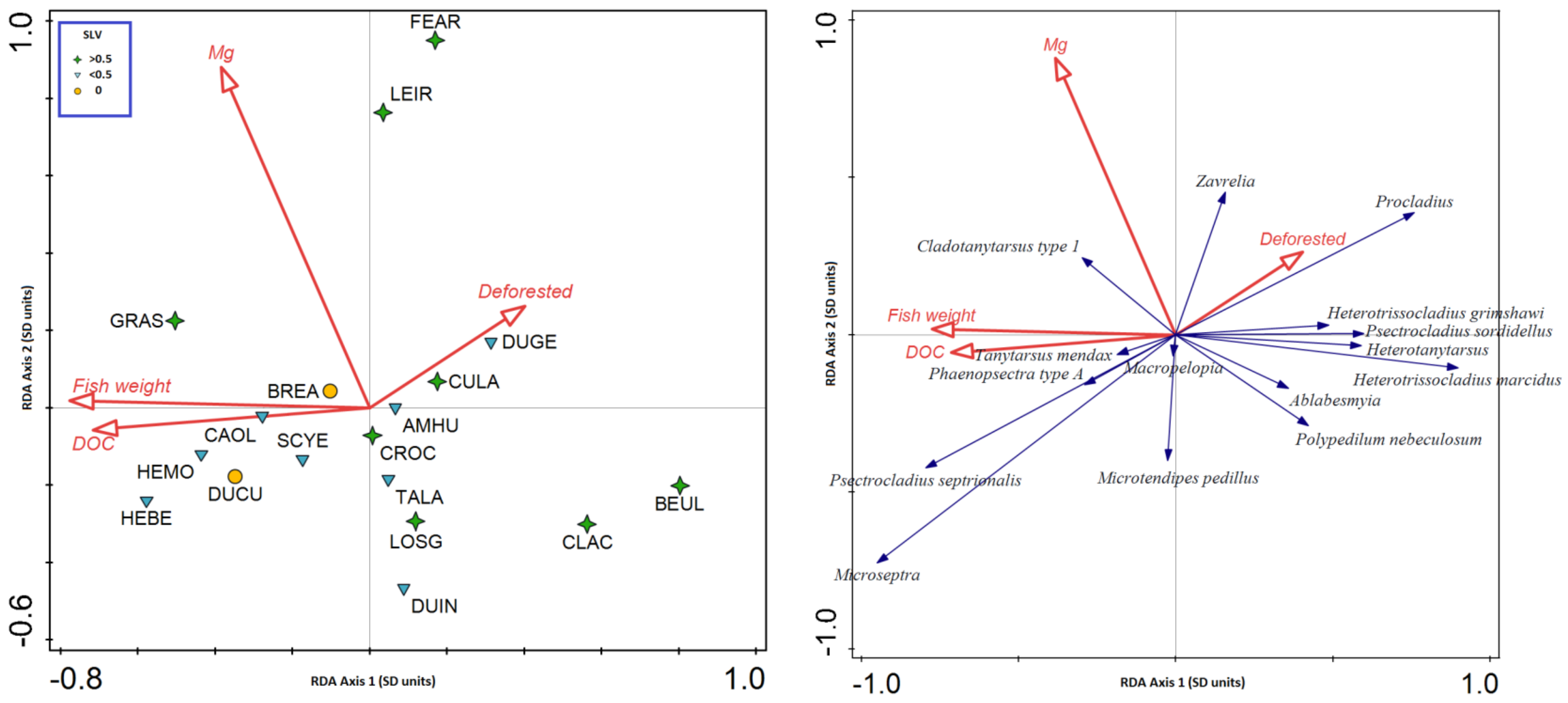


Figure 3.48 Axis 1 and 2 of a PCA showing the relationship between the 20 most frequently occurring species of chironomid and the study lochs, total number of species recorded at each site is shown to the left of the plot

Factors structuring chironomid communities

Redundancy analysis (RDA) was used to examine the patterns in chironomid community composition in relation to environmental variables. Significant variables were identified using forward selection, Mg, mean fish weight, DOC and percentage of deforested area within a 500m buffer of the loch were all identified as significant explanatory variables, in total explaining 41.4% of the community variation



Name	Explains %	pseudo-F	P
Fish weight	16.5	3.2	0.002
Magnesium	8.7	1.7	0.05
DOC	8.8	1.9	0.05
Deforested	7.4	1.6	0.088

Figure 3.49 Axis 1 and 2 of a RDA showing the relationship between (LEFT) chironomids and forward selected environmental variables (calcium (Ca), percentage vegetation cover, blanket bog, sodium (Na) and maximum water depth (Max. water depth)), and (RIGHT) the study lochs and forward selected environmental variables (calcium (Ca), percentage vegetation cover, blanket bog, sodium (Na) and maximum water depth (Max. water depth))

3.4.1.6 Fish communities

Fish can be an important top-down driver of loch ecology. Characterising the communities and abundance of fish within lochs is particularly relevant in studies of diving water birds as they are commonly competing for the same habitat and food resources. Although no fish stocking or electrofishing data was available for the lochs, brown trout and stickleback were surveyed in the 18 study lochs between 2009 and 2011 in a study by RSPB; a total of 154 trout were caught in a total of 170 rod hours (two sites were not surveyed in 2010). The number of trout caught per loch in each 5-hour survey ranged from 0 to 26 (Table 3.10). Fish were not caught at four of the 18 lochs (BEUL, CLAC, DUIN and LOSG). However, evidence from other sources (predominantly related to recommendations for trout fishing) indicate that BEUL, DUIN and LOSG are known to contain trout (Sandison, 2015; Hall, 1884). The diet of brown trout caught in the study lochs was determined by examining the stomach contents of those caught and was found to consist of freshwater macroinvertebrates, predominantly Trichoptera larvae, Hemiptera adults, Plecoptera larvae, Bivalvia and chironomid larvae (M. Hancock pers. comm.).

Loch Code	**Number of Fish caught in 5 rod hours**		**Fish per rod hour**	**Species recorded**	**Mean weight**
	2010	2011			
AMHU	**20**	**7**	2.7	**Brown Trout**	91.5
BEUL[×]	**0**	**0**	*0*	**Brown Trout**	0
BREA	**12**	**4**	1.6	**Brown Trout**	58.3
CAOL	**1**	**3**	0.4	**Brown Trout, Stickleback**	307.5
CLAC	**0**	**0**	*0*	**-**	0
CROC	**0**	**1**[+]	0.1	**Brown Trout**	1986
CULA	**4**	**1**	0.5	**Brown Trout, Stickleback**	114.2
DUCU	*****	**26**	5.2	**Brown Trout**	129.1
DUGE[×]	**0**	**0**	*0*	**Brown Trout**	0
DUIN[×]	**0**	**0**	*0*	**Brown Trout**	0
FEAR	**2**	**1**	0.3	**Brown Trout, Stickleback**	446.7
GRAS	**4**	**3**	0.7	**Brown Trout, Stickleback**	178.0
HEBE	**8**	**5**	1.3	**Brown Trout, Stickleback**	271.3
HEMO	**6**	**2**	0.8	**Brown Trout, Stickleback**	192.9
LEIR	**11**	**9**	2	**Brown Trout, Stickleback**	97.6
LOSG[×]	**0**	**0**	0	**Brown Trout**	0
SCYE	*****	**2**	0.4	**Brown Trout**	259.5
TALA	**9**	**7**	1.6	**Brown Trout**	95.0

***** No survey, [×] *Other local knowledge on fish in this loch,* **[+]** *Stocked by estate with 5000 Trout in 2005*

Table 3.9 Results from the 2010 and 2011 fish surveys of the 18 study lochs (RSPB data)

3.4.1.8 Sites overview

Whilst physically Flow Country lochs appear quite similar, in terms of bathymetry, maximum water depth and sediment types, examination of the chemistry of the lochs indicates four distinct groups associated with different chemical variables including pH and conductivity and DOC. Macrophyte cover in the lochs ranged from 0 to 100% (mean 25%) and aquatic macrophytes have colonised the deepest parts of 8 out of the 18 sites. Macrophyte species are typical of those associated with low, nutrient and acidic conditions; three lochs are categorised as type 1, seven type 2 and six type 3, the remaining two are type 4 lochs (Duigan *et al.,* 2006). Ordination analysis indicates that there is some overlap in species occurring at the lochs, with FEAR, HEBE and LOSG the only distinct outliers. Diatom communities of the study sites are again typical of acidic systems. However, there is some evidence of nutrient tolerant species occurring at some sites. Ordination indicates 3-4 distinguishable groups, with AMHU and HEBE particular outliers. Chironomid species observed in the surface sediments are typical of low cool, low nutrient lakes; abundance of chironomids was greatest in HEBE and lowest in DUCU. The chironomid communities are spread throughout the ordination space making differentiation of groups difficult, but HEBE is again a distinct outlier. Fish weight, DOC, Mg and deforested area explain a significant proportion of the variation in chironomid communities. Fish in the lochs include brown trout and stickleback, however the robustness of the rod and line survey data is somewhat questionable, as several lochs that recorded no fish are known to contain trout and are recommended for sports fishing. Despite this the fish data could give an approximate estimation of relative fish density within the lochs and mean fish weight was shown to be an influential variable explaining variation in chironomid communities.

Figure.3.50 shows axis 1 and 2 of a PCA of summarising the within loch variables. The largest, deepest lochs (SCYE and DUGE) are positioned in the lower right corner of the plot associated with high total area, mean water depth and max water depth. Proportion of the loch below 1m (or overall loch shallowness) is in the opposite corner and is also correlated with high sediment scores (denoting fine particle sediment types), lochs CLAC, DUIN, LOSG and TALA are associated with these variables. Measures of high plant and invertebrate abundance are drawn into the lower left side of the plot, associated with high Na and NO_3 and low DOC and fish abundance. Sites associated with these variables are BEUL, CULA, FEAR and GRAS all sites with a scoter loch value of >0.5. Opposite in the upper right of the plot and associated with high DOC, fish abundance, pH, chlorophyll A and K are AMHU, BREA HEMO, LEIR, of these sites only loch LEIR has a scoter loch value of >0.5.

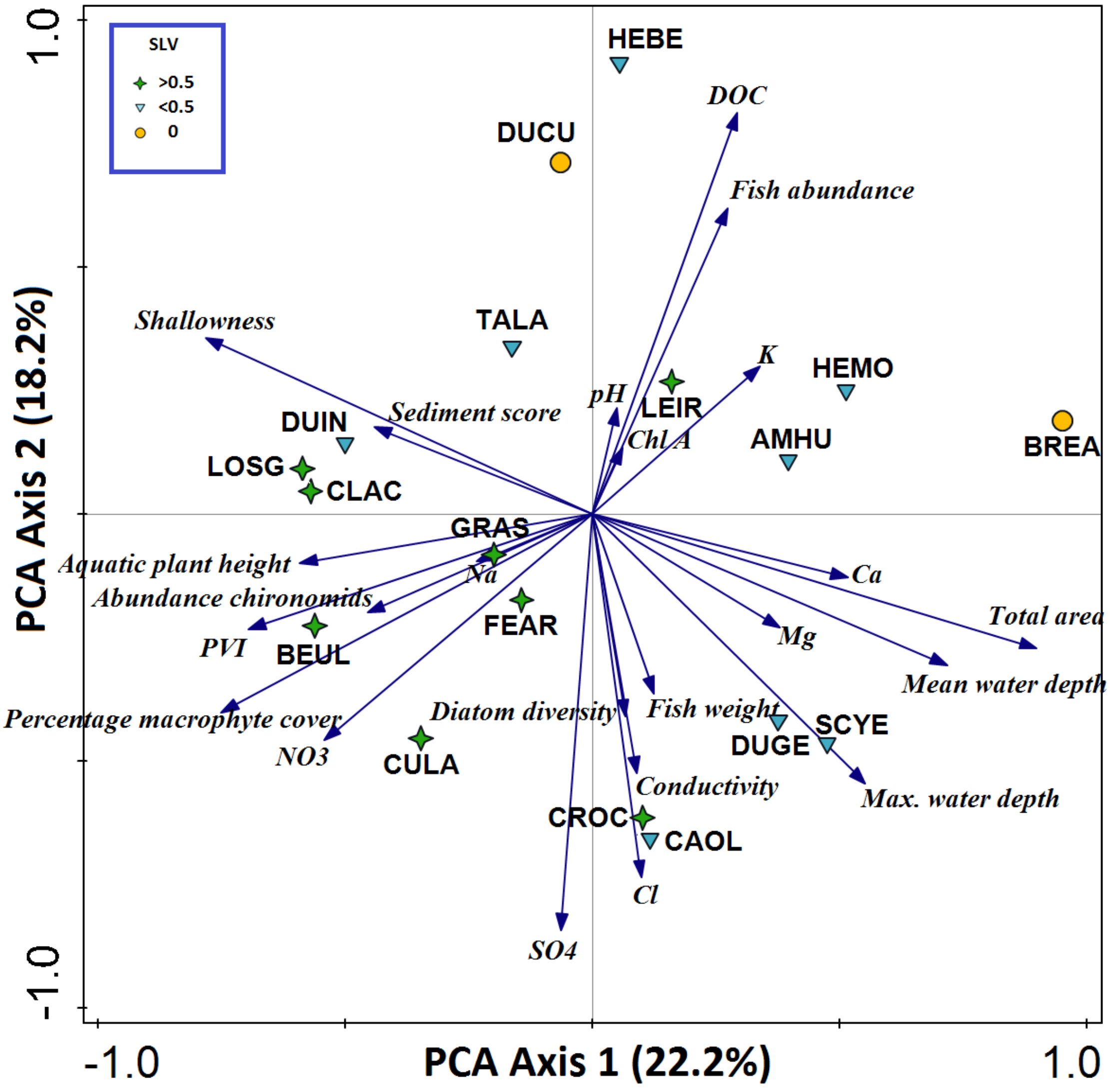


Figure 3.50 Axis 1 and 2 of a PCA of the 18 study sites by (summary) environmental variables, Chlorophyll A (Chl A), pH, dissolved organic carbon (DOC), fish abundance, potassium (K), calcium (Ca), total area, mean water depth, magnesium (Mg), maximum water depth, fish weight, conductivity (Cond), chloride (Cl) sulphate (SO4), nitrate (NO3), mean percentage cover, abundance of chironomids (Ab chiros), diatom diversity, percent volume inhabited (PVI) mean plant height, sediment score (Sed score) and proportion of the loch below 1m depth (shallowness).

3.4.2 Developing hypotheses for common scoter decline using general linear models

The results presented so far have characterised the current conditions within Flow Country lochs and examined some of the potential factors structuring communities of aquatic plants, diatoms and chironomids. The second part of this chapter will build on these data by using them in a modelling approach to identify statistically significant associations between loch characteristic and scoter loch use outlined in section 3.3.5.2 and Section 3.4.1 and Table 3.1). General linear model refinement of the biological, chemical and physical sub-models (section 3.3.5.2) identified five variables to be used in the final model: DOC, mean percentage macrophyte cover, fish abundance (fish caught per rod hour), sediment score (high sediment score denotes fine particle sediments and low scores coarse grain sediments) and proportion of the loch below 1m deep (method detailed in 2.4.2.3). The final model was itself simplified to give a minimum adequate model which contained DOC, sediment score and proportion below 1m and a significant interaction between sediment score and proportion below 1m (Table 3.11).

Coefficients:	Estimate (std. error)	Degrees of freedom	t value	p-value
Intercept	-5.574779 (1.756485)	4, 13	-3.174	0.007328
DOC	-0.062053 (0.014013)	4, 13	-4.428	0.000681
Sediment score	1.676562 (0.457900)	4, 13	3.661	0.002874
Proportion below 1m	0.095006 (0.026488)	4, 13	3.587	0.003314
Sediment score x prop below 1m	-0.023748 (0.006883)	4, 13	-3.450	0.004305

Table 3.10 Significant variables and interactions in the minimum adequate model of scoter loch value with environmental variables

There is a statistically significant decrease in scoter loch value (Table 3.1) with increasing DOC (Figure 3.51). Sediment score and proportion of the loch below 1m in depth are also significant explanatory variables with a significant interaction. At deep lochs (where proportion below 1m is low) scoter site value increases significantly with sediment score; at moderately deep lochs the relationship remains positive but is less strong. In shallow lochs (where proportion below 1m is high) there is a negative relationship between scoter site value and sediment score (Figure 3.52).

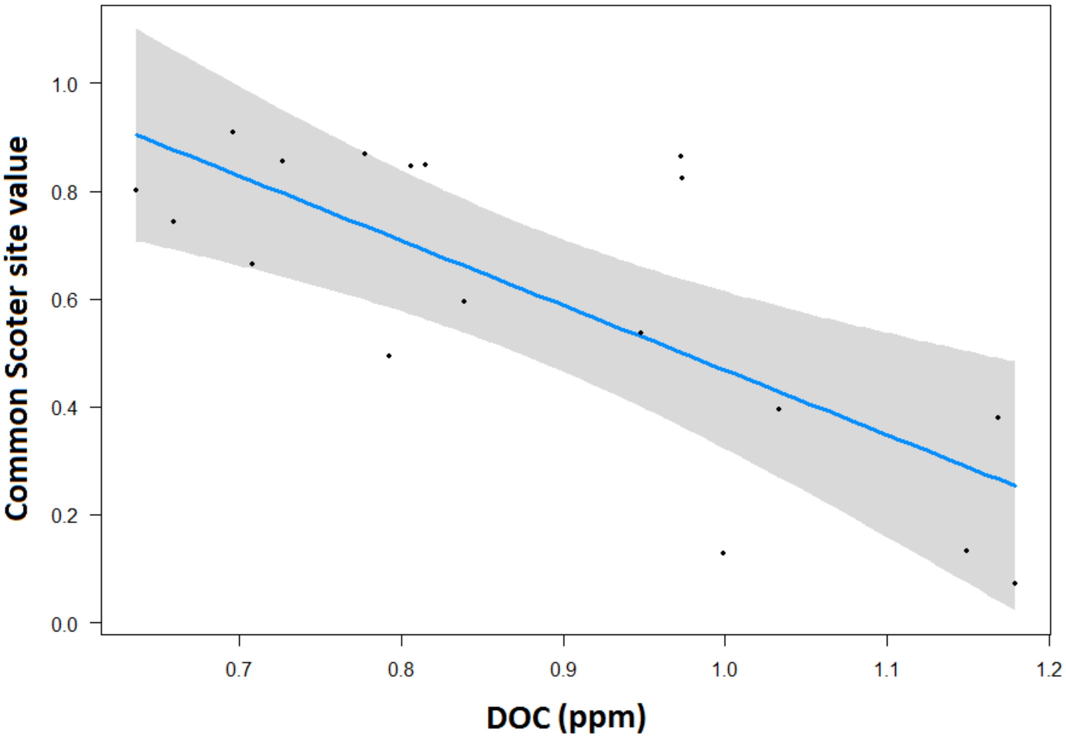


Figure 3.51 Relationship between common scoter loch value and dissolved organic carbon (DOC), with 95% confidence interval indicated by the grey area.

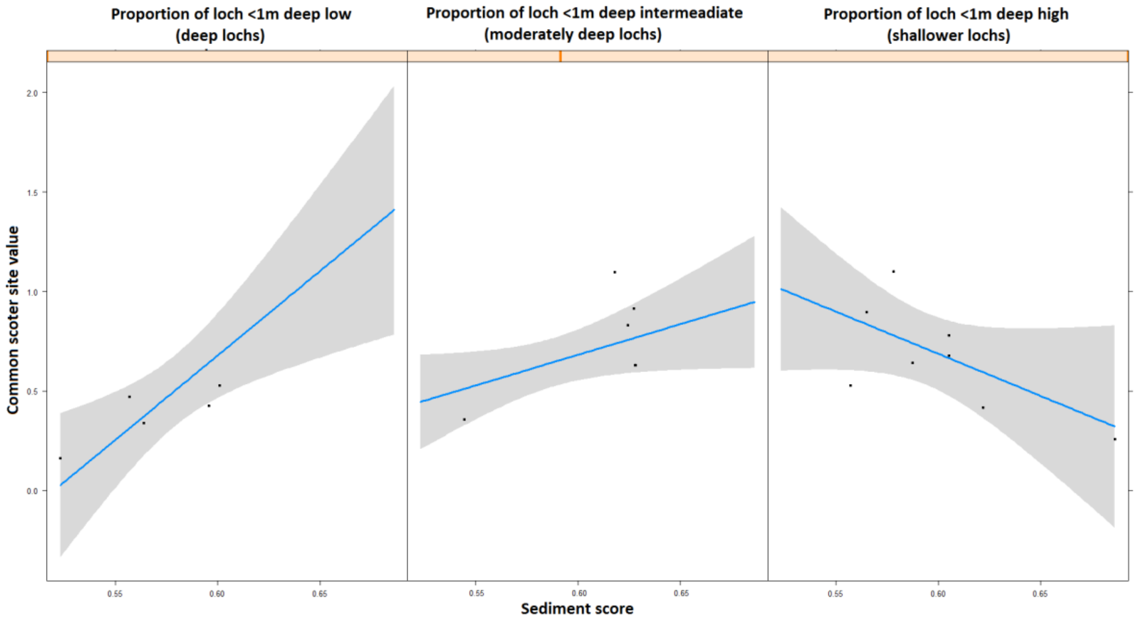


Figure 3.52 Relationship between common scoter loch value and sediment score at three intervals or proportional shallowness, with 95% confidence interval indicated by the grey area.

3.5 Discussion

The characterisation of 18 Flow Country Lochs

Characterisation of 18 lochs has demonstrated that chemically, biologically and physically the Flow Country systems are comparable to other peatland lochs in Scotland and northern Europe (Maitland *et al.,* 1994; Rydin and Jeglum, 2013); typically shallow, acidic and low nutrient systems. However, despite the superficially homogenous appearance of the lochs, there is a substantial amount of between-loch variability, even at sites that are closely located. The dynamic and complex nature of freshwater lochs is easy to underestimate, particularly in a landscape like the Flow Country. It is evident that multiple factors are coming together on a loch by loch basis to create a heterogeneous wetland landscape that is able to support a variety of species. Consideration of landscape and regional scale influences on these systems is an important next step, which could highlight key drivers of loch ecology and influences on loch functioning, these areas will be covered in Chapter 4. The site characterisation process undertaken in this chapter has provided a single snap shot of conditions within the lochs. Disentangling the drivers of loch ecology and functioning would also benefit from a longer-term perspective in which current day conditions can be considered. Chapters 5 and 6 use a palaeolimnological approach to provide a temporal context to the contemporary characterisation undertaken in chapter 3.

Developing hypotheses for common scoter decline

This chapter has demonstrated a statistically significantly relationship between common scoter loch use and dissolved organic carbon (DOC), sediment type and shallowness.

The DOC concentrations recorded in this study were lower than seasonal averages recorded in other studies of European peatland lakes (20-40mg/l Rydin & Jeglum (2013)) but similar to concentrations recorded at Irish lakes (Drinan *et al.,* 2013). In addition to being related to common scoter use, constrained ordinations have shown that DOC is also influential in explaining variation in chironomid, diatom and macrophyte communities. DOC in peatland lakes enters from allochthonous and groundwater sources, and organic rich soils, such as peatlands, can result in particularly high concentrations especially when damaged. The export of DOC from terrestrial peatland is estimated at between 1.5 to 14 $tCkm^2$ year depending on the condition of the peatland and anthropogenic management (Clark *et al.,* 2007; Hope *et al.,* 1997; Koehler *et al.,* 2009; Ryder *et al.,* 2014). Studies have demonstrated an increase in DOC concentrations in Britain's freshwaters since the 1990s (Worrall and Burt, 2007). It has been postulated that the increase has been caused by changes in climate (particularly increasing temperature (Freeman *et al.,* 2001; Worrall *et al.,* 2003), drought Holden and Burt, 2003), decreased acidity (Davies *et al.,* 2005; Evans *et al.,* 2001) and land use changes (such as forestry and rotational burning, Clay *et al.,* 2009a; Nieminen, 2004; Yallop and Clutterbuck, 2009). Coloured DOC can directly influence water clarity, and an association between low growing isoetid species and low DOC levels was highlighted in the constrained ordinations, suggesting DOC could be influential in light attenuation. No statistically significant correlation between DOC and secchi depth could be identified. However, this could be due to the fact that in many Flow Country lakes the recorded secchi depth was equal to loch depth, with the disc still being visible on the bottom of the loch. In addition to changing water colour, increases in DOC can lead to increased retention of metal elements (such as aluminium and iron) due to complexation with DOC. Such metals have been shown to have detrimental effects on invertebrate and fish populations (Evans *et al.,* 2005) and therefore could indirectly have implications for breeding scoter using the lochs. However, without data from a wider spatial and/or temporal scale it is difficult to identify trends and drivers of DOC in Flow Country lochs.

The physical structure of the lochs has been shown to be significantly related to scoter loch use. Soft sediments (with small particle size) have been shown to be more important to scoter in deeper lochs (where proportion of the loch below 1m is low), whilst at shallow sites the importance of fine sediments is reduced. The mechanism by which common scoter feed is not well understood. Diet studies indicate they are able to consume prey items that are embedded in the benthos (such as bivalves and chironomids, Fox, 2003), within stands of aquatic macrophytes (such as Trichoptera), and also fast moving, motile prey items (such as sticklebacks, Coleoptera and Hemiptera) (L.Griffin, G. Hilton pers. comm.); young scoter have also been observed feeding on invertebrates emerging at the surface of lochs (M. Hancock pers. comm.).

The results from this study indicate that soft sediments are more important to common scoter on deeper lakes, which could suggest an energetic balance is being struck. The energetic cost of feeding at deeper depths may be somewhat ameliorated by ingesting food that requires less energetic cost to consume, such as sedentary benthic invertebrates and bivalves in soft sediments. Whilst in shallow lochs, where the energetic costs of diving are less, time and energy can be spent pursuing more motile species or grazing on invertebrates in stands of aquatic macrophytes.

Aerial photographs of the lochs from the 1940s suggest there has been little change in the size, shape and therefore presumably depth of the lochs in the last 60-70 years. However anthropogenic peatland management (such as rotational burning, grazing, peat cutting, drainage and forestry plantations) has the potential to indirectly influence the sediment composition in several ways; by effecting hydrological pathways and levels of infiltration in the surrounding peatland, and/or reducing or changing vegetation cover, all of which can ultimately result in increased rates of erosion and inputs of allochthonous peat sediment (Anderson *et al.,* 2000; Drinan *et al.,* 2013a; Drinan *et al.,* 2013b; Holden *et al.,* 2004; J. Miller *et al.,* 1996; Kenttämies, 1981; McElarney *et al.,* 2010; Ramchunder *et al.,* 2009; Turkia *et al.,* 1998; Yallop and Clutterbuck, 2009). However, it is not possible to determine whether any change in the composition of lochs sediments has taken place that could be effecting common scoter loch use without long term survey data. Chapters five and six of this thesis will address this by examining the character of sediments in dated lake cores.

Aquatic macrophyte, chironomid and fish abundance were also shown to be ecologically important to common scoter loch use, despite not being statistically significant, with each variable being carried through from the sub-models before refinement of the final model excluded them from the minimum adequate model. Macrophyte and invertebrate composition and abundance in freshwater lochs are influenced by both top down (predation/grazing) and bottom up (water chemistry and habitat) processes. In the current study, the abundance of chironomids and macrophytes have been shown to be negatively correlated with both brown trout abundance and water chemistry variables such as DOC. Similarly, the composition of both chironomid and macrophyte communities have been shown to be significantly influenced by both top down (fish weight) and bottom up (DOC, Mg) variables.

Hancock *et al.,*(2015) demonstrated a significant negative relationship between large bodied invertebrate abundance and brown trout abundance in Flow Country lochs, and a statistically significant (positive) relationship between scoter loch type and large bodied invertebrates. However, statistically significant relationships were also identified between common scoter loch type and water level stability and macrophyte abundance. This could suggest that large bodied invertebrate abundance is higher in lochs with more macrophyte cover because higher macrophyte abundance provides structure in which invertebrates can conceal themselves from trout. Whilst no direct statistically significant association could be identified between common scoter loch type and brown trout abundance, it was hypothesised that changes in the competitive balance between common scoter and brown trout could have resulted in common scoter declines at Flow Country lochs. In contrast to Hancock *et al.,* (2015), the results from this chapter place the most emphasis on bottom up drivers of loch ecology, with DOC, sediment type and water depth being the most influential factors effecting common scoter loch use. There is no indication of common scoter loch use being influenced by either predator presence (Hancock *et al.,* 2015) or limits on available nesting habitat. Therefore, declines in the Flow Country are considered primarily in relation to within-loch characteristics, and particularly those which influence levels of invertebrate food availability. By combining data from this chapter with current literature and knowledge of pertinent Flow Country issues, the following hypothesis for common scoter decline can be identified:

(1) That afforestation and drainage of the Flow Country catchments in the 1980s has altered the physico-chemistry of lochs through increased sedimentation and/or DOC import which could adversely affect physical loch structure and/or invertebrate food supply for the common scoter.

(2) Common scoters compete with brown trout for food, and the competitive balance between brown trout and scoters may have altered in recent decades, either as a result of decreased fishing pressure or fish stocking events. Changes in brown trout abundance or population structure could have resulted reduced invertebrate abundance which could be detrimental for common scoter.

Evidence from contemporary ecological data indicates that both bottom up (water chemistry, habitat) and top down (predation) process are influencing both invertebrate abundance and common scoter loch use; it is therefore not possible to disentangle competing hypotheses for decline using contemporary data alone. The addition of a spatial and a temporal context to these contemporary data could help to disentangle these conflicting hypotheses, and provide a firm foundation for conservation management. Chapter 4 of this thesis will examine how landscape scale processes, and annual variations in regional climate, could be influencing common scoter distribution and abundance in the Flow Country. Long term perspectives from two temporal scales will be presented in Chapters 5 and 6, to provide firstly information concerning the type and extent of change that has occurred over the last 150-200 years and secondly a fine temporal scale perspective of environmental change, contemporaneous with common scoter decline.

3.6 Key findings and implications

- Flow Country lochs are diverse heterogeneous systems despite superficial similarities. Groups of lochs have been identified representing the different types of loch identified by Palmer, (1992).
  - ⟶ The management of Flow Country lochs needs to be adaptable and responsive to the different types of systems identified.
- Communities of Flow Country lochs are influenced by both bottom up and top down processes
  - ⟶ The drivers of Flow Country loch ecology are complex and difficult to interpret with a single snap shot of current conditions
- There is a statistically significant relationship between common scoter loch use and DOC and physical loch properties (shallowness and sediment type); there has also been shown to be an ecological relevant (although not statistically significant) relationship between common scoter loch use and aquatic macrophytes, fish and invertebrates
  - ⟶ The physcial, chemical and biological characteristics of Flow country lochs have the potential to influence common scoter breeding success. Understanding how these features vary spatially and temporally could be vital in understanding recent common scoter declines

CHAPTER 4: ANNUAL CLIMATE VARIATION AND LANDSCAPE INFLUENCES ON COMMON SCOTER ABUNDANCE AND DISTRIBUTION IN THE FLOW COUNTRY

4.1. Overview

This chapter examines landscape and climate influences on common scoter decline in the Flow Country. The effects of annual climate variation on changes in common scoter numbers are examined at both local and regional scales using general linear modelling analysis. Landscape scale features associated with common scoter presence are explored using a species distribution modelling (SDM) approach, namely Maxent. The indirect influences of key landscape features on within-loch variables important to common scoter (as identified in the previous chapter) are also examined.

4.2. Introduction

In chapter 3 the limnological characteristics of 18 Flow Country lochs were examined; the sites being a mixture of current and historic scoter breeding lochs. The analysis demonstrated that despite superficial similarities there is much between-loch variation in Flow Country loch communities, and that community variation is driven by both top down and bottom up processes. Female common scoter counts for the early part of the breeding season (April-June) between 1988-2014, were used to assign a scoter loch value (SLV) to each of the 18 sites. This was used as a response variable in a GLM which examined the relationship between scoter loch value and a number of loch characteristics. Statistically significant variables were DOC, sediment type and water depth. The abundance of brown trout, chironomids and aquatic macrophytes were also identified as being somewhat influential explanatory variables, which were taken through the initial model refinement process. These variables were also identified as significant explanatory variables in the multivariate analysis of diatom, chironomid and macrophyte communities. Identifying the loch characteristics directly associated with common scoter presence (using GLMs), and the potential mechanisms structuring these variables (using multivariate community analysis) is just the first step towards determining what are the most pertinent driver of common scoter decline. A vital next step is to examine the wider context of decline and assess the role of both landscape and climate processes, both directly (by influencing scoter themselves) and indirectly (by influencing the quality of the habitat available to scoter).

At the southern edge of their breeding range, the decline of common scoter in the Flow Country has been attributed to a northwards shift in the population, seemingly supported by populations in more northerly parts of the breeding range reporting stable or slightly increasing populations (Birdlife International, 2017). However, common scoter in Scotland have long been outside of the climate envelope typically associated with the species, and indeed models of common scoter distribution in Europe (developed based on climate data associated with peak common scoter populations in Britain) have failed to predict their presence in either Scotland or Ireland (Huntley *et al.,* 2007). Attributing the decline to climate change should perhaps therefore be treated with caution, especially as it has the potential to significantly influence conservation management and planning for the species in Britain. The examination of whether changes in common scoter abundance in the Flow Country are associated with annual variations in climate may provide useful insights into the extent to which longer term climate change may affect the species in Scotland. Annual climate variation has the potential to influence common scoter breeding in the Flow Country both directly, by effecting breeding propensity and success and wintering mortality rates, and indirectly, by influencing loch ecology and particularly the availability and timing of invertebrate food resources. Detrimental climate and/or extreme weather events during winter could affect common scoter numbers by increasing mortality and/or reducing body condition and therefore the likelihood of both attempting to breed and breeding success. Cold, wet conditions on the breeding grounds have been shown to effect body condition (Lehikoinen *et al.,* 2006), breeding propensity (Coulson, 2010) and nest success (Iles, 2012) of other subarctic seaduck species. Laying and incubating have high energetic demands for females, and the addition of adverse climate conditions could further drain resources. To compensate, more time may need to be spent away from the nest feeding, increasing the likelihood of both nest failure and/or predation. Adverse conditions later in the breeding season, during brood rearing, can also be detrimental to ducklings whose thermoregulatory capacity is limited (Koskimies and Lahti, 1964) and death from exposure a particular risk. It is possible however that rather than poor climate conditions being detrimental for the birds indirectly, an indirect effect of poor weather is to change the abundance and phenology of key resources, such as freshwater invertebrates, resulting in phenological mismatch (Drever and Clark, 2007). Common scoter, as species which breed late in the season, could be particularly susceptible to changes in the timings of resources as there is less opportunity for second laying attempts.

Changes in total common scoter breeding numbers associated with either the direct or indirect effects of annual climate variation could potentially be identified by examining numbers both the following year (if non-breeding juveniles are returning to the breeding grounds) or following a two-year lag (if birds are waiting until sexual maturity before returning to the breeding grounds). Common scoter can breed from two years of age; however anecdotal evidence suggests non-breeding birds may be returning to Scottish breeding grounds as one-year olds. Therefore, in this chapter the effects of annual climate variation on the number of birds at the breeding grounds will be examined in the context of both a one year and two-year lag. Three hypotheses around the effect of annual climate variations on numbers of common scoter in the Flow Country will be explored in this chapter and can be summarised as follows:

i) Number of common scoter in the Flow Country will be lower in years following harsh European winter conditions due to increased mortality and/or breeding deferral

ii) Common scoter numbers will be lower in years which follow those with poor (cold, wet) summer (April-August) due to lower breeding success and therefore fewer juveniles returning to the breeding grounds the following year

iii) Common scoter numbers will be lower in years which experienced poor (cold, wet) summer (April-August) two summers previously due to lower breeding success and therefore fewer birds returning to the breeding grounds once sexually mature

Landscape scale processes, such as geology and land use, can have a significant influences on the chemistry and biology of oligotrophic lochs, particularly in ombrotrophic peatlands (Drinan *et al.,* 2013b). However, few studies have examined these processes in relation to breeding water birds. Landscape features that have the potential to influence common scoter in the Flow Country fall into two categories. Firstly, landscape features that can influence the ecology of the loch directly, such as surrounding land use, loch management and connectivity (via streams) effecting processes such as nutrient inputs, erosion rates and water levels/quality. Secondly there are landscape features that could act as proxies for other mechanisms structuring common scoter distribution; connectivity of sites for human access (by tracks and roads) could increase disturbance rates or indirectly represent the extent of predator control and/or management of scoter competitors (such as brown trout). Maxent is a useful analytical tool that enables exploration of numerous potential landscape features that could be influencing species distribution. The contribution of all potentially influential features can be assessed in relation to a species distribution, rather than non-statistically significant variables being excluded (as with GLMs) (Elith *et al.,* 2011). This adaptive approach will be useful for common scoter in the Flow Country as it allows examination of all the hypothesised influences on scoter distribution. Previous studies of peatland lochs have highlighted the importance of geology, forestry, clear felling and bog quality (Clay *et al.,* 2009b; Cummins and Farrell, 2003a; Drinan *et al.,* 2013b, 2013c; Miller *et al.,* 1996; McElarney *et al.,* 2010; Tetzlaff *et al.,* 2007; Titus and Malcolm, 1992; Turkia *et al.,* 1998; Wilkie and Mayhew, 2003) in structuring loch communities, and these factors will therefore be considered in relation to common scoter distribution in the Flow Country. Number of streams and proximity of roads/tracks will also be included to give an indication of anthropogenic accessibility and wetland connectivity which may also be important to scoter. The relationship between landscape features (identified as influential by Maxent) and the within loch characteristics identified as important in Chapter 3 (DOC, sediment type, shallowness, macrophyte cover, chironomid and fish abundance and fish weight) will be examined using GLM approach to identify potential links between landscape scale processes and within-loch characteristics.

The overall aim of this chapter is to build on results from chapter 3 (that characterised lochs used by common scoter, Figure 4.1a). Annual climate variation and potentially influential landscape variables will be considered in relation to their direct impact on scoter phenology (Figure 4.1b and 4.1c). In addition, the indirect effects of landscape scale processes on breeding success via alterations to Flow Country loch ecology will also be assessed (Figure 4.1.d).

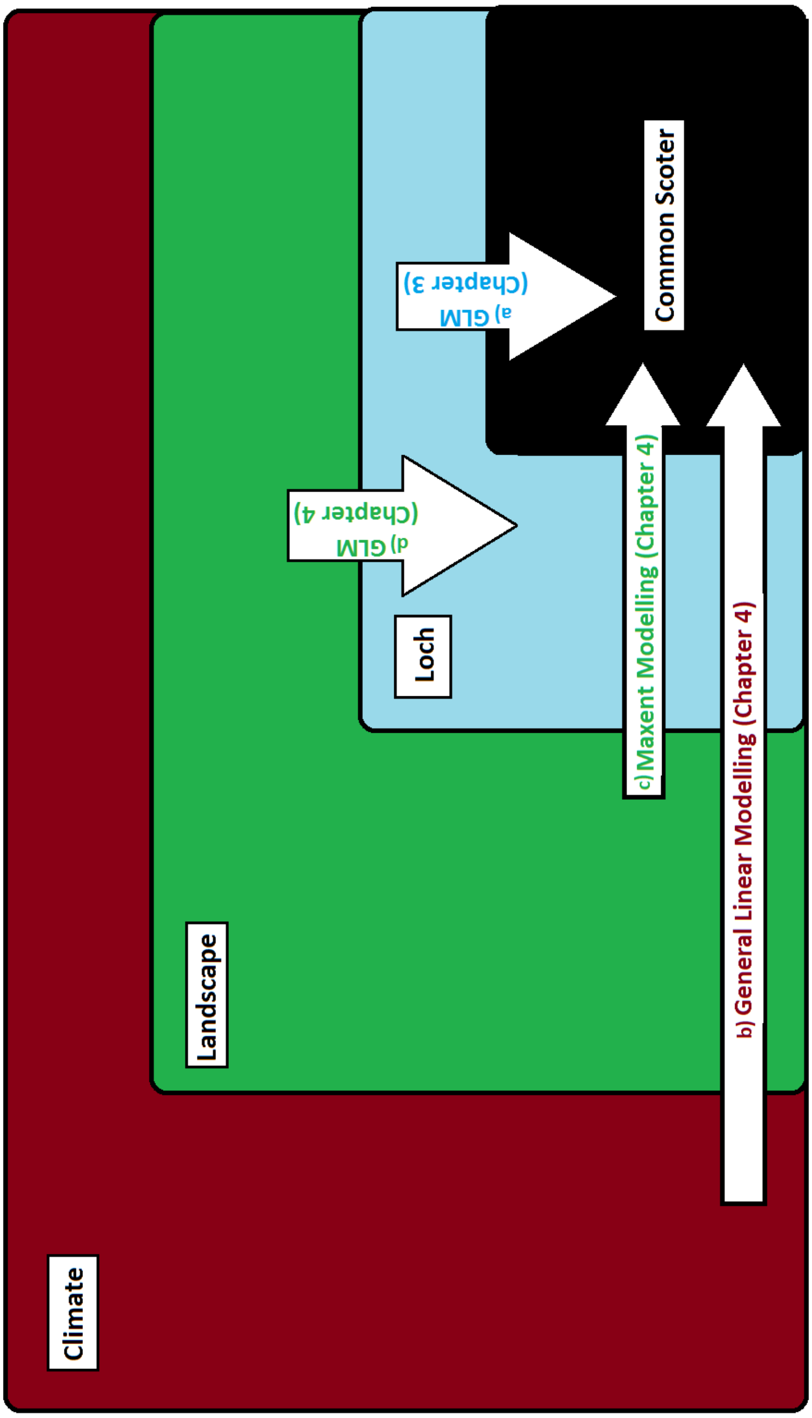


Figure 4.1 Schematic diagram illustrating the three spatial scales which are examined in relation to common scoter in chapters 3 and 4, a) relationship between common scoter and loch variables (investigated in chapter 3), b) relationship between common scoter populations and climate investigated using (this chapter), c) influential landscape characteristics will be examined using Maxent analysis (this chapter), d) relationship between landscape and loch characteristics will be examined using GLMs (this

4.3Methods

4.3.1 Study Area

The Flow Country peatlands in northern Scotland is the study area focused upon in this chapter, details and descriptions of which are provided in Chapter 2.1.

4.3.2 Study sites

The basis of site selection is detailed in Chapter 2.3. The Flow Country is considered at two spatial scales in this chapter. Firstly, annual climate variation is examined at a regional scale, using data that relates to climatic conditions for Europe and northern Scotland. Secondly, the maximum entropy (Maxent) analysis will examine landscape scale variables and will focus on an area of approximately 100,000 hectares of the Flow Country as shown in Figure 4.2. This area includes all known common scoter breeding lochs in the Flow Country together with additional lochs known to be unused by common scoter and those which have not been surveyed. Approximately 100 lochs (with perimeter above 100m) are included in this analysis (Figure 4.2). The relationship between influential landscape features (identified by Maxent analysis) and ecologically relevant within-loch characteristics associated with common scoter presence (identified in Chapter 3) will be examined at 18 lochs. Selection of these sites is detailed in Section 2.2.

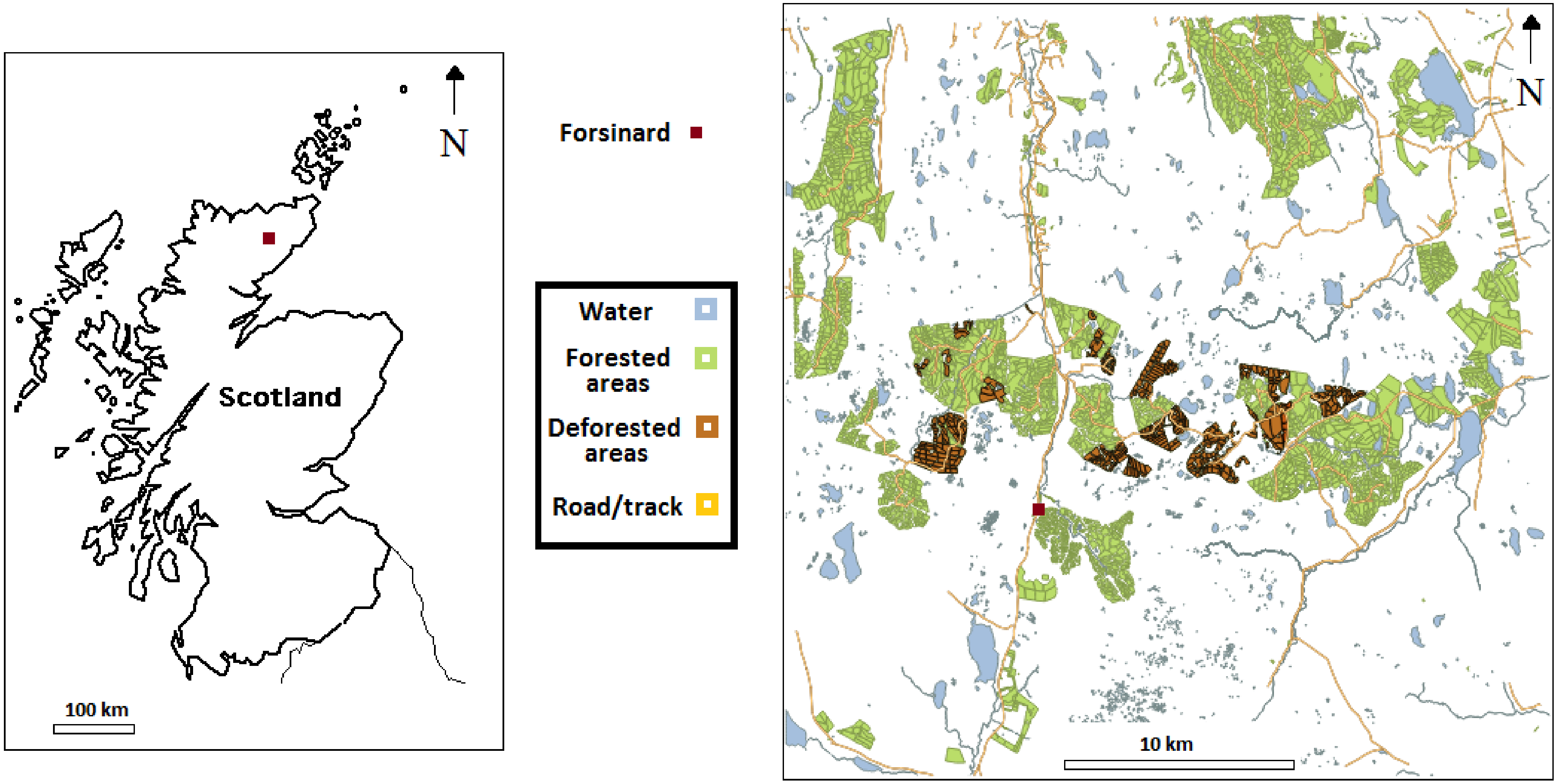


Figure 4.2 Location of Forsinard in Scotland (left panel) and the Flow Country (right panel). The lochs, roads/tracks and areas of forestry and deforestation are also shown in the left panel.

4.3.3 Statistical analysis and data presentation

4.3.3.1 Annual climate variation and change in common scoter numbers in the Flow Country

General linear models (GLMs) were used to examine the relationship between the change in annual numbers of breeding common scoter and climate variables; GLMs are a robust tool for determining the significance of relationships between a single response variable and multiple explanatory variables (Zuur *et al.,* 2009).

Response variable

The response variable used in the GLM was the annual change in common scoter numbers in the Flow Country, calculated as lambda (Figure.4.3); a lambda value of 1 means there has been no change in the total numbers of female scoter between years, whilst values less than 1 indicate decline and more than 1 indicate increases. Lambda was used in preference to raw breeding numbers as the aim of the analysis was to examine the factors associated with changes in common scoter numbers rather than those associated with different absolute numbers of scoter. Lambda also reduces the degree of temporal autocorrelation that would be generated by using absolute numbers.

$$\text{Lambda } \lambda = N_{(t)+1}/N_{(t)}$$

Figure. 4.3 Calculation of lambda, N = abundance, t= time

Explanatory variables

Both temperature and rainfall have been identified as climate variables pertinent to breeding common scoter (Huntley *et al.,* 2007). These were therefore used as explanatory variables in the GLM. The North Atlantic Oscillation (NAO) was also used to give an indication of wider European trends in temperature and rainfall (Table 4.1).

Climate Variable (Data Source)	Description
Temperature (Wick, Met Office)	The mean of minimum temperatures (°C) recorded at Wick between April and August.
Rainfall (Wick, Met Office)	Total rainfall (mm) recorded at Wick between April to August
Summer North Atlantic Oscillation (NAO)(National Center for Atmospheric Research Staff, 2017)	Summer NAO is based on the difference of normalised sea level pressure for the region between Portugal and Iceland for the months of July to August. Positive summer NAO signifies warmer, drier conditions, negative values indicate colder, wetter summers. Data will be used from i) the previous summer and ii) two summers previously
Winter North Atlantic Oscillation (NAO)(National Center for Atmospheric Research Staff, 2017)	Winter NAO is based on the difference of normalised sea level pressure for the region between Portugal and Iceland for the months of December to March. Winter NAO above zero indicate warmer, wetter conditions whilst values below zero indicate colder, drier winters. Data will be used from the winter previous to the summers breeding record

Table 4.1 Data sources and description of climate variables used to examine influence of climate on common scoter breeding in the Flow Country, Scotland.

GLM refinement and data presentation

The model underwent step wise deletion of the least significant variable (determined using the drop1 function in R). General linear modelling was carried out in R (R Core Team, 2016) and related figures produced using ggplot package (Wickham 2009) and the computer software package C2 (Juggins, 2007).

4.3.3.2 Landscape scale variables in relation to scoter breeding distribution

Maxent overview

The machine learning method, maximum entropy, was used to examine the relationship between common scoter presences and landscape variables. The analysis was carried out using the Maxent software version 3.3.3k (Phillips *et al.,* 2011). The Maxent algorithm estimates the distribution of a species by constraining the occurrence data by landscape (or other environmental) variables. Maxent includes regularisation mechanisms which reduces the risk of overfitting and means there is less need to remove correlated explanatory variables (Elith *et al.,* 2011). Maxent has been extensively validated and is considered one of the most effective methods for modelling species distributions, particularly from presence-only data (Elith *et al.,* 2011).

Presence data

The Maxent software uses point data for species presences. These data were collated from RSPB annual monitoring records (RSPB unpublished data). Records of female presence at a loch between the period from April to mid-June for the years 2004 to 2014 were used to identify ca. 30 lochs at which scoter were known to be present, the remaining lochs were those which had either been surveyed and found not to have scoter present or those which had not been surveyed. Maxent has been developed to deal with presence only data (Phillips and Dudík, 2008), therefore non-presence points being a mixture of surveyed and unsurveyed sites would not substantially effect the results. Female scoter presence for use in the Maxent analysis was denoted by a point positioned in the centre of each loch centroid.

Environmental data

Maxent uses Geographic Information Systems (GIS) raster layers for environmental variables. Open source software QGIS version 2.1.4.3 (QGIS Development Team, 2016) was used to produce rasterised layers for the lochs that derived landscape data based on characteristics within a 500m buffer. A buffer zone around each loch was used in preference to using catchment sized areas as the area would represent the terrestrial habitat the birds were likely to be using for nesting. Common scoter use of the Flow Country is centred on freshwater lochs, therefore, the environmental rasters also focus on the lochs by only including data representative of the loch and a 500m buffer around the loch and excluding data for other parts of the terrestrial peatland. This meant that areas of terrestrial peatland without lochs would not be identified as possible habitat for scoter presence by Maxent. The percentage of bog within a 500m loch buffer, track proximity, number of proximal streams, soil moisture and superficial and bedrock geology were used in the Maxent analysis. These variables were selected as they have the potential to influence either common scoter directly or the important within-loch variables identified in Chapter 3 via processes such as erosion, nutrient availability and water quality. A description of the data and the sources are identified in Table 4.2. Landcover type was divided into broadly, into either forestry or bog. No data was available about specific nest habitats or microhabitat use by scoter in the areas around the lochs therefore the focus was on how larger scale landscape features may be influencing distribution across the Flow Country. Variables such as slope, altitude and terrestrial vegetation (classified using normalized difference vegetation index (NDVI)) community were not included in the Maxent as no data is available concerning how scoter use terrestrial areas of the Flow Country. Bedrock geology was categorised into three types (1 igneous types (predominantly granite), sedimentary (2, sandstone, siltstone) and metamorphic (3, predominantly limestone).

Variable	Description and data source
Stream	Number of streams within 500m around each loch (EDINA, 2017)
Road and Track	Minimum distance from each loch to the nearest road or track. Road layer from EDINA, (2017), track data digitised from Bing aerial maps and OS maps
Area of bog within 500m	Three land cover types are disguisable within 500m of lochs in the Flow Country, areas of bog, forestry and deforestation. The percentage of each 500m loch buffer that contained bog was used in the Maxent analysis as a measure of bog area, by considering percentage bog in reverse this metric can also give an indication of forested and deforested area within the 500m buffer.
Soil wetness	Tasselled cap transformation is a conversion of the image received by a satellite (in this case Landsat 8) to create new composite bands that have specific interpretations including greenness, yellowness and wetness. The tasselled cap wetness score was calculated from Landsat 8 (L8 OLI/TRS) images of the Flow country taken in 2001. Mean tasselled cap wetness scores for land within a 500m buffer zone were calculated for each loch to give an indication of habitat quality or bog condition.
Superficial Geology	Dominant surface geologies within a 500m buffer area of each loch was determined from EDINA (2017), categories comprised i) peat, ii) clay silt and sand, iii) clay silt gravel iv) diamicton, sand and gravel
Bedrock Geology	Bedrock geologies from the 500m loch buffers were determined from EDINA (2017), and amalgamated into three broad categories 1 igneous types (predominantly granite), 2 sedimentary (sandstone, siltstone) and 3 metamorphic (predominantly limestone)

Table 4.2 Data sources and description of physical variables used to examine influence of landscape on common scoter breeding in the Flow Country

Maxent analysis configuration

Common scoter loch presence was divided into training (80% of the samples) and test (20% of the samples) datasets. The procedure was repeated 10 times using the "random seeds" option to allow cross validation (Phillips *et al.,* 2011).

Maxent outputs

Each pixel in the study area is assigned a raw, cumulative and logistic value denoting the likelihood of species occurrence. All three outputs are monotonically related; the logistic output provides a likelihood of presence (scaled between 0 and 1) and is easiest to interpret ecologically. Response curves for each environmental variable are also produced that illustrate how each variable affects the Maxent prediction. Maxent does not determine the statistical significance of variables being used to model species distribution (or output p-values) rather it determines how much each is contributing to the model fitting process and therefore the relative important of each variable. This approach can allow a more holistic view to be taken than in GLMs, with the ability to consider the relevance of all variables without exclusion based on arbitrary statistical significance.

Model evaluation

Maxent models are evaluated based on Area Under Curve (AUC) values, which assess the capacity of the model to accurately distinguish presences from absences. For AUC values <0.5 predictions are considered to be no better than random, while AUC values >0.75 are considered suitable for conservation planning (Elith *et al.,* 2011).

4.3.3.3 Landscape scale variables in relation to limnology of 18 Flow Country lochs

The relationship between significant landscape variables (identified by the Maxent analysis) and the ecological relevant within-loch variables (identified in Chapter 3) was examined using a general linear modelling approach at the 18 lochs focused on in Chapter 3. The aim was to identify whether any of the loch characteristics important to common scoter could be explained by any of the influential landscape derived variables identified by Maxent. Four GLMs were run in R using DOC, sediment score, shallowness (proportion of the loch less than 1m deep), fish abundance and percentage macrophyte cover as response variables. The three variables that contributed most to the Maxent model (85%) were used as explanatory variables. Each GLM underwent step-wise deletion of the least significant variable (determined using the drop1 function in R) to determine the minimum adequate model.

4.4. Results

4.4.1 The influence of annual climate variation on common scoter in the Flow Country

Relationships between numbers of common scoter breeding in the Flow Country and climatic variables was examined from 1987 to 2014, during this period there were just four years (1989, 1990, 1992 and 2000) during which no co-ordinated count data was available for the Flow Country region (Figures 4.4 and 4.5).

General linear models run to examine annual changes in the number of breeding common scoter (calculated as lambda) in relation to regional and local climate conditions could not identify any statistically significant explanatory variable (p >0.05 in all cases) (Table 4.3).

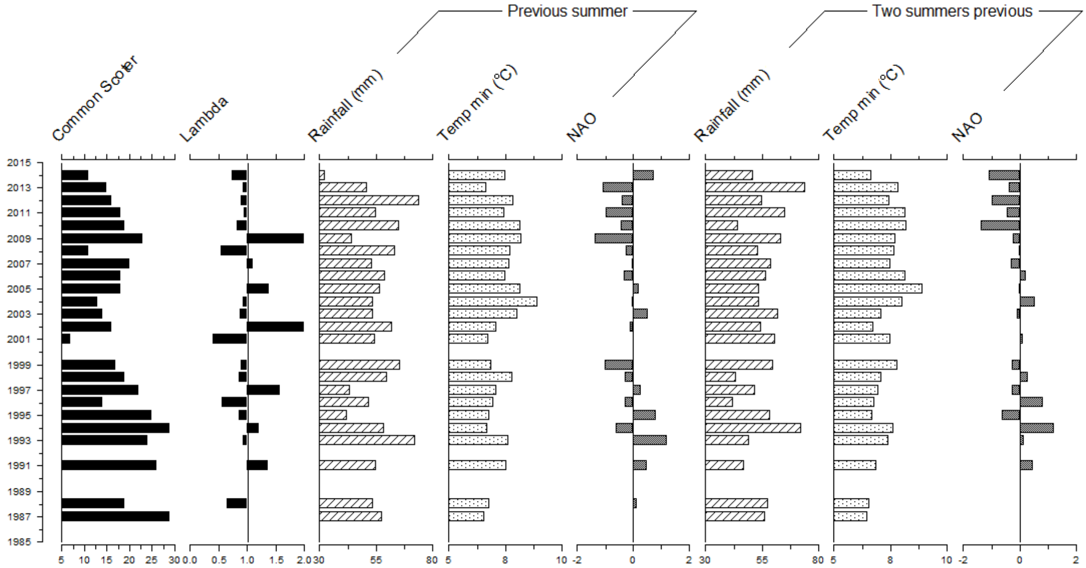


Figure.4.4 Annual number of female common scoter and change in numbers (lambda) recorded in the Flow Country between 1987-2014 (no counts available for 1989, 1990, 1992 and 2000), mean summer rainfall (mm), mean summer temperature (°C) and summer NAO in the previous two years.

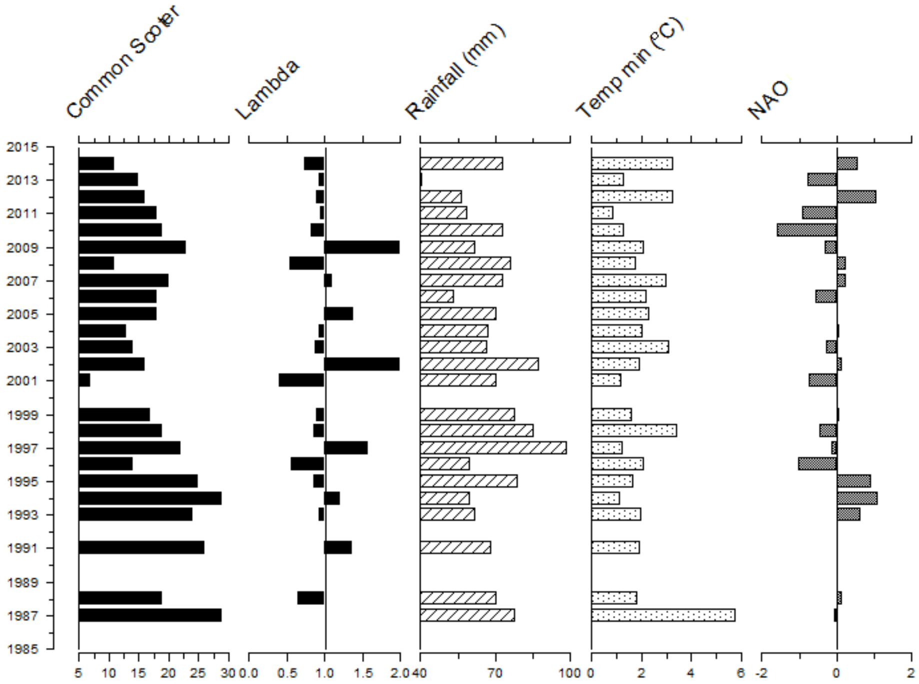


Figure 4.5 Annual number of female common scoter and change in numbers (lambda) recorded in the Flow Country between 1987-2014 (no counts available for 1989, 1990, 1992 and 2000), and mean winter rainfall (mm) and previous winter temperature (°C) for the (October to March)

Model	**Coefficients**	**Estimate (std. error)**	**d.f**	**t-value**	**p-value**
1) Previous winter	Intercept	0.612089 (0.576986)	3,20	1.061	0.301
	Rainfall	0.007063 (0.007917)	3,20	0.892	0.383
	Temperature	-0.027850 (0.093799)	3,20	-0.297	0.770
	NAO	0.074435 (0.147641)	3,20	0.504	0.620
2) Previous summer	Intercept	0.457030 (1.241714)	3,20	0.368	0.717
	Rainfall	-0.006053 (0.010457)	3,20	-0.579	0.569
	Temperature	0.121337 (0.157725)	3,20	0.769	0.451
	NAO	-0.137608 (0.152515)	3,20	-0.902	0.378
3) Two summers previously	Intercept	0.587635 (1.250011)	3,20	0.470	0.643
	Rainfall	0.008149 (0.012857)	3,20	0.634	0.533
	Temperature	-0.001221 (0.158931)	3,20	-0.008	0.994
	NAO	0.033507 (0.171873)	3,20	0.195	0.847

Table 4.3 Results from three general linear models used to examine the relationship between change in numbers of common scoter in the Flow Country and climate variables

4.4.2 Landscape scale influences on the breeding distribution of common scoter in the Flow Country

Maxent model output

The likelihood of common scoter occurrence at lochs across the study area is visualised in Figure 4.6. Lochs with the highest likelihood of occurrence are centred around the core of the Flow Country peatland area.

The most important predictors of scoter breeding presence identified by Maxent were percentage bog area (within 500m buffer of the loch), soil moisture (mean tassel cap score within 500m buffer of the loch) and bed geology (a categorical variable), which explained 48.8, 29.9 and 17.4% of scoter breeding variability respectively (Table 4.4).

The relationship between individual variables and probability of scoter presence are shown in Figure 4.6. The land cover in the 500m loch buffers was categorised as bog or forestry (forestry included areas of deforested plantation), and therefore the extent of bog in the buffer could be equally considered as the area not covered by forestry. Probability of female scoter presence was low where percentage of bog was low (and therefore forestry was high). The probability of scoter presence increased with proportion of bog in the buffer, peaking at approximately 60% bog (or 40% forestry). Between 60-100% bog the probability of scoter presence again declined (Figure 4.7.a). Tasselled cap moisture scores represent relative soil moisture across the surveyed area (the ca. 100km^2 area identified in Figure 4.2). Probability of scoter presence peaks at intermediate moisture values, indicating scoter presence is more likely were soil moisture is neither extremely low or high. The probability of common scoter presence was shown to be highest in lochs situated on granite bedrocks. The other variables (number of streams and proximity of roads) together (on average across 10 model runs) explain <2% of the variation.

Model run	Contribution					
	Soil moisture	Proportion of bog	Bedrock geology	Surface geology	Road Proximity	Stream frequency
1	19.0513	57.1266	16.3215	4.8447	0.5986	2.0572
2	8.5215	89.0216	2.4559	0.001	0	0
3	32.5071	19.6081	38.3556	8.1643	0	1.3649
4	20.6355	57.452	13.078	4.6539	2.8696	1.311
5	57.3482	25.5648	14.2152	2.8718	0	0
6	40.9391	47.6718	11.0503	0.3389	0	0
7	44.9403	24.4712	26.8561	3.7325	0	0
8	51.2296	13.4025	32.9932	2.3746	0	0
9	5.6565	86.993	6.7801	0.1233	0	0.4471
10	18.652	66.3578	11.9594	2.2861	0	0.7447
Av.	29.9481	48.7669	17.4065	2.9391	0.3468	0.5925

Table 4.4 Contribution of variables to each of the 10 Maxent model runs

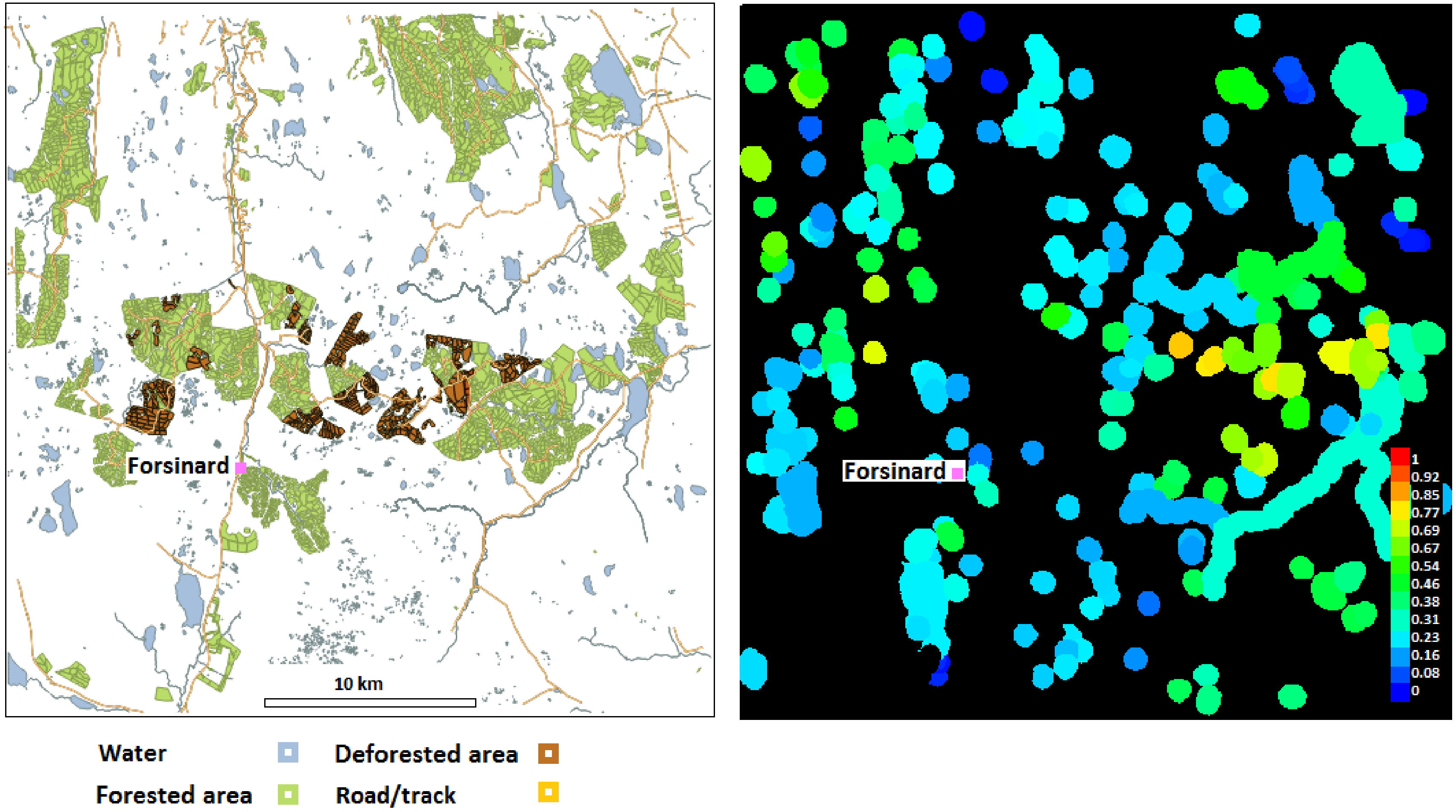


Figure 4.6 Logistic output from maxent analysis for lochs and 500m buffer, showing the likelihood of common scoter presence on a 0 (low probability) to 1 (high probability) scale.

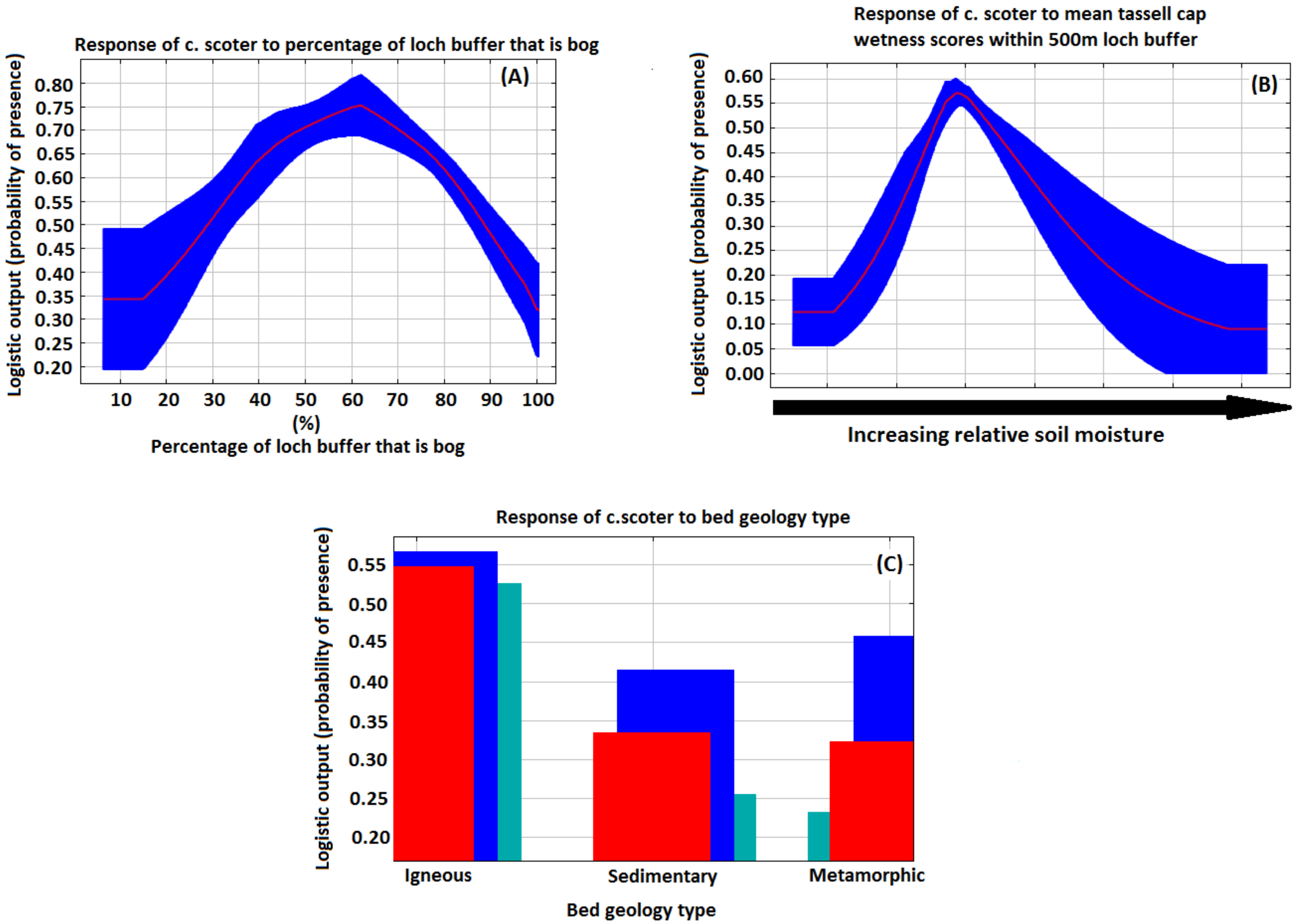


Figure 4.7 Logistic outputs from the maxent model, showing the relationship between the three most influential variables and probability of female scoter presence. Red = mean of 10 Maxent model runs, blue/green = +/- one standard deviation

Maxent model evaluation

The mean training AUC from the 10 bootstrapped model runs was 0.8263 (range 0.7750-0.9203) and the mean test AUC was 0.7593 (range 0.4324-0.9893) (Table 4.5). Both results are above the random threshold (0.5) and conservation planning threshold (0.75 (Franklin, 2010)). The difference between the training and testing AUCs was small (average difference 0.067), as was the standard deviation (0.09) of the 10 test AUC values suggesting little over-fitting of the model.

Model run	Training AUC	Test gain	Test AUC	Test AUC Standard Deviation
1	0.92	0.88	0.89	0.02
2	0.81	1.93	0.99	0.00
3	0.80	-0.15	0.60	0.17
4	0.82	-0.48	0.43	0.10
5	0.83	0.60	0.82	0.07
6	0.80	0.89	0.92	0.02
7	0.78	0.00	0.65	0.11
8	0.79	0.25	0.69	0.17
9	0.78	0.49	0.76	0.09
10	0.84	0.99	0.75	0.18
Av.	0.82	0.54	0.75	0.09

Table 4.5 Results of Maxent model evaluation for each of the 10 model runs

4.4.3 Landscape scale drivers of loch ecology in relation to hypotheses for common scoter decline

The relationship between the three most influential landscape variables identified in the Maxent analysis (bog area, soil moisture score and dominant bedrock geology that together explain 96% of scoter breeding presence) and within loch characteristics identified in Chapter 3 (DOC, sediment score, proportion below 1m deep, fish abundance and percentage vegetation cover) were examined using a series of general linear models. No significant relationship was identified between landscape and within-loch features of the 18 lochs.

4.5. Discussion

Studies suggest that annual climate variation at both overwintering sites and breeding grounds have the potential to influence numbers of breeding seaducks (Coulson, 2010; Jónsson *et al.,* 2009; Lehikoinen *et al.,* 2016, 2006; Swennen, 1983). Direct effects include changes in migration timing and behaviour (e.g. breeding propensity) and timing mismatches with peaks in food resources. The indirect consequences of annual climate variation are diverse, and potentially include changes to competitor, predator and/or pathogen frequencies, as well as changes to habitat quantity or quality. Results from the current study, however, show that changes in common scoter breeding numbers since 1987 are not significantly associated with annual variations in climate, at either local (breeding grounds) or regional (wintering ground) scales. This result contrasts with Zipkin *et al.,* (2010) who demonstrated significant association between wintering numbers of seaducks (12 species of the Tribe Mergini) in North America and NAO. Similarly, Lehikoinen *et al.,* (2006) documented positive correlations between body condition and NAO in populations of female eider in north Europe. However, Oja and Pöysä, (2007) found no evidence of an effect of NAO on the timing of hatching in species of mallard (*Anas platyrhynchos*) and common goldeneye (*Bucephala clangula).* As suggested by Zipkin *et al.,* (2010) the response of seaducks to annual climate variation is likely to be both intricate and indirect. Whilst annual climate fluctuations may be influencing the behaviour, timing and success of seaduck migrations and breeding, any associated variations in the total number of birds attempting to breed, may be more difficult to detect, particularly as birds that are forced to winter further south, or arrive at the breeding grounds in poorer condition, may still attempt to breed. In conditions where summer climate is less extreme than is typical for the species (such as common scoter in Scotland compared to common scoter in sub-arctic Russia) the effects of suboptimal climate, such as poor body condition may be less detrimental and therefore have less of an impact on total numbers and/or breeding success.

The Flow Country is a unique landscape in Britain, its oligotrophic lochs are more akin to the subarctic lakes of Scandinavia and Russia which corresponds to the core breeding distribution of common scoter. Indeed, climate envelope models, based on climate data from the 1990s (prior to common scoter decline), failed to accurately predict common scoter breeding presence in either Ireland or Scotland. Whilst this could suggest that common scoter have always been outside their typical climate envelope in Britain, it could equally suggest that other factors (such as geology, topography and land use resulting from Britain's geographic position in Europe) are combining to create an atypical habitat that make Scotland available for breeding scoter.

The landscape variables that were the most influential in explaining common scoter distribution in the Flow Country were the proportion of bog close to the loch, soil moisture and bedrock geology. Maxent analysis identified the proportion of bog as the most influential variable in predicting common scoter presence in the Flow Country. The proportion of bog close to the loch could equally be considered in terms of proportion of forested (and deforested) area, as these constituted the remaining percentage of the area not accounted for by bog. The probability of common scoter presence was found to be highest at 50-70% bog or 30-50% forest/deforested area. Commercial forestry in the Flow Country has been a controversial issue since planting took place in the 1980s, with many conservationists concerned about the effects of forestry and its associated activities (drainage and fertiliser addition) on the acidic, low nutrient and predominantly treeless environment of the Flow Country (Stroud *et al.,* 1988). The consequences for lochs of these forestry activities on catchments of deep peat was not particularly well studied at the time. However, concerns included acidification and eutrophication as well as increases in sediment movement by erosion and via drainage channels (Lindsay *et al.,* 1988; Nature Conservancy Council, 1986; Stroud *et al.,* 1988). Evidence to date has not been able to establish a strong relationship between common scoter loch use and plantation forestry (Harris, 1995), suggesting that if there is a relationship then it is not linear or easy to detect. Common scoter do not avoid lochs with forestry, and indeed some of the lochs that are most productive for scoter are those surrounded by, or close to large forestry blocks. In accordance with other evidence the results from this study suggest that any relationship between forestry and common scoter is complex and not a simple positive or negative relationship. Ecologically there appear to two possible interpretations of the relationship identified by Maxent, one correlative and the other causal. The distribution of forestry in the Flow Country is typically localised in large blocks (ranging from <1km^2 to ca. 40km^2). The most substantial area of forestry is located between Forsinard and Loch More, which is also where the majority of common scoter breeding lochs are located. Common scoter are known to have been breeding in this core area since before the forestry was planted. It is therefore possible that the relationship between forestry and common scoter is coincidental rather than causal. Common scoter are known to be strongly site faithful in other parts of the breeding range (E. Burrell and I.K. Peterson pers. comm.). It is therefore possible that birds in the Flow Country are continuing to breed at sites at which they have historically bred, regardless of disturbance or ecological changes caused by the forestry. If this is the case, and the birds are continuing to attempt breeding despite forestry, which could have implications for the observed decline. Changes in terrestrial and aquatic habitats associated with the forestry could be having a detrimental effect on food supplies by reducing invertebrate abundance or substantially influencing community composition.

Alternatively, it is possible that the observed association between common scoter and forestry is causal. The optima identified by the Maxent analysis (30-50%) could suggest that some forestry in the catchment is beneficial to common scoter, and that is why they are more likely to be found at these sites. Moderate amounts of forestry close to the lochs could have indirect consequences for common scoter; for example, they may provide habitat for alternative prey species, that are preferable to predators that would typically feed on scoter. This was demonstrated by Bêty *et al.,* (2001) who observed strong patterns with breeding goose success and predator prey oscillations in Canada. Areas of forestry have also been shown to influence lochs by increasing inputs of both sediments (by erosion and drainage (Ramchunder *et al.,* 2009) and/or nutrients (from fertilisers, Cummins and Farrell, 2003b; Nieminen, 2004). Increasing nutrients could make the lochs more productive (and therefore likely to contain more food); changes in sediment composition could make lochs more profitable feeding areas for common scoter by influencing loch bathymetry and sediment types. However, if forestry was having a positive effect on food supply and feeding habitat, the relationship between scoter distribution and proportion of forestry would be positive, with common scoter being most probable at sites where forestry was highest, instead of the distribution identified by Maxent.

Overall, it appears more likely that the relationship between forestry and common scoter distribution is correlative rather than causal; despite forestry being planted in the core of the common scoter range they continue to attempt breeding. Common scoter declines could therefore be indicative of changes occurring as a result of forestry activities, particularly as common scoter have been shown to be significantly associated with loch characteristics that are known to be influenced by forestry (DOC, Muller and Tankéré-Muller, 2012), sediment type (via erosion Turkia *et al.,* 1998) and the abundance of invertebrates and fish (Drinan *et al.,* 2013b; Graham *et al.,* 2014). GLM analysis was, however, unable to identify any significant association between forestry and the important loch characteristics identified in Chapter 3. Subtle and/or indirect influences of forestry on these variables could be difficult to determine using only a contemporary snap shot of conditions. A temporal perspective is necessary to more fully understand the changes forestry may have had on the ecology of Flow Country lochs since the 1980s.

Soil moisture was the second most influential variable identified by the Maxent and, similarly to proportion of forestry, showed a unimodal relationship, with likelihood of scoter presence peaking at intermediate soil moisture values. Extremes in soil moisture may be avoided by scoter as they represent more challenging nesting conditions, where nests are more likely to be flooded (in extremely wet areas) or to be exposed/difficult to conceal in extremely dry areas where vegetation may be sparse. Whilst it is possible soil moisture is indirectly affecting common scoter by influencing loch ecology (through processes such as increased sediment transport in areas of low soil moisture), no significant relationship could be identified using GLM.

Bedrock geology accounted for an average of 13% of the scoter distribution, with scoter being more likely at sites with igneous bedrock types. Bedrock geology can influence loch ecology by influencing water chemistry. However, none of the variables identified in Chapter 3 were found to be significantly associated with bedrock geology. As the bedrock geology of the Flow Country will not have changed over the period of common scoter decline, it is more likely therefore that geology is just one of several factors contributing to the heterogeneity of Flow Country lochs and the distribution of common scoter.

Brown trout populations in Flow Country lochs are influenced by levels of fishing and overall levels of reproduction and restocking. The proximity of lochs to tracks and the connectivity of lochs by streams were included in the Maxent analysis as possible proxies for fishing pressure (with lochs closer to tracks potentially receiving more frequent visits by anglers) and fish abundance (with lochs connected to higher number of streams potentially providing more areas of gravel/coarse sediments for depositing eggs). Common scoter distribution was not substantially influenced by either proximity of tracks or degree of stream connectivity, suggesting that common scoter distribution is not influenced by brown trout, although it is conceded that neither of these proxies is particularly robust.

Common scoter abundance in the Flow Country is not related to recent climate variations. Analysis was able to identify several landscape features that are associated with common scoter presence, the most influential of which was forestry. However, determining the nature of these relationships (whether causal or correlative) proved more difficult. It was not possible to establish the extent to which landscape scale processes directly influence loch charactersitics that are important to common scoter. In cases where the variables relating to competing hypotheses are not spatially separable (as is the case here) but are temporally distinct, a longer-term perspective is vital. Chapters 5 and 6 of this thesis will use palaeolimnology to add this necessary temporal perspective. By examining timescales both concurrent to decline and prior to its initiation, palaeolimnology has the potential to disentangle competing hypotheses with spatially correlated variables, and additionally place present day conditions within the context of long term variability.

4.6 Key findings and implications

- No statistically significant relationship was identified between changes in the number of common scoter breeding in the Flow Country and annual climate variations at either regional (wintering sites) or local (breeding grounds) scales

    ⟶ Annual climate variation does not appear to be a strong factor influencing decline of common scoter in the Flow Country either directly (by effecting the birds themselves) or indirectly (by effecting habitat quality, quantity or timings of resources), which could indicate other factors besides climate are more pertinent to common scoter use of the atypical Flow Country environment.

- Species distribution modelling identified the proportion of bog and forestry close to lochs as being the most influential variable explaining common scoter distribution, followed by soil moisture and bedrock geology. Both bog and soil moisture display unimodal relationships with probability of scoter presence, whilst igneous type bedrock geologies were most strongly associated with common scoter presence.

    ⟶ Landscape variables associated with common scoter presence could be correlative or causal, however on the balance of evidence a correlative relationship appears more probable. The core of common scoter breeding area in the Flow Country is located in the centre of the area selected for forestry activities. The unimodal relationship between scoter presence and proportion of forestry, together with continued scoter declines, does not support the theory that scoter are benefiting from or avoiding changes occurring in consequence of the forestry.

- Examination of the relationships between landscape features influencing scoter distribution and within-loch variables (identified as important in Chapter 3) revealed no statistically significant relationship between landscape and within-loch features important to common scoter.

    ⟶ Whilst a landscape perspective has provided evidence of the influence of forestry on scoter distribution, it has not been able to provide substantial evidence of the direct or indirect landscape influences on common scoter decline. A temporal perspective that can disentangle spatially correlated hypotheses may be a useful next step.

CHAPTER 5 THE USE OF TOP-BOTTOM PALAEOLIMNOLOGICAL ANALYSIS TO EXAMINE RECENT ENVIRONMENTAL CHANGE AT 18 FLOW COUNTRY LOCHS AND INVESTIGATING THE VALUE OF A COASRE TEMPORAL SCALE PERSPECTIVE ON COMMON SCOTER DECLINE

5.1 Overview

This chapter examines the feasibility of using sediment cores taken from shallow lakes to investigate recent environmental change. The integrity of the cores will be examined using lithostratigraphic and geochemical techniques. The timescale covered by each core will be established using heavy metal profiles and corroborated by radiometric dating of 3 of the 18 cores. Taxa representing different trophic groups (diatoms and chironomids) will be used to examine recent environmental change using a top-bottom palaeolimnological approach. The extent and type of community change experienced at Flow Country lochs will be further explored in the context of current common scoter loch use, with the aim of gaining insights into the causes of decline.

5.2 Introduction

The Flow Country is an atypical environment in Britain; its remote location and challenging terrain have resulted in a vast wetland landscape, which superficially appears little influenced by the usual anthropogenic pressures. However, closer examination reveals a history of peat cutting and low intensity grazing, land management for shooting and fishing pursuits and more recently forestry plantations and windfarm developments. With a highly distinctive wetland flora and fauna, and recent declines in iconic species (such as the common scoter), the Flow Country is a priority for conservation. Chapter 3 of this thesis used detailed survey data to characterise 18 lochs in the Flow Country and established that, despite superficial similarities, there is currently much physical, chemical and biological variation between the lochs. The causes of this variation were explored in Chapters 3 and 4 by examining the landscape scale, climate variability and within loch processes structuring communities. Similar to much other freshwater research, this thesis has so far used only contemporary data to provide an overview of current environmental conditions. Additional analyses have been used to identify the loch and landscape characteristics associated with a species of interest, in this case the common scoter. This approach has identified a number of hypotheses for common scoter decline. However, a major limitation of using only contemporary data is that they provide only a single snapshot of conditions. This can be insufficient to disentangle competing hypotheses for decline, or to establish how current conditions relate to longer term trends and natural variability. Palaeolimnology is a technique that can be used to provide long term environmental data by examining information archived in lake sediments. Biological remains and geochemical analysis of dated sediment cores taken from lochs, can be used to reconstruct past algal, invertebrate and plant communities. Palaeolimnology is reliant on sediments within a loch being deposited in a time-depth sequence and remaining undisturbed by bioturbation or mixing by strong water currents. Despite the technique being applied in a diverse range of freshwater habitats, there are still reservations in the conservation community about its application, particularly in shallow, potentially wind-stressed systems such as the Flow Country. This chapter aims to evaluate the use of lake sediment cores in a potentially challenging palaeolimnological environment, namely shallow, wind-stressed lochs containing soft sediments which have the potential to be easily disturbed. Lithostratigraphic analysis will be used to assess the stratigraphy of 18 cores. This will be complemented by geochemical analysis of heavy metal concentrations throughout the core lengths, which will provide further evidence regarding core integrity, and an estimate of timescales covered. The analysis of large numbers of samples from fine resolution sediment cores for multiple taxa, is a time intensive and potentially costly process. This chapter will therefore investigate the use of a less time intensive, top-bottom approach to examine coarse resolution changes over a large number of sites. Top-bottom analysis focuses on a sample taken from the surface slices of a core (representing modern communities) and a historic sample taken from a slice towards the base of a core; both the extent and type (or direction) of community change can be examined. Top-bottom analysis has been successfully employed to assess the extent of anthropogenic impacts (Bradshaw *et al.,* 2006; Brooks *et al.,* 2005), and to identify reference or pre-disturbance conditions to guide loch management and restoration (Bennion *et al.,* 2010; Dalton *et al.,* 2009;

Dixit and Smol, 1994). In this chapter top-bottom analysis will be used to provide a temporal context to the contemporary environmental data presented in Chapters 3 and 4. The extent and type of change in communities representative of different trophic levels (diatom algae and chironomid midge larvae) will be determined for a time approximately representing 150-200 years BP and present day.

The use of palaeolimnological data to address issues of current conservation concern, such as species decline, is only slowly increasing, despite a growing body of evidence demonstrating its applicability to a range of conservation issues (Ayres *et al.,* 2007; Bennion *et al.,* 1996a; Birks, 1996; Davies and Bunting, 2010; Davies *et al.,* 2014; Sayer *et al.,* 2012). Waterbirds are particularly sensitive to changes in habitat quality (Lehikoinen *et al.,* 2016; Rodríguez-Pérez and Green, 2012) and have been shown to be valuable indicators of wetland health (Green and Elmberg, 2014). Disentangling the hypotheses for an observed decline in waterbird numbers to effectively prioritise conservation management, is often difficult due to a lack of long term environmental data contemporaneous with that of the decline. Despite palaeolimnology being a well-established technique by which historic environmental conditions in freshwater can be established, there have only been two examples of palaeolimnology being used to examine water bird declines in the UK (Allott *et al.,* 1994; Brooks *et al.,* 2012). Chapters 5 and 6 of this thesis will therefore also assess the use of palaeolimnology to disentangle hypotheses for a water bird decline. Competing hypotheses for common scoter decline in the Scottish Flow Country peatlands established in Chapters 3 and 4 and Hancock *et al.,* (2015) centre around both bottom up and top down controls of the abiotic and biotic characteristics of lochs where they breed.

Community change at 18 lochs will be examined in the context of common scoter decline. The extent of current common scoter loch use was established in Chapter 3 (and termed scoter loch value, SLV) and will be used in this chapter to compare the type and extent of community change in the lochs relative to current scoter loch value.

Overall this chapter has two components the first will use lithostratigraphic and geochemical analysis of samples along the entire core length, together with top-bottom analysis of diatom and chironomid communities to:

i) Determine the integrity of cores from shallow, wind stressed lochs and establish the suitability of cores from challenging conditions, such as the Flow Country, for use in palaeolimnological studies;
ii) Provide a temporal context for the contemporary data presented in Chapters 3 and 4, by examining the extent and type of recent environmental change experienced at 18 Flow Country lochs over the last 150-200 years
iii) Explore whether groupings of lochs (section 3.4.1.8) identified in Chapter 3 are consistent over centennial scales;
iv) Identify a smaller number of sites suitable for more detailed fine resolution, multiproxy palaeolimnological analysis (Chapter 6)

Secondly, this chapter will investigate the use of palaeolimnology to address an issue of current conservation concern, the decline of the common scoter in the Flow Country. Recent environmental change at 18 lochs will be examined (using a top-bottom approach) in the context of current scoter loch use to:

i) Investigate the extent of ecosystem change in lochs with high and low current scoter loch value;
ii) Establish the type/direction of ecosystem change in lochs with high and low current scoter loch value;
iii) Highlight temporal variation in loch characteristics, with a particular focus on those that have been shown to be associated with current scoter loch use and distribution, invertebrate, fish and macrophyte abundance, DOC, sediment composition and water depth

5.3 Methods

5.3.1 Study Area

This chapter focuses on 18 lochs in the Flow Country, Northern Scotland. Further information about the area is provided in Chapter 2.1.

5.3.2 Site Selection

The 18 lochs that are the focus of this chapter are a mixture of current and historic common scoter breeding lochs, set in a mixture of landscape settings. The basis for the selection of these 18 sites is detailed in 2.2. The full loch names and four letter abbreviated loch codes are provided in Table 2.4, hereafter this chapter uses the loch codes to denote the study sites. Descriptions and characterisation of the sites is provided in Chapters 2 and 3. A scoter loch value (SLV) was calculated for each of the lochs in Chapter 3 (section 3.3.5.2, Table 3.1). This value represents the relative current common scoter use on a normalised scale (1 most used, 0 not used) and is used in this chapter in the interpretation of temporal change within the lochs.

5.3.3 Field and Laboratory Methods

This chapter uses a palaeolimnological approach to examine recent environmental change in Flow Country lochs. Short sediment cores were taken from 18 lochs (detailed in 2.4.2.1.1) in 2013 and sliced at 1cm intervals. Lithostratigraphic analysis (2.4.2.2.2) was conducted along the entire length of each of these cores to examine core integrity. Geochemical X-ray fluorescence (XRF) analysis was used to examine heavy metal profiles along the core and provide further evidence of core integrity as well as an approximate dating estimate (2.4.2.2.3). Slices from the top (1-2cm) and the bottom (ranging between 5 and 27 cm) of the core were analysed for diatom and chironomid remains. Details of the laboratory methods used are presented in 2.4.2.2.5 and 2.4.2.2.6. Three of the 18 cores were dated using radiometric ^{210}Pb dating methods (2.4.2.2.4).

5.3.4 Statistical analysis and data presentation

Unconstrained ordinations are useful for examining and comparing community composition across sites (Legendre and Birks, 2012), and are used in this chapter to examine which species are associated with the lochs in the bottoms and tops of the cores. Diatom data underwent DCA and chironomid data PCA. The choice of method was based on gradient lengths, determined in Canoco ver 5.

Procrustes rotation analysis is an effective tool for comparing two or more ordinations by determining the deviation between corresponding points from two (or more) datasets. In a top-bottom context, procrustes rotation can be used to establish the amount of community change at a site between the bottom and top of a core. The method compares the two ordinations by applying uniform scaling to one ordination (core bottom) to minimise the sum of squared deviations (termed m2) between it and a target ordination (core top). Small m2 values denote sites at which the tops and bottoms are similar, whilst large m2 values indicate sites which have experienced substantial community change. The deviations between samples in the two ordinations are called residuals and can be represented in a separate plot to facilitate comparison between sites, with the median and 3rd quartile ranges highlighted.

The procrustean randomisation test (PROTEST) is an analysis of congruence and is conducted to formalise the results of the procrustes analysis by determining whether the m2 value generated is smaller (or samples from tops and bottoms are more similar) than would have been expected by chance. The PROTEST randomly reorders one dataset whilst maintaining the integrity of the other. The original m2 value is then compared to the randomly generated one. This procedure is carried out multiple times (in this case 999) and a probability of obtaining an m2 equal to or smaller than that obtained for the original dataset determined and given a p value. The level of agreement between ordinations results is indicated by the rotation sum of squares (RSS) and the root mean square error (RMSE), with lower values indicating better agreement.

Constrained ordination, with forward selection of explanatory variables, is useful in top-bottom analysis to provide insights into the potential drivers of community change, as sites “move” in the ordination space relative to environmental variables. In this chapter, the procedure was carried out for both chironomid and diatom communities. Constrained ordinations of the samples from the tops of the cores were first completed, with significant environmental variables identified using partial Monte Carlo permutation tests in Canoco. The samples from the bottoms of the cores were then passively plotted onto the same ordination space. Diatom data underwent CCA and chironomid data RDA, the choice of method being based on gradient lengths, determined in Canoco ver 5.

Data transformation followed methods detailed in Chapter 2 section 2.4.2.3. All ordination analyses were carried out in Canoco ver5 (ter Braak and Smilauer, 2012). Procrustes rotation and procrustean randomisation tests (PROTEST) (Jackson, 1995) were conducted in R (R Core Team, 2016) using the vegan package (Oksanen *et al.,* 2007). The stratigraphic plots from lithostratigraphic and geochemical analyses were constructed using C2 software (Juggins, 2007) and radiometric dating results are illustrated using Microsoft Excel.

5.4. Results

5.4.1 Lithostratigraphy

The core stratigraphies varied between sites (Figures 5.1 and 5.2). However, no consistent spatial pattern could be identified between the profiles of the different lochs. 13 cores did include 1 or 2 distinct sandy sediment layers but no discernible pattern could be determined in relation to either the depth at which the layers occurred, loch location or dominant surrounding land cover type.

CAOL, CULA, DUCU, HEMO, SCYE and TALA all showed little variation in organic content along the core length, although slight increases were evident at CULA and CULA. With the exception of TALA, all these sites are those in which no sandy layers were visible, and which have no or minimal forestry close by. Loch TALA is the exception having both sand visible along its core length and large areas of forestry nearby (which was deforested in the 1990s). The profile of loch TALA is unusual compared to the other 17 cores in having an organic content of less than 5% along its length. The five sites with stable LOI profiles and little/no proximal forestry are, however, not the only sites without forestry. HEBE, DUIN and LOSG are three sites which are particularly distant from forestry and yet these sites have distinct changes in their LOI profiles and visible sandy layers.

BREA, BEUL, CROC, DUGE and DUIN all have very high organic content, close to 100% for the majority of the core, with declines in LOI associated with sandy layers apparent at different points along the core length.

Overall, LOI data (Figure 5.1) suggests the cores taken from these shallow Flow Country lochs have visible stratigraphies (rather than a homogenous LOI) which suggests the cores integrity is intact. Several lochs have periods of dynamic change associated with visible sandy layers. However, there is no consistent pattern discernible in relation to either overall LOI profile or landscape features such as tracks or forestry.

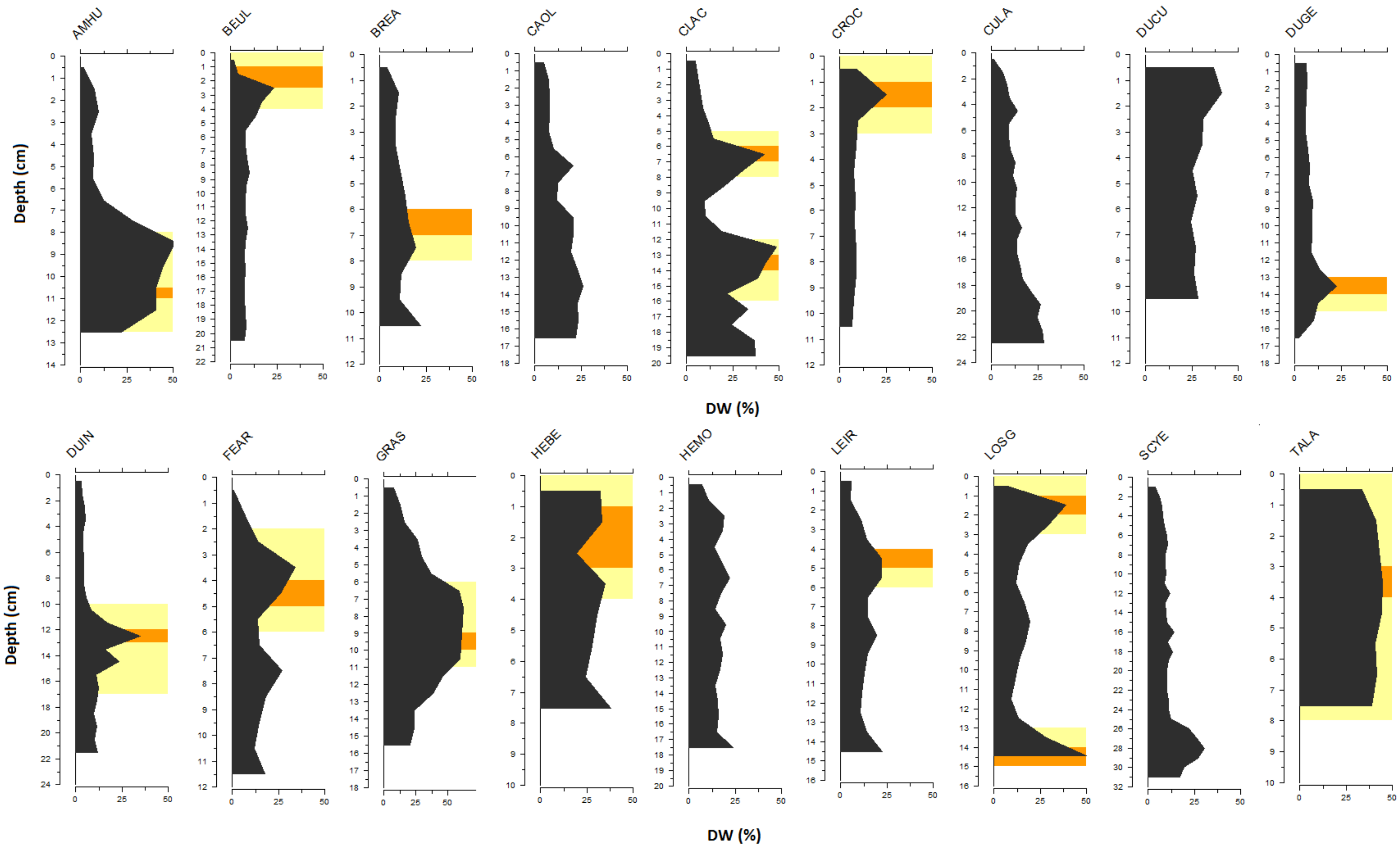


Figure.5.1 Results of dry weight analysis for 18 study sites, yellow=some sand evident but predominantly silt, orange=predominantly sand, some silt.

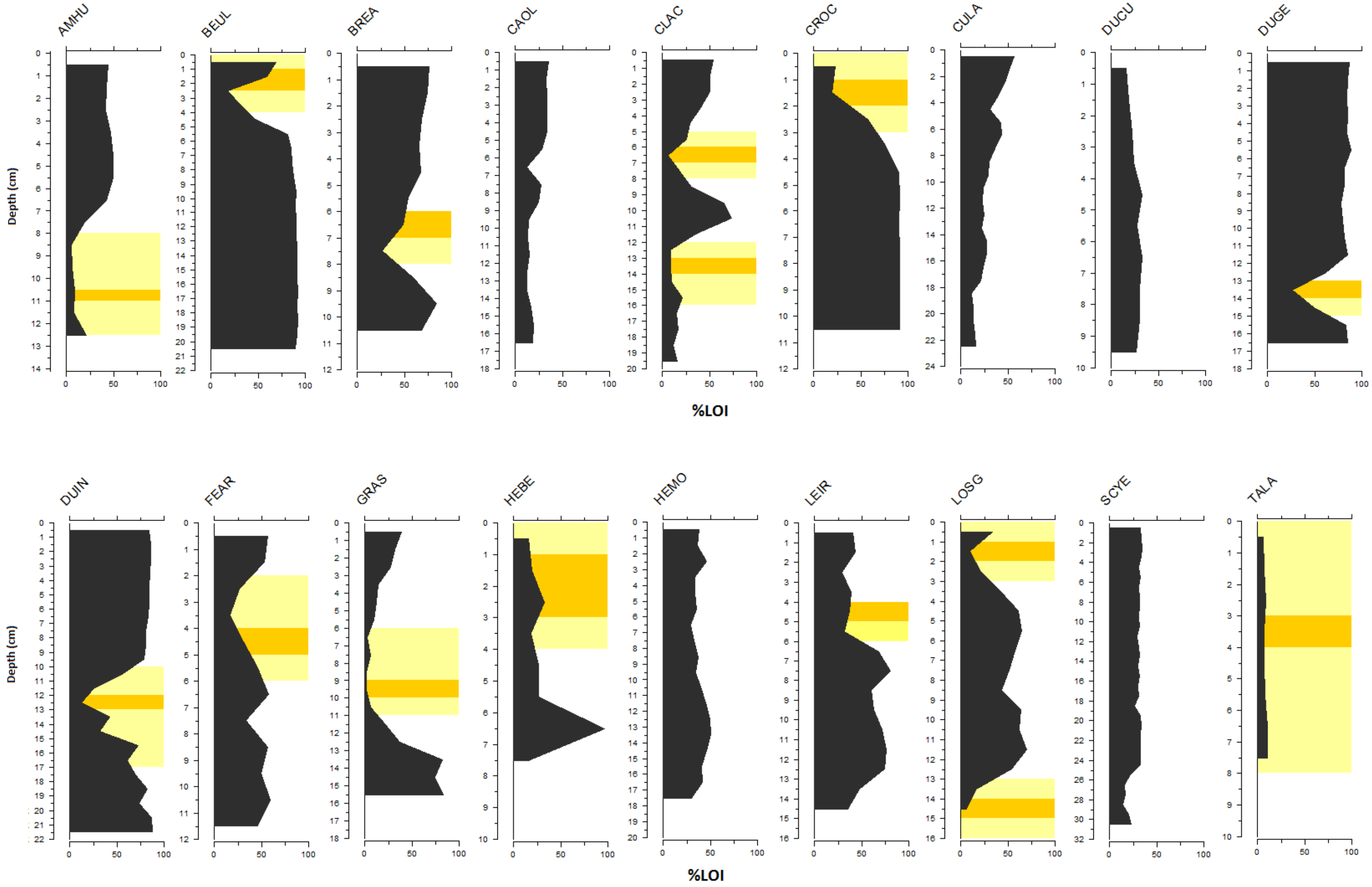


Figure 5.2 Loss on ignition at 550°C results for the 18 sites, yellow=some sand evident but predominantly silt, orange=predominantly sand, some silt.

5.4.2 Core Chronology

X-ray fluorescence analysis

Studies have shown that even remote lakes have experienced increases in the atmospheric deposition of heavy metals since industrialisation (Yang *et al.,* 2002). Flow Country lochs lack industrial activities within their catchments, the closest industrial centre being Inverness 100km to the south. Consequently, heavy metals detected within Flow Country loch sediments will be solely from atmospheric, long range pollution sources. Any change observed in the heavy metal concentrations along the cores (as described in section 2.4.2.2.3) can be used to establish an approximate timescale for the period covered by the core. In this chapter XRF analysis was used to establish both core integrity and an approximate estimate of timescale using heavy metal lead (Pb) profiles (Figure 5.3).

The cores all have visible stratigraphies indicating the integrity of the cores has not been compromised. AMHU, BEUL, CAOL, CLAC, CULA, DUCU, DUGE, DUIN, FEAR, GRAS, LEIR and TALA demonstrated the typical peak in heavy metal Pb concentrations followed by a decrease. At sites LOSG and CROC the rise is observable but the following decrease is not clear, perhaps indicating that the tops of these two cores had been disturbed/missing. The profiles of BREA, HEBE, HEMO and SYCE do follow a pattern of increased Pb followed by a decrease but the peak of Pb is not well defined.

XRF dating estimates were corroborated by more robust ^{210}Pb dating for 3 of the 18 cores (the results of which are detailed in the following section). 1900 and 1960, established by the ^{210}Pb method, are indicated on the XRF profiles and the age-depth curves for LEIR, GRAS and CAOL in Figure 5.4. Whilst 1960 is fairly consistently placed between 2 and 4 cm depths, the depth range at which 1900 is recorded varies more substantially between the three lochs (3, 6 and 10cm respectively). The sediment accumulation rate at LEIR is particularly low.

The position of samples selected for top-bottom analysis of chironomid and diatom communities are also illustrated in Figure 5.3. The surface samples taken from 1-2 cm represent conditions post-1960 based on the data from the three dated cores. Whilst some surface samples may represent contemporary communities, the slow accumulation rate of some systems may mean that the slice represents several decades. The bottom samples were initially taken from 1cm above the base of the core, but where insufficient heads (chironomids) or valves (diatoms) were found in the slice, a sample was taken from 1-2cm further up the core. Chironomid concentrations at CULA and especially GRAS were particularly low in the base of the core and consequently samples were taken from several cm further up the core. The dates for the bottom samples were estimated based on the position of the sample in the XRF profile. Approximate dates were categorised as being either prior to 1850 (before an increase in Pb concentrations) or between 1850-1970 (during the rise in Pb concentration but before the reductions). Details of the estimated dates for the chironomid and diatom samples are shown in Table 5.1.

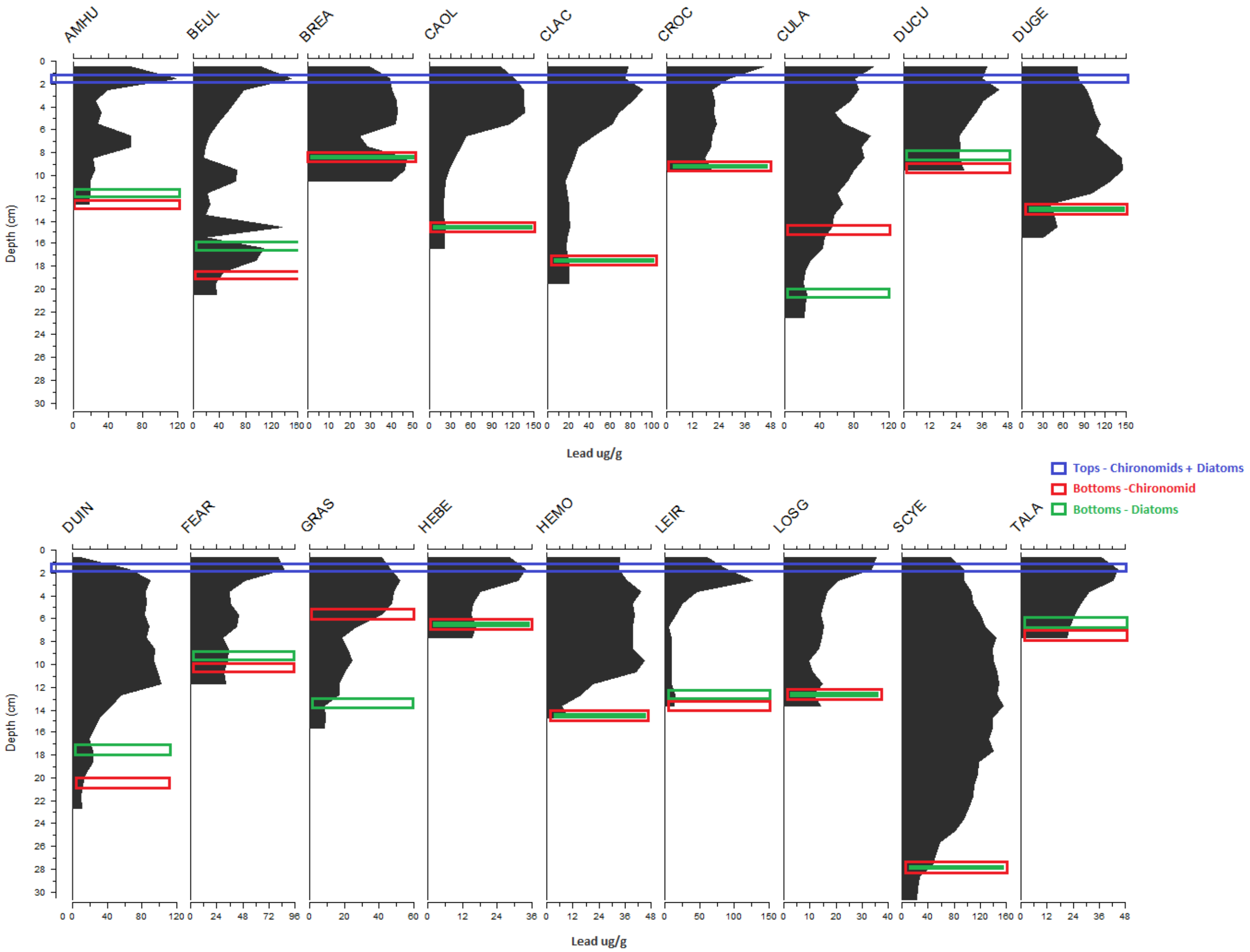


Figure 5.3 XRF Pb profiles for the 18 sites. Blue delimited area indicates the top sample for both diatoms and chironomids; the red area indicates the position of the bottom chironomid sample and the green area the bottom sample for diatoms

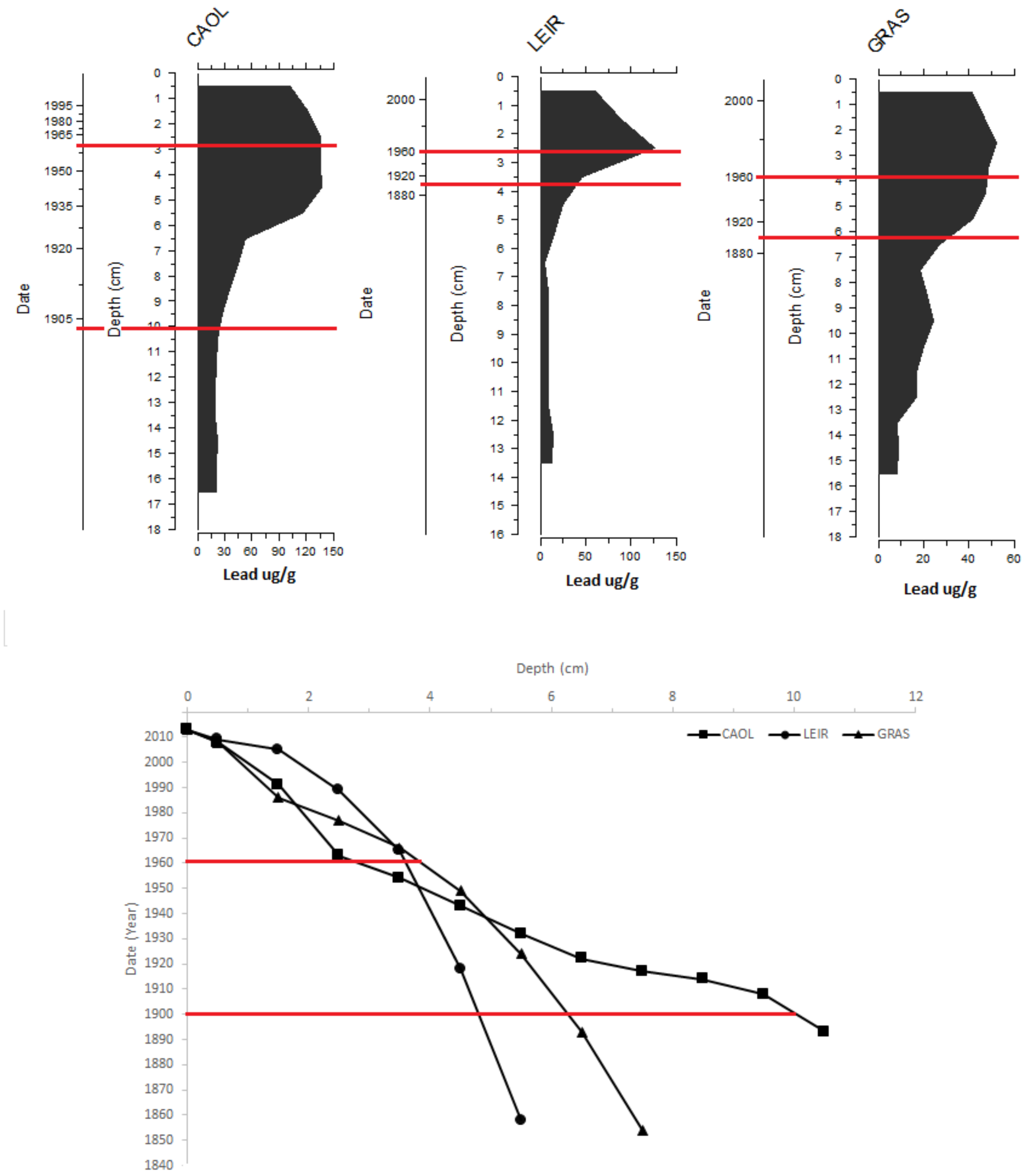


Figure 5.4 The XRF Pb profiles (A) and age-depth curves (B) for CAOL, LEIR and GRAS with the dates for 1960 and 1900 as determined by radiometric technique indicated by the red line

Site	***Chironomid bottom sample***		***Diatom bottom sample***	
	Depth (cm)	***Estimated date***	***Depth (cm)***	***Estimated date***
AMHU	*12-13*	*Pre-1850*	*11-12*	*Pre-1850*
BEUL	*18-19*	*Pre-1850*	*16-17*	*Pre-1850*
BREA	*8-9*	*Pre-1850*	*8-9*	*Pre-1850*
CAOL	*14-15*	*Pre-1850*	*14-15*	*Pre-1850*
CLAC	*17-18*	*Pre-1850*	*17-18*	*Pre-1850*
CROC	*9-10*	*Pre-1850*	*9-10*	*Pre-1850*
CULA	*14-15*	*1850-1970*	*19-20*	*Pre-1850*
DUCU	*8-9*	*Pre-1850*	*7-8*	*Pre-1850*
DUGE	*12-13*	*Pre-1850*	*12-13*	*Pre-1850*
DUIN	*20-21*	*Pre-1850*	*17-18*	*Pre-1850*
FEAR	*10-11*	*Pre-1850*	*9-10*	*Pre-1850*
GRAS	*5-6*	*1850-1970*	*13-14*	*Pre-1850*
HEBE	*6-7*	*Pre-1850*	*6-7*	*Pre-1850*
HEMO	*14-15*	*Pre-1850*	*14-15*	*Pre-1850*
LEIR	*13-14*	*Pre-1850*	*12-13*	*Pre-1850*
LOSG	*11-12*	*Pre-1850*	*11-12*	*Pre-1850*
SCYE	*26-27*	*Pre-1850*	*26-27*	*Pre-1850*
TALA	*6-7*	*1850-1970*	*5-6*	*1850-1970*

Table 5.1 The time period for the bottom samples of diatom and chironomids estimated from the position on the Pb XRF profile

Radiometric dating

Due to cost constraints, only 3 of the 18 cores were radiometrically dated. The results confirmed the approximate dates calculated using XRF analysis. 1963 was calculated as being at 2.5cm sediment depth in CAOL and 3.5cm in LEIR and GRAS.

When dating recent lake sediments using ^{210}Pb, models are typically validated by examining the ^{137}Cs and ^{241}Am peaks associated with nuclear weapons testing in 1963 and the Chernobyl accident in 1986 (Appleby, 2002).

The results for radiometric dating of CAOL are shown in Figures 5.5, 5.6 and Table 5.2. Total ^{210}Pb reaches equilibrium with supported ^{210}Pb at approximately 12cm. A stable sediment accumulation rate is indicated by the more or less exponential decline in unsupported ^{210}Pb activities from 1-6cm. Dips in unsupported ^{210}Pb at 6.5 and 8.5 indicate increased sediment accumulation rates during these periods. The reduction in sediment accumulation rate towards the top of the core, combined with the maximum level of ^{137}Cs activity, could indicate some surface sediments are missing, however, this is not supported by the XRF Pb profile which indicates this core is intact and not missing its top. The ^{137}Cs versus depth profile is of little use for dating as the signal does not show a clear peak, just a steady decline from the surface sediment. A clearly defined ^{241}Am peak at 2.5cm, combined with the concurrent levels of ^{137}Cs activity, correlates with fallout from atmospheric weapons testing in 1963. Core chronologies were calculated using the CRS model due to non-monotonic variation of unsupported ^{210}Pb in the core. The chronology was corrected using the ^{241}Am recorded peak of 2.5cm being formed in 1963.

The radiometric dating results from loch LEIR are shown in Figures 5.7, 5.8 and Table 5.3. The total ^{210}Pb activity reached equilibrium with unsupported ^{210}Pb at 6cm. The decline in the gradient of unsupported ^{210}Pb activities from 4.5cm to the surface sediment indicates a gradual increase in sediment accumulation rates during this period (ca. 1920 to 2013). Similar to CAOL, the ^{137}Cs activity versus depth profile shows a decline from the surface sediments which means the ^{137}Cs is not useful for dating. A sharp peak of ^{241}Am was recorded at 3.5cm which suggests this was the period of the 1963 nuclear weapons testing. Loch LEIR core chronologies were calculated using the CRS dating model, which places 1963 at 3.5cm and agrees with the ^{241}Am record. Sediment accumulation rates in the core show a slow increase from 0.0039 g cm^{-2} yr^{-1} in the 1910s to 0.007 g cm^{-2} yr^{-1} in the present day (Figure 5.8).

Loch GRAS radiometric dating results are shown in Figures 5.9, 5.10 and Table 5.4. Total ^{210}Pb activity reached equilibrium depth with supported ^{210}Pb activity at c. 7.5 cm of the core. An increase in recent sediment accumulation rates is indicated by irregular declines in unsupported ^{210}Pb with depth. The ^{137}Cs peak was recorded at 1.5cm which is likely to be derived from the 1986 Chernobyl fallout. The small peak of ^{241}Am might be derived from the fallout of the atmospheric testing of nuclear weapons but is less useful for dating due to the low value. Chronologies of the core were calculated using the CRS dating model which was corrected using the ^{137}Cs peak, identifying 1.5 cm as from in 1986. The corrected CRS model places 1963 around 3.5 cm, which is in agreement with the ^{241}Am record. Sediment accumulation rates at GRAS are fairly uniform up until ca. 1986 following which a steep decline can be observed, although showing an increase in recent years.

In the three cores radiometrically dated in this chapter some of the ^{137}CS peaks were difficult to discern, which could result from sediment mixing. However the evidence from the heavy metal profiles and the presence of a clear ^{241}Am peak shows the core stratigraphies are intact, and that rather than physically mixing the ^{137}Cs has possibly experienced chemical diffusion in the surface sediments (Appleby, 1997).

Sediment accumulation rate in the three sites has been relatively stable for at least the last 80 years (Figures, 5.6, 5.8 and 5.8), indicating no strong influence of forestry activities on sediment accumulation rate. CAOL_1 is the only site that shows substantial change in sediment accumulation rate, with two peaks at ca. 1915 and ca. 1930.

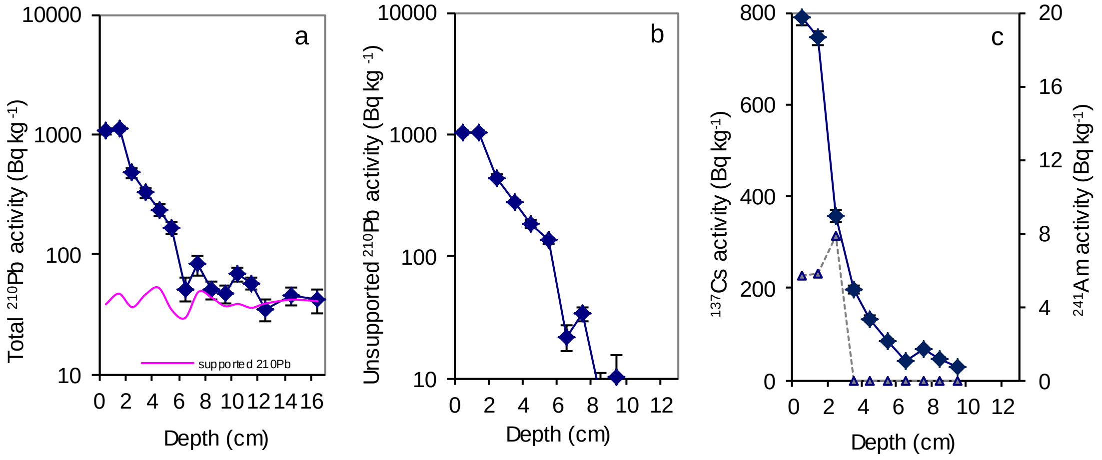


Figure 5.5 Fallout radionuclide concentrations in core COAL, showing (a) total ^{210}Pb (solid pink line) and unsupported ^{210}Pb (solid blue line) (b) unsupported ^{210}Pb, and (c) ^{137}Cs (solid blue line) and ^{241}Am (dashed line) concentrations versus depth.

Depth	Drymass	Chronology			Sediment accumulation rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2013	0				
0.5	0.0255	2008	5	2	0.0052	0.083	7.1
1.5	0.0927	1991	22	4	0.003	0.04	7.7
2.5	0.1761	1963	50	12	0.0045	0.036	13.9
3.5	0.2589	1954	59	12	0.0084	0.102	17.1
4.5	0.3402	1943	70	13	0.0092	0.102	21.5
5.5	0.4368	1932	81	15	0.0084	0.062	26.8
6.5	0.6114	1922	91	23	0.034	0.189	63.2
7.5	0.7922	1917	96	26	0.0166	0.107	62.7
8.5	0.9216	1914	99	27	0.034	0.214	76.1
9.5	1.1101	1908	105	29	0.041	0.19	96
10.5	1.3533	1893	120	30	0.0087	0.037	78.9

Table 5.2. ^{210}Pb chronology of core CAOL_1, Scotland.

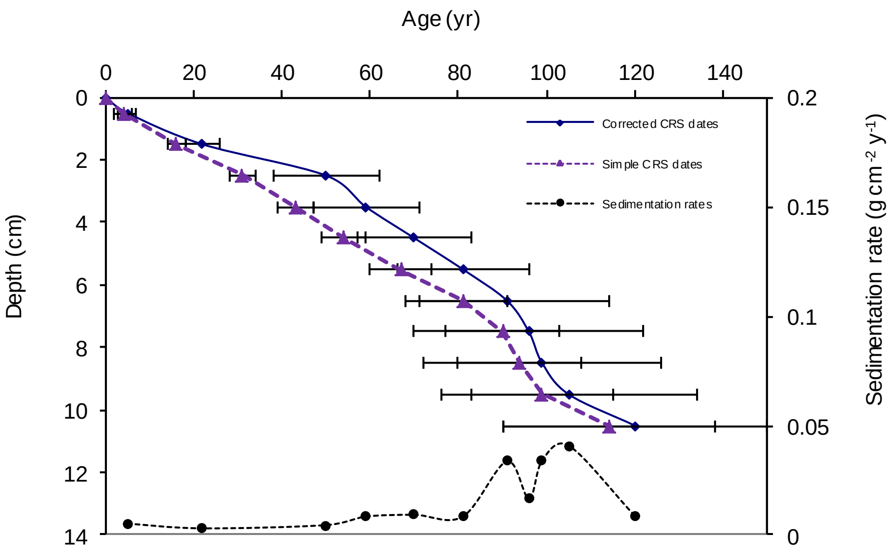


Figure 5.6. Radiometric chronology of core COAL, showing the CRS model ^{210}Pb dates (dashed line), corrected CRS dates (solid blue line) and sediment accumulation rates (black dashed line)

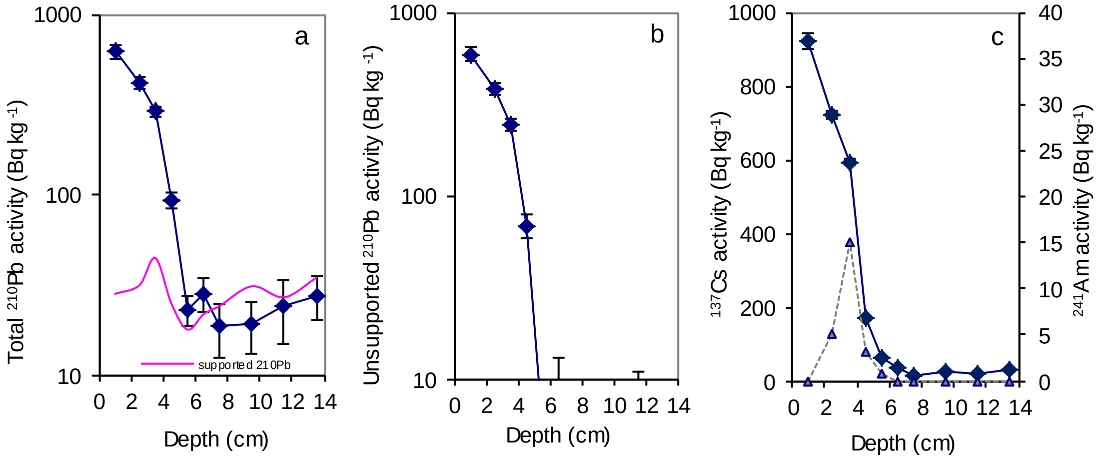


Figure 5.7. Fallout radionuclide concentrations in core LEIR_1, showing (a) total ^{210}Pb (solid pink line) and unsupported ^{210}Pb (solid blue line) (b) unsupported ^{210}Pb, and (c) ^{137}Cs (solid blue line) and ^{241}Am (dashed line) concentrations versus depth.

Depth	Drymass	Chronology			Sediment accumulation rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2013	0				
1	0.0527	2005	8	2	0.007	0.108	10
2.5	0.1619	1989	24	2	0.0065	0.066	10.1
3.5	0.2972	1965	48	3	0.0048	0.028	12.3
4.5	0.5075	1918	95	8	0.0039	0.016	28
5.5	0.8036	1858	155	28	0.0081	0.033	117

Table 5.3. ^{210}Pb chronology of core LEIR_1.

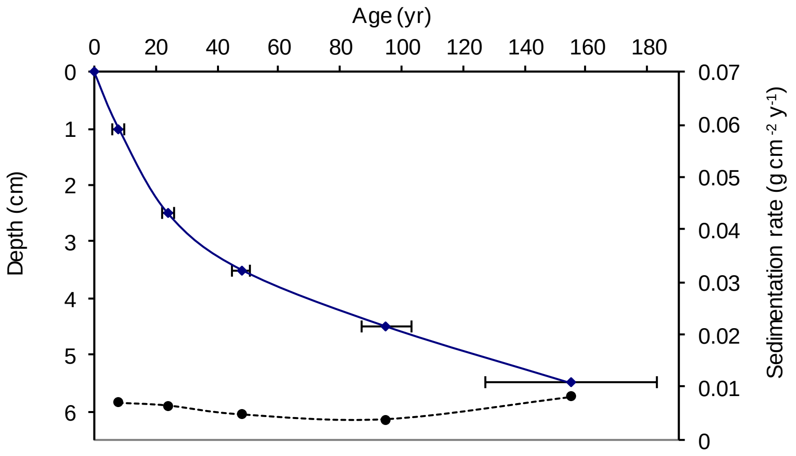


Figure 5.8. Radiometric chronology of core LEIR_1, showing the corrected CRS dates (solid blue line) and sediment accumulation rates (black dashed line)

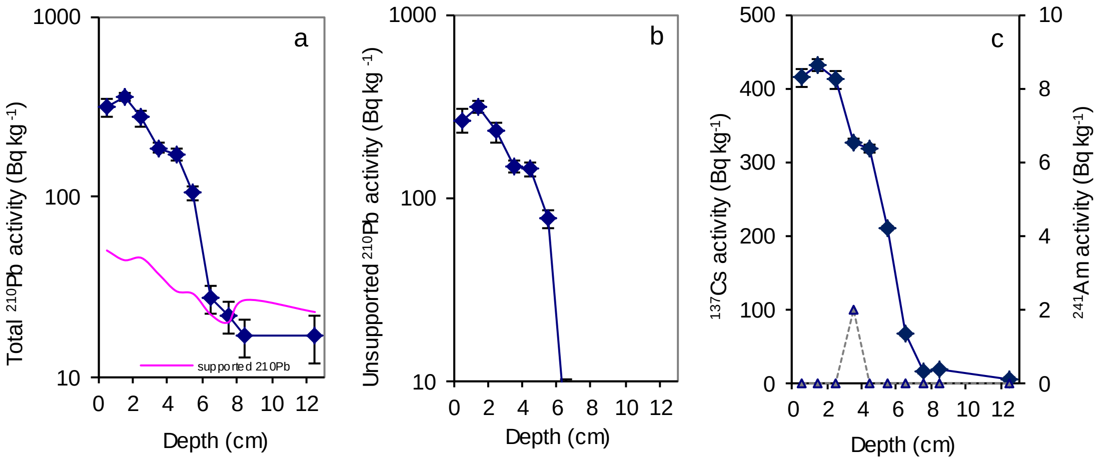


Figure 5.9. Fallout radionuclide concentrations in core GRAS_1, showing (a) total ^{210}Pb (solid pink line) and unsupported ^{210}Pb (solid blue line) (b) unsupported ^{210}Pb, and (c) ^{137}Cs (solid blue line) and ^{241}Am (dashed line) concentrations versus depth.

Depth	Drymass	Chronology			Sediment accumulation rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2013	0				
0.5	0.0406	2008	5	6	0.0073	0.074	71.4
1.5	0.1466	1986	27	6	0.0032	0.025	7.2
2.5	0.2984	1977	36	6	0.0199	0.1	11
3.5	0.5445	1966	47	6	0.02	0.071	9.1
4.5	0.871	1949	64	6	0.018	0.048	11.7
5.5	1.3006	1924	89	8	0.021	0.036	19
6.5	2.0439	1893	120	14	0.024	0.029	56
7.5	2.9717	1854	159	22	0.024	0.026	85.7

Table 5.4. ^{210}Pb chronology of core GRAS_1.

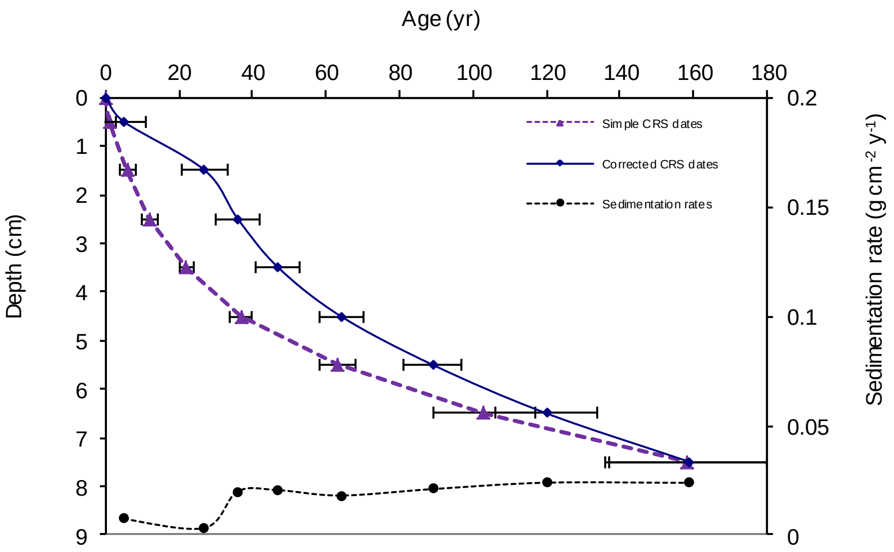


Figure 5.10 Radiometric chronology of core GRAS_1 showing the CRS model ^{210}Pb dates (dashed line), corrected CRS dates (solid blue line) and sediment accumulation rates (black dashed line)

5.4.3 Recent environmental change at Flow Country lochs using a top-bottom palaeolimnological approach

5.4.3.1 Community change in Flow Country lochs

The short sediment cores taken from 18 Flow Country lochs have been shown to have an intact stratigraphy, without evidence of physical sediment mixing due to wind or bioturbation. A top-bottom examination of diatom and chironomid communities was undertaken with the aim of examining recent environmental change at the sites over the last 150-200 years. The contemporary limnological data detailed in Chapter 3 will be examined in a temporal context, loch groupings identified during the previous analyses will be explored. Diatoms and chironomids are useful indicators of environmental change because they represent different levels within the loch's trophic structure and are sensitive to both water chemistry, climate and structural and habitat change.

Diatoms

The twenty most commonly occurring diatom species in the tops and bottoms of the 18 cores are illustrated in Figure 5.11. Typically, the communities are dominated by benthic species in both the tops and bottoms of the cores. *Fragilaria sensu lato* species are the most common in both the tops and bottoms of the cores, particularly *Fragillaria exigua* and *Staurosira construens var. venter. Eunotia* and *Achnanthes* taxa also occur in both bottoms and tops, and include species commonly associated with low nutrient, acidic conditions. *Asterionella formosa*, a species typically associated with more nutrient rich habitats, occurs more frequently in communities in the tops of the cores, being present in 5 out of the 18 sites currently, whilst in the bottom samples it is only present at 3 sites. Overall levels of diversity (number of species recorded) in the tops and bottoms of the cores are shown in Figure 5.12, whilst these data must be treated with caution, as they potentially represent slightly different time periods, they can none the less give a useful indication of relative levels of diversity between contemporary and historic communities. The maximum number of species recorded is similar in both the tops and bottoms. The range is smaller in the surface samples, which could indicate that the flora of the loch is becoming more diverse, particularly as there was no strong evidence of diatom degradation/damage in the historic samples. SCYE is the most diverse site in both the tops and bottoms, and HEMO the least diverse in both instances. There appears to be no clear pattern in change in diversity in relation to known changes in landscape setting, such as forestry.

Unconstrained ordinations of the tops and bottoms are presented separately in Figure 5.13. Separate ordinations were presented partly to explore whether sites were characterised by similar species in both the tops and bottoms of the cores, and also to give an impression of whether the groupings of the sites observed in the contemporary samples were mirrored in the historic records. It is acknowledged however that these conclusions need to be considered with caution, as the samples from the bottoms of the cores may represent different points in the lochs ecological history. In both top and bottom ordinations CLAC, CROC, DUIN, DUGE and LOSG are all positioned on the left side of the ordination space, and are associated with species of Eunotia. CULA is also positioned within this group of sites in the bottom ordination but not in the top ordination. Conversely BEUL is positioned in this group in the top ordination, but in the bottom ordination is located closer to the main group of sites, although still remains a slight outlier. In the bottom ordination, the remaining sites are similar to one another, forming a closely located group on the right-hand side of the ordination space. The only exception is FEAR. This site is clearly separate from the main two groups in the bottom ordination, and is characterised by *Nitzhia gracilis, S. pinnata, A. saxonica* and *N. Jaernefelti.* In the surface samples FEAR is located within the main group of lochs, indicating the community composition has become more similar to the other sites over the last 150 to 200 years. Overall the groupings of lochs by diatom communities are relatively similar in the tops and tops of the core, with the exception of BEUL, CULA and FEAR.

Procrustes rotation of the diatom ordinations for the tops and bottoms of the cores was carried out to examine the similarity and underlying gradients of the datasets (Birks *et al.,* 2012). Figure 5.14 indicates the difference in fitted site values between the bottom (the closed circles) and top samples (arrow heads) for the diatom communities. The comparative length of residuals for each site can be seen in Figure 5.14 inset (B). Residuals highlight patterns of correspondence, large residuals indicate samples that do not have similar communities in the tops and bottoms of the cores, and small residuals highlight bottom samples which have similar community composition. Overall the diatom communities show low concordance between tops and bottoms of the cores (*m2* =0.8033), however, this is not statistically significant (p=0.073) (Figure 5.14). Sites with the highest concordance (small procrustes residuals) are BEUL, CLAC, CROC, CULA, DUGE and SCYE. HEMBE has the largest procrustes residual with respect to diatom communities. The loch with the largest amount of forestry surrounding it CROC is also the site with the least community change, whilst some of the sites with the lowest percentage of surrounding forestry display the most floristic change in diatom communities. No correlation is evident between trout abundance and amount of diatom community change.

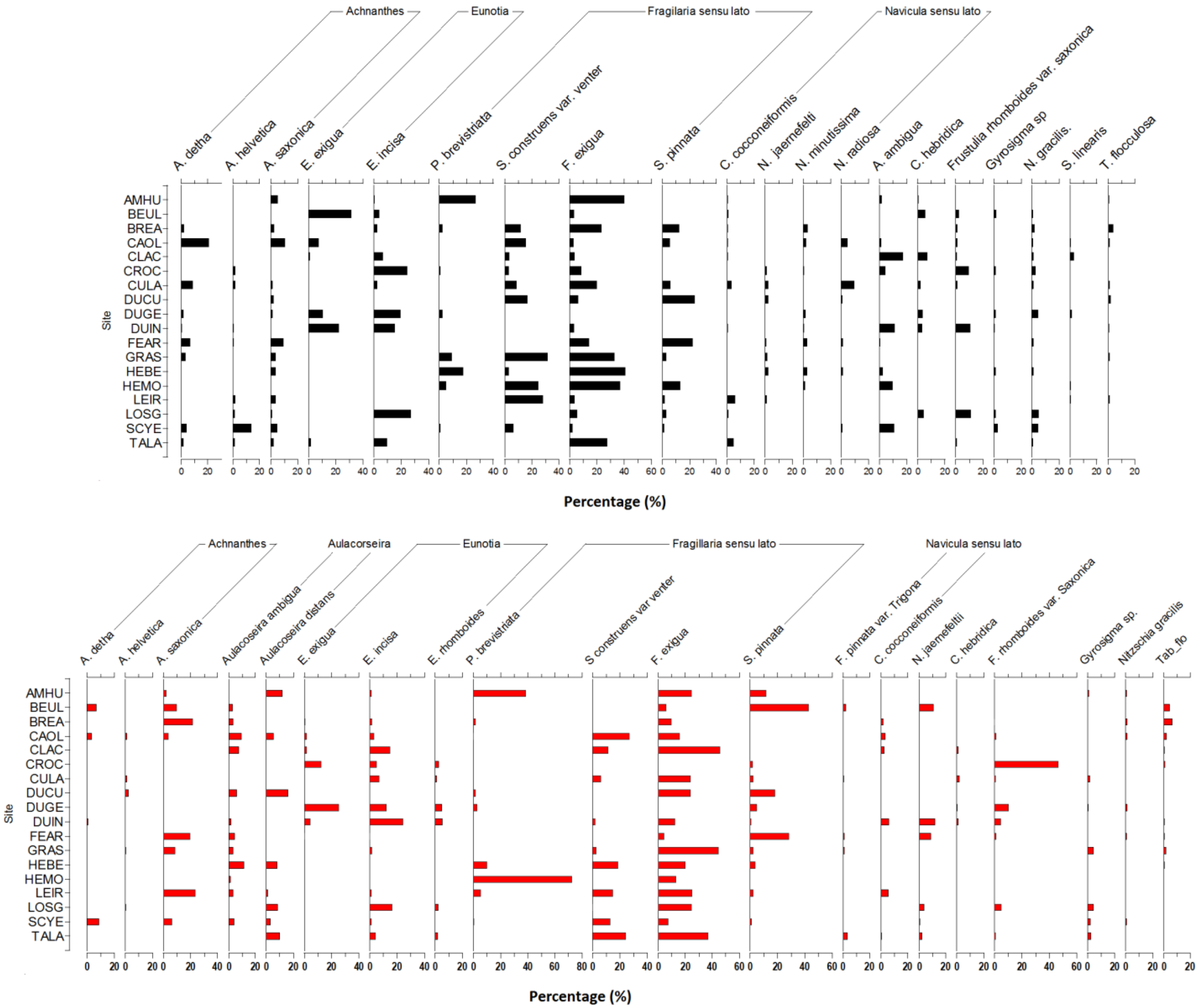


Figure 5.11 The percentage abundance of the 20 most frequently occurring diatom species in the top (black) and bottom (red) of the 18 cores

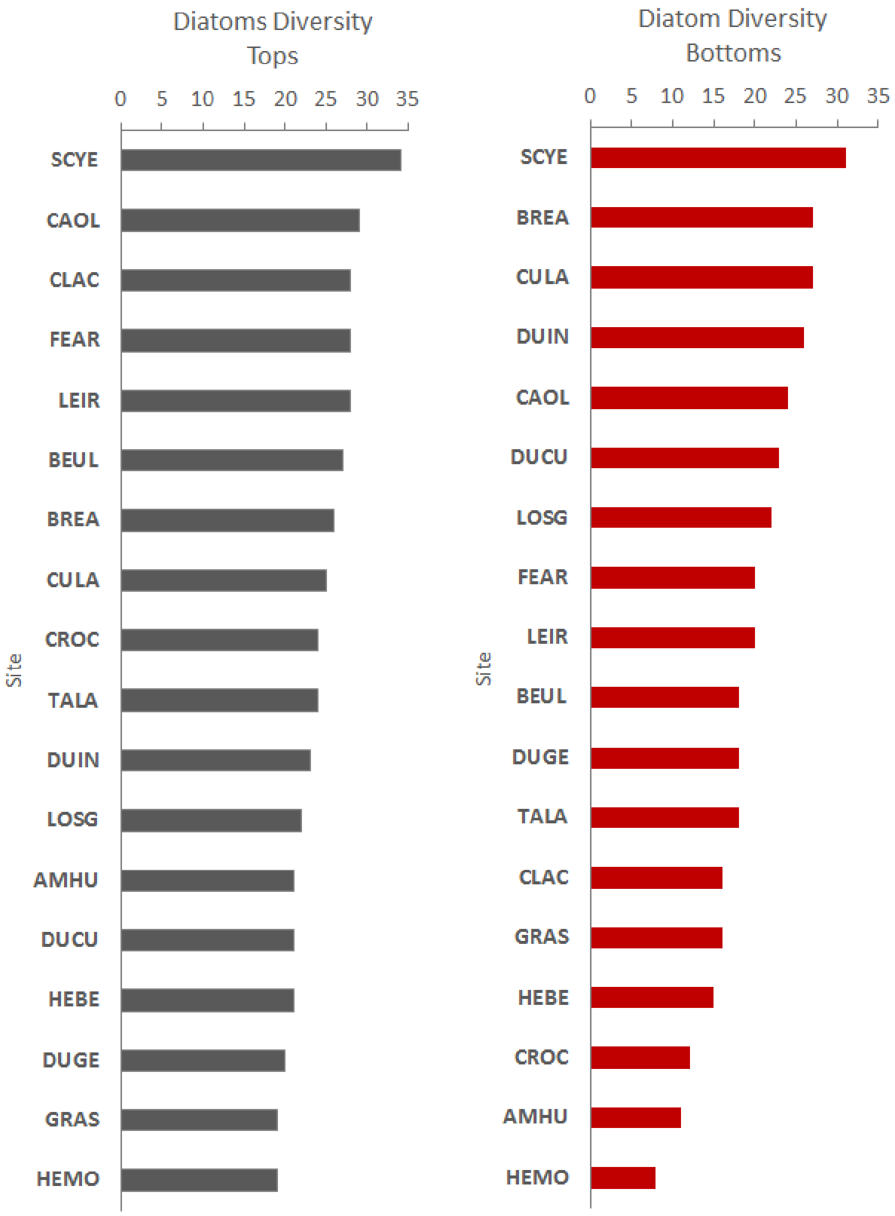


Figure 5.12 Diatom diversity (total number of species) in the tops (black) and bottoms (red) of the 18 cores

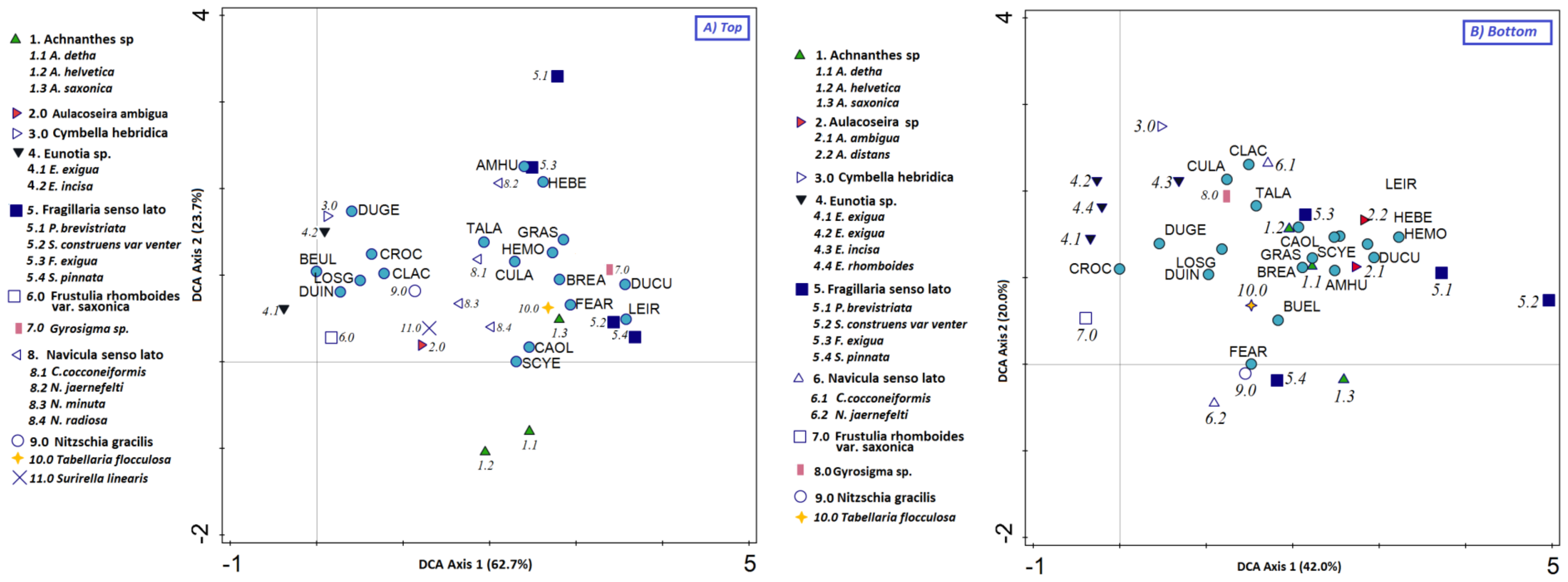
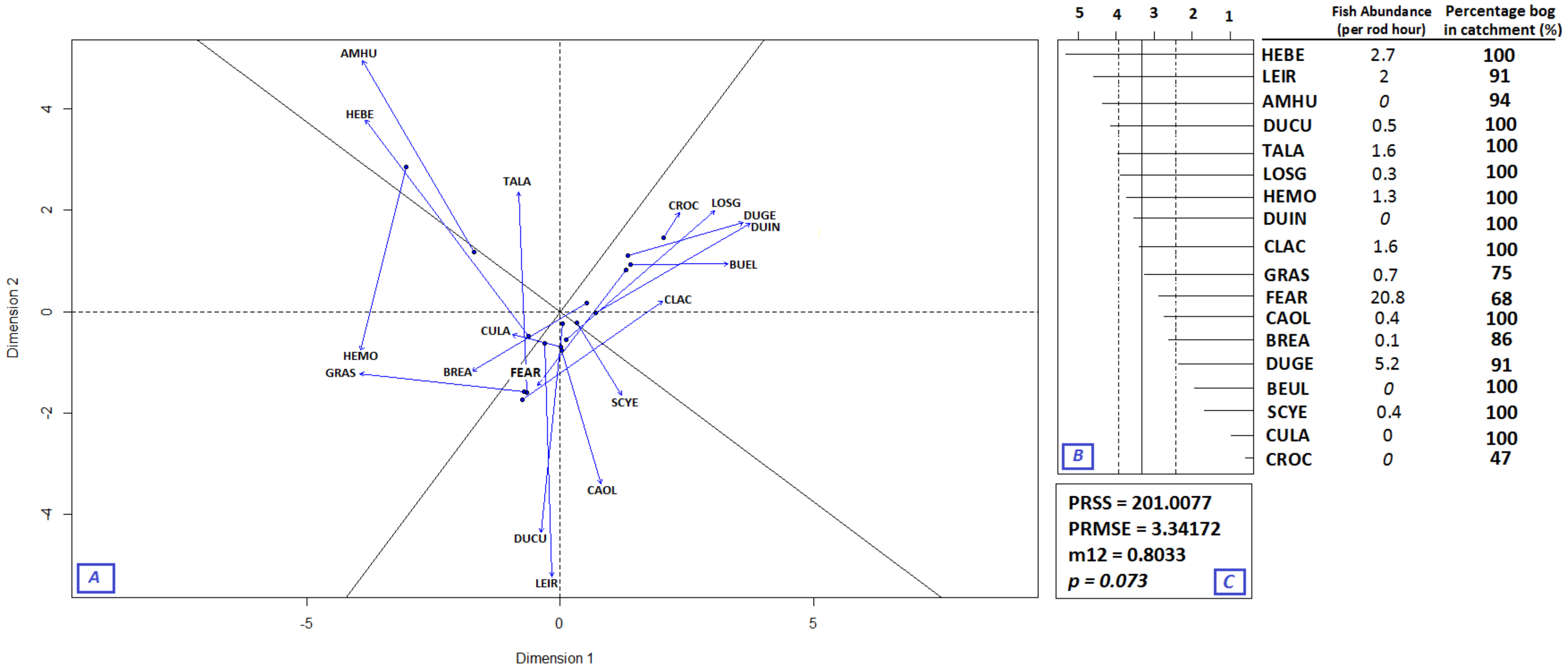


Figure 5.13 Axis 1 and 2 of DCA ordinations of the diatom communities in the top (A) and bottoms (B) of the cores



	Fish Abundance (per rod hour)	Percentage bog in catchment (%)
HEBE	2.7	100
LEIR	2	91
AMHU	*0*	94
DUCU	0.5	100
TALA	1.6	100
LOSG	0.3	100
HEMO	1.3	100
DUIN	*0*	100
CLAC	1.6	100
GRAS	0.7	75
FEAR	20.8	68
CAOL	0.4	100
BREA	0.1	86
DUGE	5.2	91
BEUL	*0*	100
SCYE	0.4	100
CULA	0	100
CROC	*0*	47

Figure 5.14 Results from the Procrustes rotation and PROTEST analysis for diatom communities (A) Procrustes superimposition plot (B) Procrustes rotation residuals plot, showing the differences between the PCA configuration for the top and bottom samples, (C) root mean square error (PRMSE), rotation sum of squares (PRSS), m12 and associated p-value. The fish abundance (per rod hour) and percentage of forestry in the catchment (from CEH data) are shown on the right

Chironomids

The stratigraphic plots (Figure 5.15) of the 20 most frequently occurring chironomid species were used to explore changes in the abundant species composition. *Cladotanytarsus type 2, Micropseptra, Phaenopsectra type A, Psectrocladius septentrionalis* are amongst the 20 most frequently occurring taxa in the tops of the cores but not in the bottoms. *Phaenopsectra* sp*.* and *Psectrocladius septentrionalis* are both taxa have been shown to be associated with acidified systems (Pillot, 2014). *Pagastiella, Pseudorthocladius, Pseudosmittia, Theinemannimyia* occur frequently in the bottom samples (in between 7-11 sites), and occur less frequently in the core tops (3-6 sites). *Pseudorthocladius* are associated with aquatic macrophytes and *Pseudosmittia* with littoral habitats in oligotrophic lakes (Pillot, 2014). Chironomid diversity and abundance in the tops and bottoms of the cores are shown in Figure 5.16. Despite the core bottom samples potentially representing different time periods the diversity recorded at each is similar to the contemporary samples. The abundance of heads per gram of wet sediment ranges from 4 to 153 in the bottoms and 19 to 135 in the tops. LOSG has a noticeably higher abundance of head capsules in the bottom sample, however it is difficult to interpret this without finer resolution dating.

Comparing ordinations for the chironomid communities in the tops and bottoms of the cores shows little overlap in groupings of sites between the tops and bottom (Figure 5.17). The sites are distributed across the ordination space in both cases and it is difficult to confidently delineate groups of similar lochs. Outliers in the tops are not the same as those outliers present in the bottom ordination.

The chironomid procrustes analysis also shows a low overall level of concordance between bottom and top samples in the 18 cores ($m2$= 0.7799) indicating change which is significant at the 0.05 level (p=0.05) (Figure 5.18). Sites with the lowest residual distances, and therefore having changed the least, are CULA, LEIR, SCYE, TALA. Lochs BEUL, CAOL, CLAC and HEBE have high residual distances outside of the third quantile range. There is no clear relationship in the amount of change indicated for chironomid communities and the environmental variables neither with fish abundance or proportion of bog in the catchments.

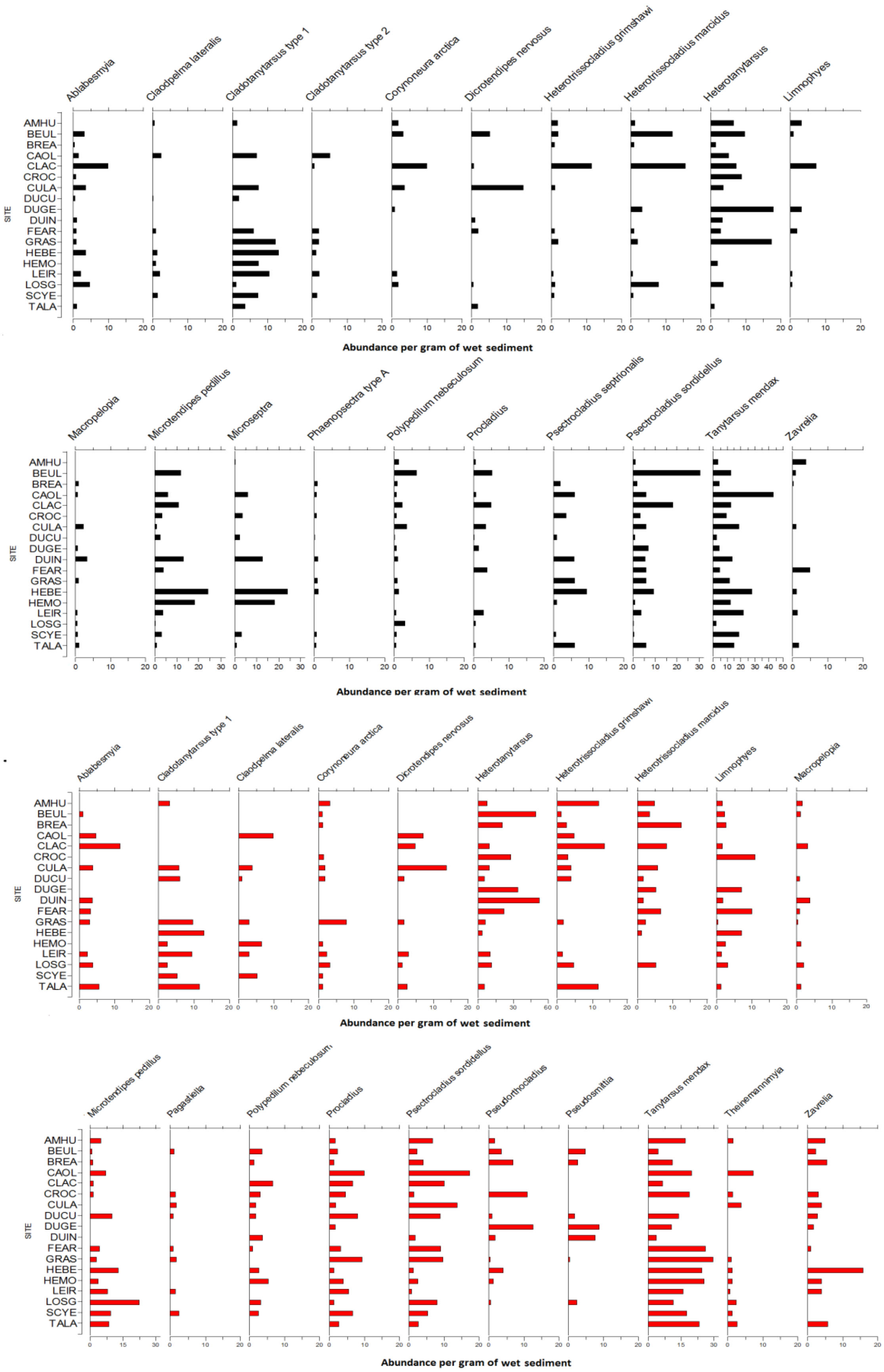


Figure 5.15 The abudance (per gram wet sediment) of the 20 most frequently occurring chironomid species in the tops (black) and bottoms (red) of the 18 cores

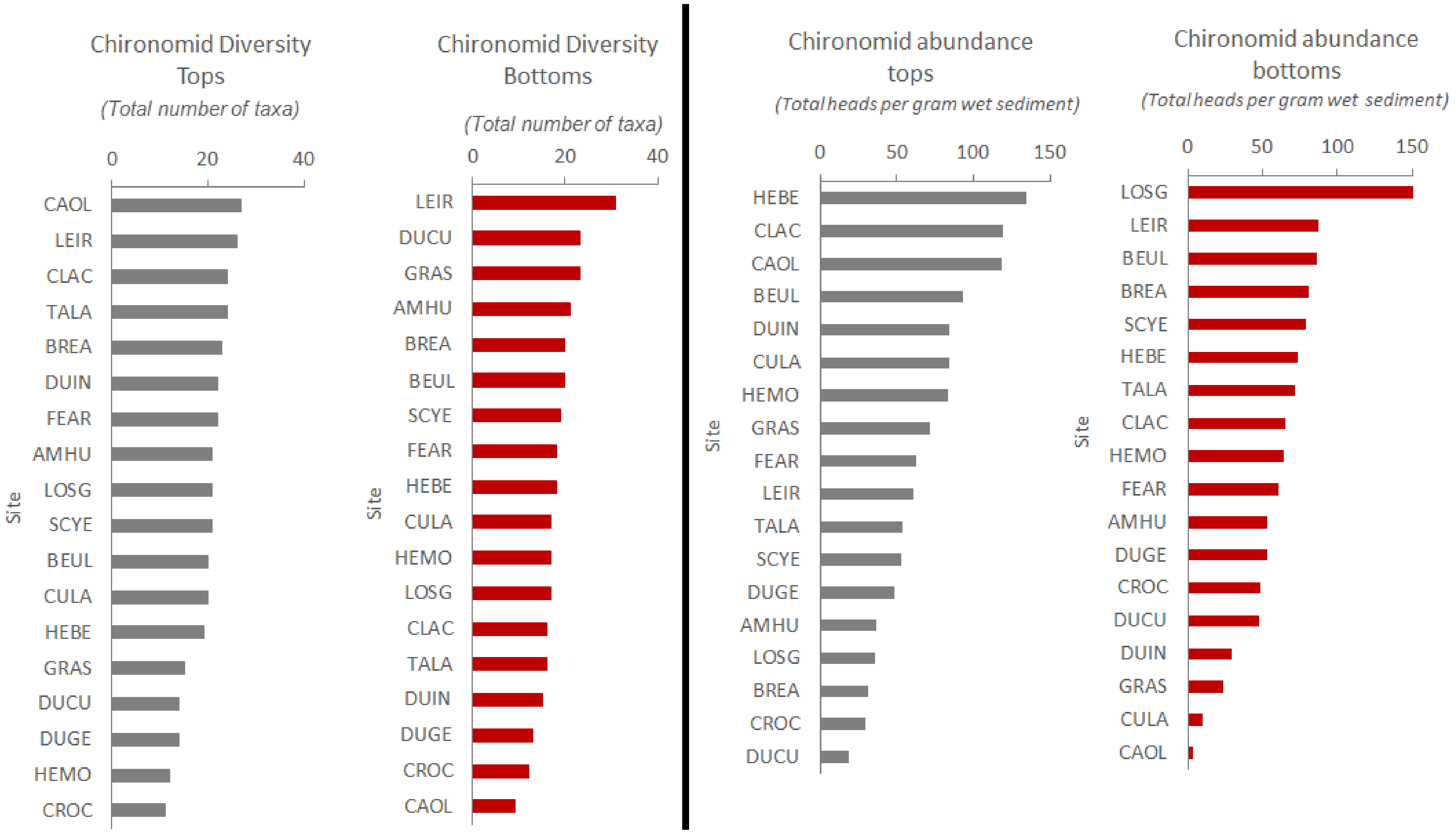


Figure 5.16 The diversity (number of taxa, left panel) and mean abundance (right panel) in the tops (black) and bottoms (red) of the 18 cores

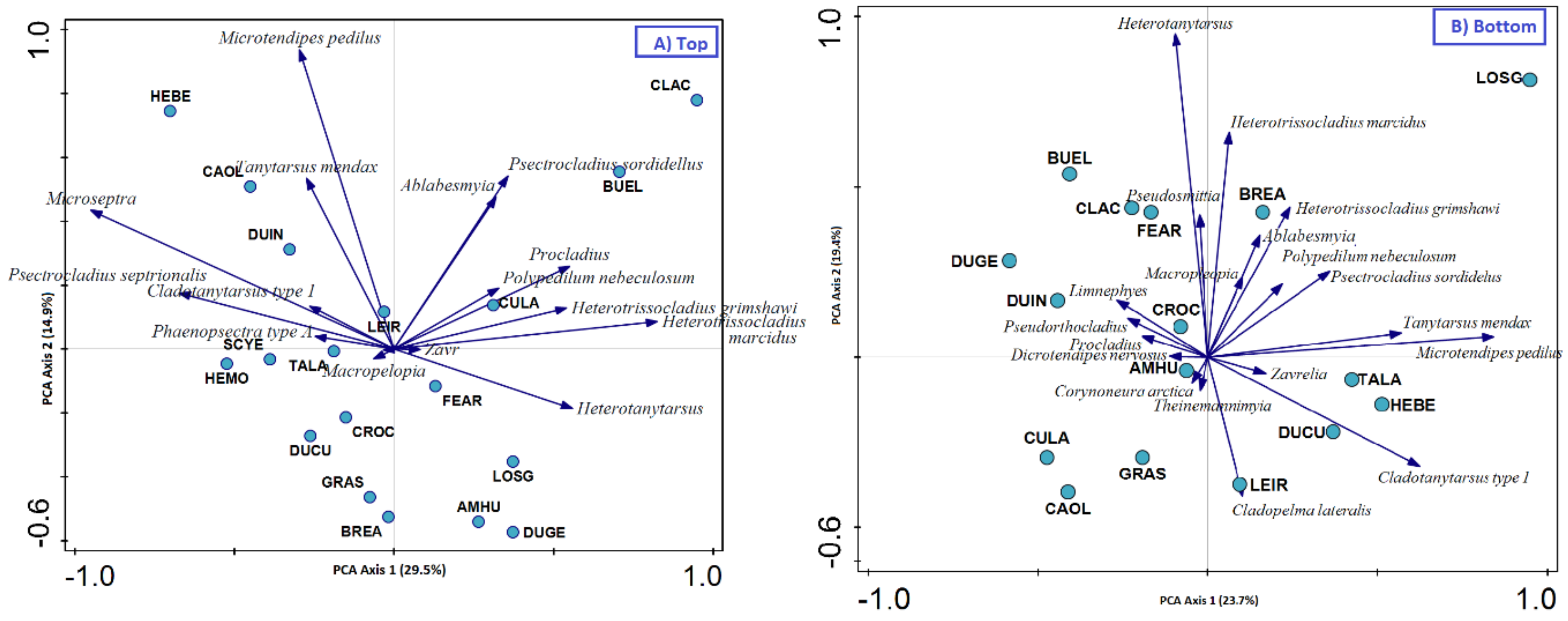
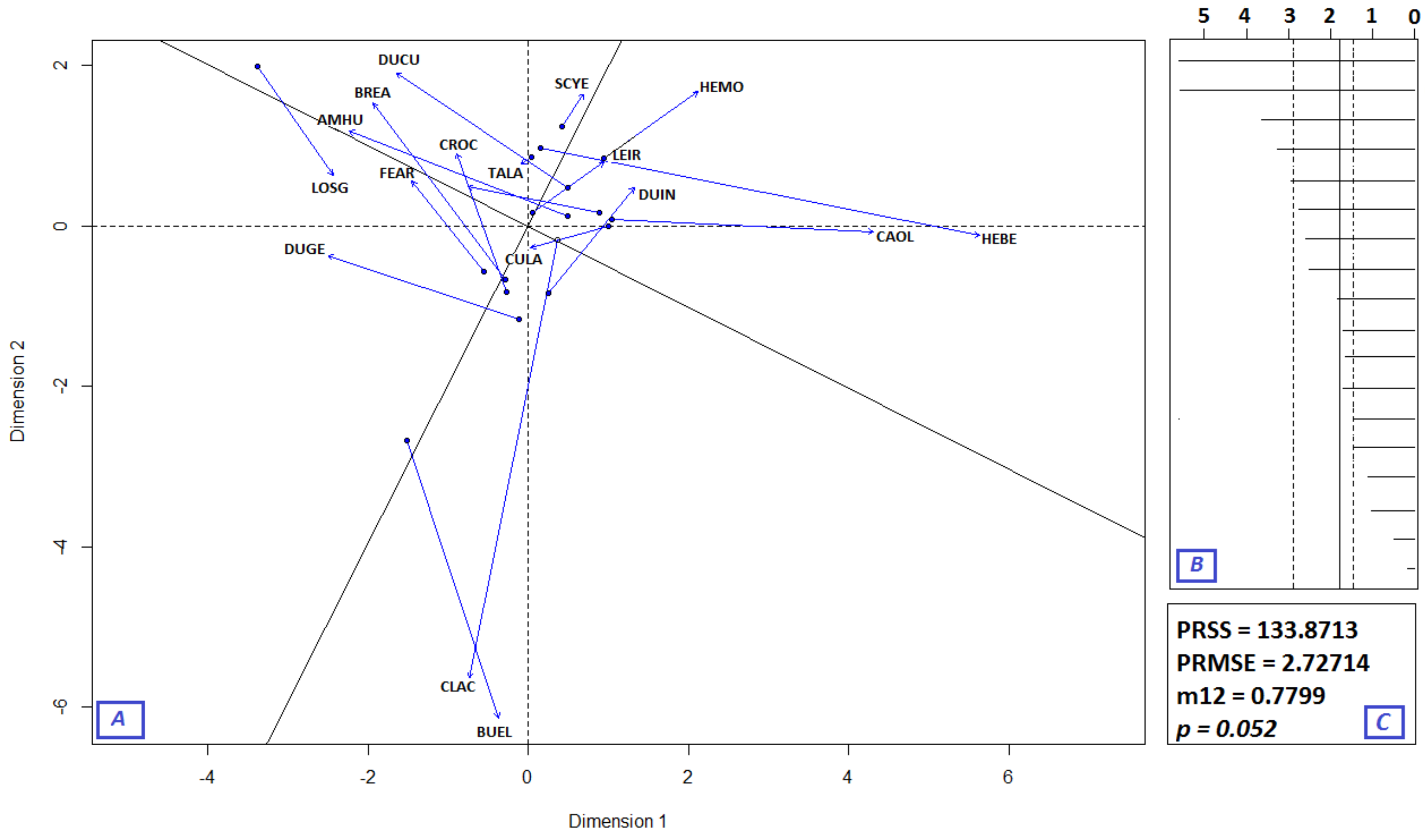


Figure 5.17 Axis 1 and 2 of PCAs of chironomid communities in the tops (left) and bottoms (right) of the cores



PRSS = 133.8713
PRMSE = 2.72714
m12 = 0.7799
p = 0.052

	Fish Abundance (per rod hour)	Percentage bog in catchment (%)
HEBE	2.7	100
CLAC	1.6	100
BEUL	*0*	100
CAOL	0.4	100
AMHU	*0*	94
BREA	0.1	86
DUCU	0.5	100
DUGE	5.2	91
CROC	*0*	47
DUIN	*0*	100
LOSG	0.3	100
GRAS	0.7	75
HEMO	1.3	100
FEAR	20.8	68
LEIR	2	91
CULA	0	100
SCYE	0.4	100
TALA	1.6	100

Figure 5.18 Results from the Procrustes rotation and PROTEST analysis for chironomid communities (A) Procrustes superimposition plot (B) Procrustes rotation residuals plot, showing the differences between the PCA configuration for the top and bottom samples, (C) root mean square error (PRMSE), rotation sum of squares (PRSS), m12 and associated p-value. The fish abundance (per rod hour) and percentage of forestry in the catchment (from CEH data) are shown on the right

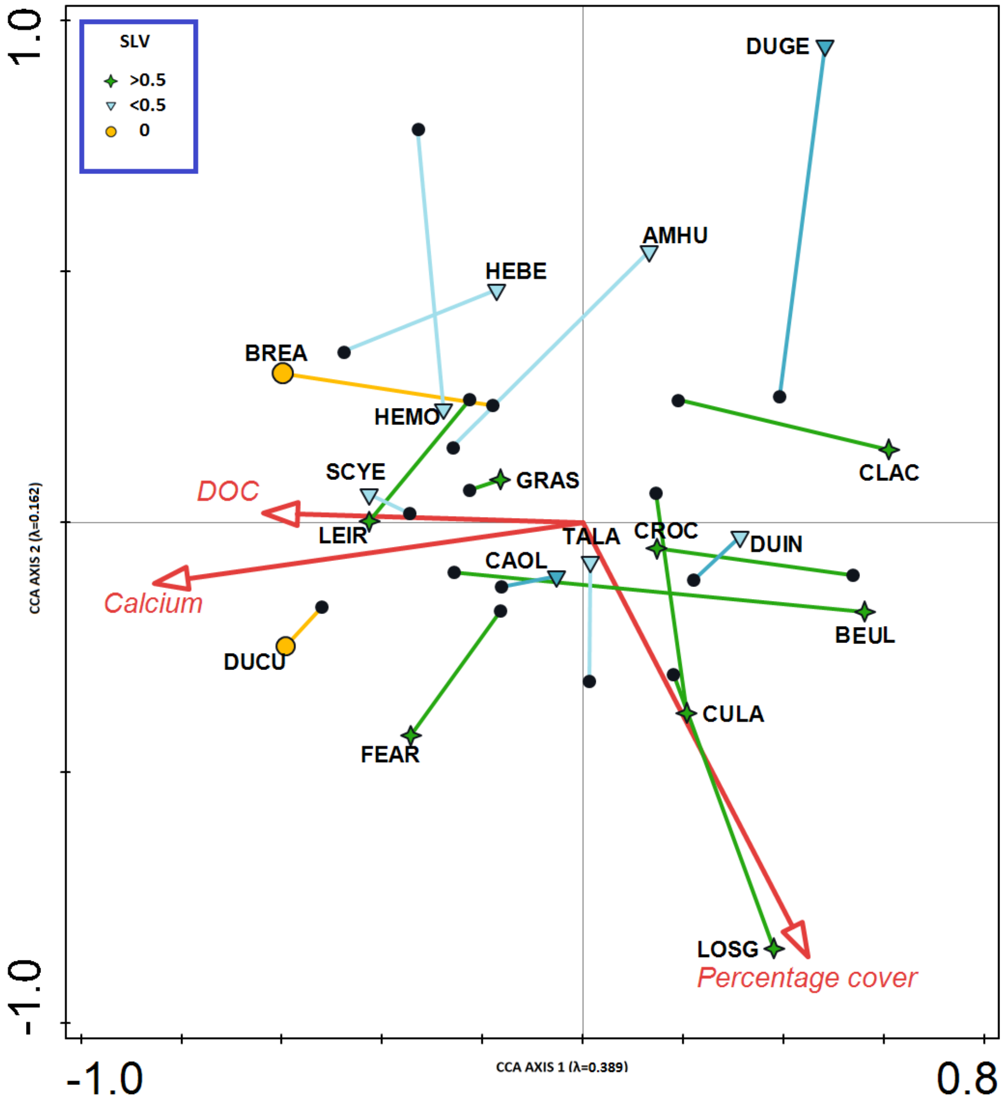
5.4.3.2 Drivers of recent ecological change and implications for breeding scoter

Figures 5.19 and 5.20 show the constrained ordinations of modern chironomid and diatom communities with significant (<0.05) environmental variables identified. Samples from the bottoms of the cores are passively plotted. Top-bottom ordination plots can be used to indicate the extent (length of line between top and bottom samples) and type (direction of line between top and bottom samples) of community change that has occurred between bottom and top samples from a core. However, inferences based on top-bottom ordination plots must be approached with caution when potentially different timescales are being considered as has been shown to be the case here.

Neither the chironomid nor diatom top-bottom plots show correlation in the direction or extent of community change in relation to scoter loch value. However, five of the eight sites with SLV <0.5 appear in the upper left of the diatom ordination for the majority of their length (AMHU, BREA, HEBE, HEMO, SCYE), indicating that the communities of these sites were distinct from the sites with higher SLV both historically and today.

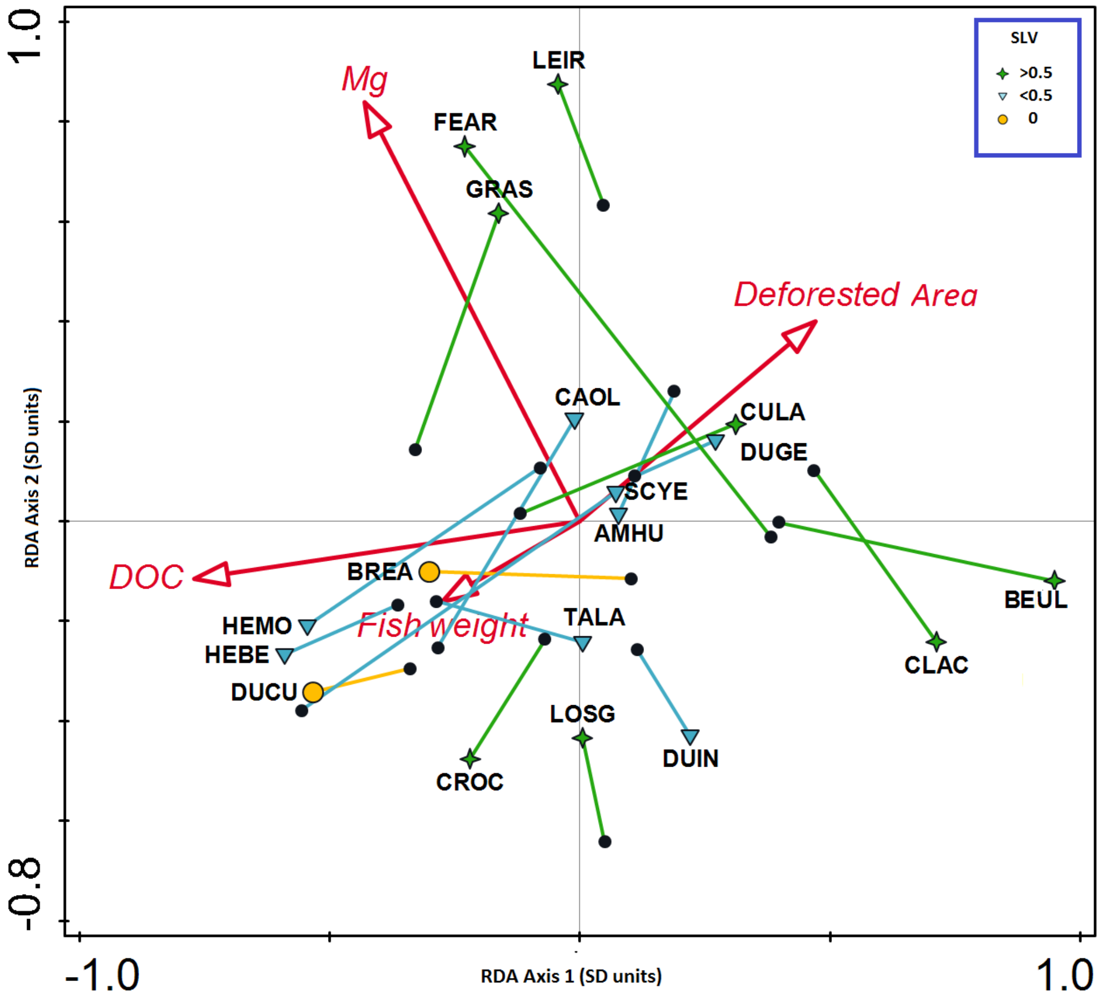
Similarly, many of the low scoring sites in the chironomid plot are positioned together in the lower left of the ordination space (associated with high DOC and fish weight) for at least part of their length. The only exceptions are CROC and LOSG high scoring SLV sites located in this area dominated by low scoring SLV sites.

The two sites with the highest SLV (LEIR and FEAR) are shown to move almost parallel to one another in both chironomid and diatom plots; as do BEUL, and CLAC, indicating the type of change experienced has been similar at these sites.



Name	Explains %	pseudo-F	P
Calcium	13.4	2.5	0.002
DOC	7.9	1.5	0.012
Total area	7.2	1.4	0.024

Figure 5.19 Axis 1 and 2 of a CCA of modern diatom communities with significant (<0.01) environmental variables identified, samples from the bottoms of the cores are passively plotted. Sites are categorised by scoter loch value (SLV), yellow SLV=0, blue SLV=<0.5, green SLV=>0.5



Name	Explains %	pseudo-F	P
Fish weight	16.5	3.2	0.002
Magnesium	8.7	1.7	0.05
DOC	8.8	1.9	0.05
Deforested *Area*	7.4	1.6	0.088

Figure 5.20 Axis 1 and 2 of a RDA of modern chironomid communities with significant (<0.01) environmental variables identified, samples from the bottoms of the cores are passively plotted. Sites are categorised by scoter loch value (SLV), yellow SLV=0, blue SLV=<0.5, green SLV=>0.5

5.5 Discussion

Core integrity

Lithostratigraphic and geochemical analysis of cores taken from 18 Flow Country lochs has established that the sediments of these shallow, potentially wind stressed, lochs have not been substantially disturbed. The cores had a visible stratigraphy, and analysis of both ^{210}Pb and heavy metals could be used to successfully establish core integrities and chronologies. In 16 of the 18 cores analysed in this chapter there was no strong evidence of sediment mixing or re-suspension. The heavy metal profiles from the remaining two sites (Loch Losgann and Lochan Croc nan Lair) did indicate that some surface sediments could be missing, which could have resulted from sediment re-deposition and/or loss during the coring process. Although the ^{137}Cs peaks were indistinct in the ^{210}Pb dated cores, validation of both core integrity and timeframe was possible using XRF profiles. These findings are in accordance with Allott and Rose, (1993), who used both radiometric and SCP approaches to date sediment cores taken from Flow Country lochs, with minimal evidence of disturbance by physical mixing.

Overall there is strong evidence from these data that sediments in these shallow lochs have not been substantially affected by physical or biological mixing.

Recent environmental change at 18 blanket bog lochs

Diatom and chironomid taxa present in the tops and bottoms of the cores are largely typical of those associated with low nutrient, acidic lochs. However, there are some indications of increasing nutrients and acidity in the tops of the cores compared to the bottoms as meso-oligotrophic species and taxa associated with acidification have become more common. Evidence of community change and particularly the increased occurrence of nutrient and acidification tolerant taxa could indicate that Flow Country lochs have experienced nutrient enrichment and/or acidification. Typical agricultural activities and human sewage (that are commonly the source of nutrient inputs in the lowlands) are not present in the Flow Country, where the landscape is predominantly low nutrient blanket bog. Sources of nutrients in the Flow Country are likely to be associated with either atmospheric deposition and/or catchment sources associated with anthropogenic land management practices (such as rotational heather burning and/or forestry plantations). Taxa tolerant of acidification identified in the tops of the cores suggest acidification could also be an issue in these systems, and is most likely a consequence of either atmospheric deposition or proximal forestry. Diatom analysis of lake sediment cores indicates that rapid acidification has occurred in lakes throughout North America and North West Europe over the last 150 years as a consequence of atmospheric deposition (Battarbee *et al.,* 1984). However there is also evidence that coniferous forestry plantations on peatlands can result in increasing acidity of proximal surface waters (Harriman and Morrison, 1982; Neal *et al.,* 2004, 2001; Reynolds *et al.,* 1995), as their foliage are particularly efficient scavengers of acid particles from atmospheric sources (Nature Conservancy Council, 1986).

Atmospheric deposition can impact sites that are remote from industrial sources of nitrogen and sulphur pollution (Fay *et al.,* 1987), and can result in increases in the biomass of primary producers such as algae, particularly in otherwise unimpacted systems (Lepori and Keck, 2012). Although quantitative measures of diatom biomass were not determined in this chapter, it is possible that the increases in nutrient tolerant taxa identified are a consequence of long distance atmospheric deposition. However, deposition data (NEGTAP, 2001) suggests the Flow Country is not a high deposition region. Top-bottom analysis does not provide the temporal resolution necessary to separate nutrient inputs from atmospheric (deposition) and catchment (forestry/burning) sources. Palaeolimnological analysis at a fine scale temporal resolution would enable signals from deposition and catchment sources to be disentangled.

The catchment-based sources of nutrients in the Flow Country are most likely to be associated with land practices such as rotational heather burning and/or coniferous forestry plantations.

The burning of peatland is a widespread practice undertaken to encourage growth of nutrient-rich grasses for grazing cattle and sheep, and in more recent times has become a key management practice on many sporting estates, to create habitat suitable for grouse and deer. In the Flow Country it was found to be the most widespread land management practice, with 51% of NCC sites surveyed having evidence of some burning, and a further 10% abundant burning (Lindsay *et al.,* 1988).

Nutrient cycling, hydrology and surface vegetation are all affected as a consequence of burning (Clay *et al.,* 2009a; Ramchunder *et al.,* 2009; Worrall *et al.,* 2007; Worrall and Clay, 2010). However, the focus of research to date is predominantly on terrestrial peatland areas, rather than open water bodies, such as lakes. Whilst evidence suggests there can be large nutrient losses following heather burning (45kg/ha of nitrogen (Allen, 1964), the main consequence for lakes and rivers documented in the literature centres around the effects on water colour and DOC, rather than increases in nutrients. However, a consensus on the extent to which heather burning effects water colour and DOC export has yet to be reached (Clay *et al.,* 2009a; Holden *et al.,* 2012). Whilst it appears unlikely that heather burning is likely to be the source of increased nutrients, fine temporal scale analysis of remains, particularly charcoal, would provide further insights into the potential effects of heather burning on Flow Country lochs.

Forestry plantations have been shown to substantially influence the ecology of boreal and/or peatland lakes (Drinan *et al.,* 2013b, 2013c; Graham *et al.,* 2014; Lepistö and Saura, 1998; Turkia and Lepistö, 1999). The application of fertilisers at the time of planting and/or in subsequent years to relieve deficiency, and the installation of drainage ditches to decrease soil saturation and enable tree growth facilitate the export of both sediments and nutrients from plantations into nearby lochs. Commonly used fertilisers are phosphate, potassium and nitrogen based; the maximum recommended application rate is 350kg/ha^{-1} for granulated rock phosphate and granulated urea fertilisers when planting (Department of Agriculture Food & the Marine, 2015). The addition of nitrogen based fertilisers is not always necessary as drainage, site preparation and P addition can increase mineralisation of N from the peat (Ramberg, 1976; Renou and Farrell, 2005). Data concerning the quantity and frequency of fertilisers applied to forestry plantations in the Flow Country was not obtainable. However, recent increases in nutrient tolerant taxa, indicated from the top-bottom analysis, suggest that nutrient export to the lochs has occurred. Whilst it is possible that this is a consequence of forestry operations, there is no clear correlation between lochs with forestry within close proximity and increases in nutrient tolerant taxa. This could indicate either that the effects of forestry affect a larger area than might be expected, or that other factors are contributing to the nutrient increases. To discern how nutrient levels in the lochs have changed since forestry plantations were established data from a fine temporal scale is necessary because both atmospheric and catchment sources could be contributing. However, the coarse-temporal resolution of the data generated in this chapter do not allow the sources to be differentiated. Fine-scale resolution analysis would enable the contribution of nutrient sources to be disentangled more clearly and will be undertaken in Chapter 6.

Recent environmental change in the context of common scoter decline

The aquatic communities of the cores from lochs with low scoter loch value are somewhat separate to those with higher scoter loch value in some instances, indicating that the ecology of high and low scoring SLV sites have probably been different for the last 150-200 years. The implication of this could be that low scoring scoter sites have always been sub-optimal for breeding common scoter, and only began to be used as the population increased. As the overall Flow Country scoter population declined, low SLV sites may have been abandoned first as more space becomes available at the optimal sites. The type and extent of community change indicated by the top-bottom analysis has also provided useful insights, which could be used to prioritise lochs for conservation management and restoration in relation to common scoter.

Site selection for further palaeolimnological analyses

This chapter has examined the coarse-scale change at a relatively large number of Flow Country sites. Results have demonstrated substantial change has occurred over the last 150-200 years, and additionally have highlighted the limitations of top-bottom analysis. These limitations could be addressed by fine scale temporal scale analysis, particularly multi-proxy analysis of the most recent sediments (the last 30-50 years). Four sites were therefore selected for further analyses partly based on the results from this chapter, and partly to include sites with a mixture of landscape settings and fish densities to allow examination of the hypotheses developed in this thesis. AMHU, FEAR, LEIR and TALA all had visible stratigraphies, and heavy metal profiles that indicated undisturbed sediment deposition. In addition, LEIR had been successfully ^{210}Pb dated which meant there was potential to cross-correlate cores for dating from this site. FEAR and LEIR have the highest scoter loch value of any of the sites and TALA and AMHU were amongst the lowest. The four sites have differing degrees of forestry/deforested area within close proximity and a mixture of fish densities. Although recent surveys indicated several of the lochs could be fishless the accuracy of these data is questionable as other sources (Bruce Sandison, 2015; Crawford, 1991) indicate the presence of trout. Consequently, sites covering a range of fish densities were selected rather than a site suspected, but not confirmed to be fishless.

5.6 Key findings and implications

- Sediment cores were successfully taken and dated (using heavy metals and ^{210}Pb analyses) from a challenging palaeolimnological environment, namely shallow, wind-stressed lochs with fine and potentially flocculent sediments.

  ⟶ The sites appear suitable for palaeolimnological work.

- Substantial community change was demonstrated in both diatoms and chironomids, although there is a noticeable increase in nutrient tolerant species there is no clear pattern in the overall community composition change in terms of either direction or extent.

  ⟶ All the lochs of the Flow Country are undergoing environmental change. The sources of increased nutrients could be either atmospheric or catchment-based. However, the coarse temporal resolution of the top-bottom approach does not allow the relative contribution of these processes to be established.

- Some groupings of lochs are apparent on the basis of SLV. Some low SLV lochs have communities distinct from sites with high SLV both now and historically, suggesting that there have always been differences between these types of sites. However, it is difficult to be confident about this interpretation because there are inconsistencies.

  ⟶ The implication could be that some sites have always been less suitable for scoter, and that use of these sites increased during past peaks in populations when overall number of scoter were higher and the population more widespread.

- The palaeolimnological data from this chapter was also used to identify four sites to be the focus of fine resolution palaeolimnological analysis which will be explored using fine scale, multiproxy analysis in Chapter 6.

CHAPTER 6: MULTIPROXY ANALYSIS OF LARGE BORE SEDIMENT CORES TO EXAMINE FINE RESOLUTION ENVIRONMENTAL CHANGE AT FOUR FLOW COUNTRY LOCHS AND ASSESS THE IMPLICATIONS FOR COMMON SCOTER DECLINES

6.1 Overview

Chapter 6 involves multiproxy analysis of wide bore sediment cores to examine recent environmental change at a temporal resolution contemporaneous with common scoter declines. Top-bottom analysis (Chapter 5) indicated that the lochs of the Flow Country have undergone substantial change over the last 150-200 years. However, with this broad scale preliminary analysis it was not possible to assess the timescale of change and consequently the most pertinent drivers of change could not be identified. This chapter assesses recent environmental change at four Flow Country lochs by examining changes in diatom, invertebrate and macrophyte community communities over the last 150-200 years. This palaeolimnological evidence is then used to evaluate the theories of common scoter decline relating to forestry and/or fish. The findings from this chapter are used to assess the use of palaeolimnology to identify the drivers of freshwater species declines and provide evidence for conservation management.

6.2 Introduction

The aim of this chapter is to use multi-proxy palaeolimnological analyses to examine recent environmental change at lochs in an internationally important UK wetland, the Flow Country. Analysis will be undertaken at a fine temporal resolution, which will enable exploration of how recent environmental change in Flow Country lochs may be influencing the decline of a priority waterbird species, the common scoter.

This chapter will firstly examine recent environmental change at four Flow Country lochs set in different landscape settings and with a range of brown trout densities. This fine temporal resolution palaeolimnological evidence will then be considered in the context of the two theories for common scoter decline. Palaeolimnological evidence will be used to explore the following questions relating to the two competing theories of common scoter decline:

i) Is there evidence of change in the fish (brown trout) populations at the four lochs, and if so what are the implications for macroinvertebrate abundance?
   a. Can fish scale evidence be used to determine whether fish introductions have occurred at the lochs?
   b. Do other macrofossil indicators provide evidence of fish introduction at the lochs?
   c. Is there evidence of a change to macroinvertebrate communities that could be associated with brown trout introductions and/or changes in population structure? i.e. is there a reduction in large bodied and/or planktonic taxa, which could be detrimental to breeding common scoter?

ii) Are the effects of afforestation (in the 1980s) evident at the four lochs?
   a. Does geochemical analysis of the cores indicate that there has been a change in sedimentation rates or sediment composition that could be a consequence of increased erosion associated with the 1980s?
   b. Is there evidence of changes to water chemistry (i.e. increased nutrients from fertilisation events or acidification as a result of forestry) during the 1980s?
   c. Has the abundance and/or composition of invertebrate communities changed since the 1980s? and could this be indicative of the effects of forestry i.e. increased sedimentation, eutrophication and/or acidification.

6.3. Methods

6.3.1 Study Area

This chapter focuses on four lochs in the Flow Country and further information about the study area is provided in Chapter 2.

6.3.2 Site Selection

Four of the 18 lochs analysed at a coarse temporal resolution in Chapter 5 were examined using wide bore, fine resolution analysis in this chapter. These were Loch a'Mhuillinn (AMHU), Loch nam Fear (FEAR), Loch Leir (LEIR) and Loch Talaheel (TALA) (Table 6.1). Hereafter this chapter will use the four-letter loch codes to denote the study sites. Details of how these sites were selected is provided in Chapter 2, Section 2.3. An overview of the site characteristics are provided in Table 6.1. Details of the landcover types both within a 500m buffer of the lochs and the wider catchment (from CEH lakes portal data, Hughes *et al.,* 2004) are provided. Based on these data TALA is categorised as bog, although it is acknowledged that there is some deforested area to the west but this is not within in the catchment of the loch. AMHU is primarily bog with small amount of forest. The catchment of FEAR contains substantially more forest than AMHU. Finally, LEIR has a catchment consisting of bog with some areas of deforestation.

Loch name (Code)	Loch type (Scoter loch value)	Brown trout density (Fish caught per rod hour)	Dominant landcover type (% of catchment)	Dominant landscape within 500m of the loch
Loch a'Mhuillinn (AMHU)	Historic (0.50)	2.7	Bog (94) Forestry (6)	Bog
Lochan nam Fear (FEAR)	Current (1.00)	0.3	Bog (68) Forestry (32)	Bog, partial forest
Loch Leir (LEIR)	Current (0.95)	9	Bog (91) Deforested area (9)	Bog, some deforested area
Loch Talaheel (TALA)	Historic (0.24)	1.6	Bog (100)	Bog, some deforested area

Table 6.1 Overview of the four study sites

6.3.3 Field and laboratory methods

Wide (15cm) bore Big Ben cores (Patmore *et al.,* 2014) were taken from each of the four sites in April 2015; the Big Ben corer was designed specifically to take large volumes of sediment in each slice and facilitate macrofossil analysis. The cores were sliced at 0.5cm intervals; the coring sites were located close to the site from which the Glew cores had previously been collected (Table 2.4 and 2.5, section 2.4.2.1.1). For detailed information concerning the field methodologies employed see Chapter 2. Section 2.4.2.1.1

The laboratory analysis of the Big Ben cores included loss on ignition analysis (Chapter 2, 2.4.2.2.1) for every slice along the length of the core. Three of the four Big Ben cores (FEAR, AMHU and TALA) were dated using radiometric analysis (Chapter 2, 2.4.2.2.4). The Glew core from LEIR had been radiometrically dated, and therefore it was possible to establish approximate dates for the LEIR Big Ben core by cross correlating using the results from the XRF (2.4.2.2,3) and LOI analysis. Due to time constraints XRF was not carried out on the Big Ben cores from FEAR, AMHU and TALA.

The cores were analysed for diatom, invertebrate and macrophyte remains. XRF analysis from the short Glew cores indicated that the top 10cm of the cores would be sufficient to cover the last 150-200 years and that the period of particular interest (ca. 1970s to present day) was likely to be covered by the top 5cm of the cores. Chironomid samples from the Big Ben cores were analysed (following the method in Chapter 2, section 2.4.2.2.6) prior to the refinement of timescales by radiometric dating and therefore every sample down to 5cm and every other sample between 5 and 10cm was analysed. Diatom and macrofossil analysis (methods detailed in Chapter 2, section 2.4.2.2.5 and 2.4.2.2.7) was carried out after the radiometric dating results were determined and therefore for every slice down to the calculated depth of 1900 was analysed.

6.3.4 Statistical analysis and data presentation

Plots of the cores' stratigraphy are useful tools for exploring changes in taxa over time; plots of the most frequently occurring taxa were produced using the C2 graphic software package (Juggins, 2007). Constrained incremental sum-of-squares clustering (CONISS) is a technique used to identify statistically significant splits or zones in stratigraphic plots (Grimm, 1987). The approach is based on cluster analysis, constrained by agglomeration of stratigraphically adjacent samples (Birks *et al.,* 2012). A pairwise dissimilarity matrix is first created (in this case using Euclidean distances) and a sum-of-squares statistic calculated for each cluster, which is recalculated as clusters are merged. Stratigraphically adjacent clusters that, when merged, result in the least increase in total dispersion are identified (Birks *et al.,* 2012). CONISS analysis was carried out in R (R Core Team, 2016), using the rioja package (Juggins, 2012) on the (untransformed) accumulation rate data for diatom, chironomid, macrophyte, zooplankton and invertebrate communities. Statistically significant splits (identified using the broken stick model (Bennett, 1996)) were illustrated on the stratigraphic plots for each group.

Ordinations are a useful tool for exploring patterns of community change over time and examining differences/similarities between lochs (Legendre and Legrendre, 2012). In this chapter change in community composition was explored using unconstrained principal component analysis (PCA) ordinations. This analysis was selected in preference to detrended correspondence analysis (DCA) based on gradient lengths assessed in Canoco ver5. For each group (diatom, chironomid, invertebrate, zooplankton and macrophyte) the cores from each site were represented in the same ordination space together with the dominant taxa, which allowed comparison of community change between cores and examination of changes in community composition over time, down the cores. Multi-indicator PCA was used to provide an overview of the type and extent of change at each site.

Data relating to the radiometric dating is represented using Microsoft excel.

6.4 Results

The result section of this chapter consists of two main sections. Firstly, palaeolimnological data will be presented to establish the integrity and timescales of the cores (sections 6.4.1.1 and 6.4.1.2), and document recent environmental change at the study sites by examining diatom, macrophyte, zooplankton and invertebrate communities (6.4.1.3-6). A summary of the environmental change experienced at each site is presented in section 6.4.1.7. Secondly these data will be used to address the questions identified in the introduction, relating to the two theories for common scoter decline in the Flow Country (section 6.4.2).

6.4.1 Recent environmental change at four Flow Country lochs

6.4.1.1 Core lithostratigraphy

Loch a'Mhuillinn (AMHU)

The appearance and lithostratigraphic analysis of the Big Ben core from AMHU (AMHU_BB) is shown in Figure 6.1. At the base of AMHU_BB (45-35cm) the sediment is grey with a consistency similar to clay, whilst for the rest of the length (35-0cm) the core is silty. The dry weight is highest at the base of the core (45cm), and decreases steadily until a depth of 16.5-17.0cm at which point there is a marked increase in dry weight (to 36%). The dry weight declined steadily from 16.5-17.0 to the top (0cm) of the core. Percentage loss on ignition at 550^{o}C (LOI) increases from the base of the core to ca. 40% at 19.5-20.0cm this is followed by a decrease. The LOI increases steadily from ca. 10% at 16.5-17.0cm to a peak of ca. 60% at 5.5-6.0cm. LOI decreases between 5.5-6.0cm and 4.0-4.5 cm depth, at the top of the core LOI increases to ca. 50%.

Loch nam Fear (FEAR)

The LOI, dry weight and appearance of the Big Ben core from FEAR (FEAR_BB) are given in Figure 6.2; the core is a mixture of silt and sand. Two distinct sandy layers are visible in the core at 8-3 cm and 26-24cm, and a less distinct sandy band is visible between 13-11cm. Along much of the core length the dry weight ranges between 10-20%, but two distinct peaks are visible towards the base of the core at 29-28cm and 24-23cm (to ca. 30% and ca. 50% respectively). LOI declines between 33 and 23cm, reaching its lowest a 24-23cm (ca. 5%), which corresponds with a peak in dry weight. Following this LOI increases rapidly to reach it highest (75%) at 21-20cm depth. From 21cm to the top of the core the LOI shows overall decreases, however with several sharp increases and decreases included.

Loch Leir (LEIR)

The appearance and lithostratigraphic analysis of the Big Ben core from LEIR (LEIR_BB) are shown in Figure 6.3. A single sandy layer can be seen at 7-6 cm depth, and above this the silt is paler in colour than the silt below. Dry weight and LOI are relatively stable in the lower part of the core ranging between 10 and 20% (dry weight) and 48 and 87% (LOI). There is a marked change at around 9 cm coinciding with a large decrease in %LOI (from 72 to 48%) between 9.5 and 7.5cm depth at the same period increases in dry weight are observed, peaking at 31 and 55% at 8 -7.5 and 6-5.5cm respectively. The top 7 cm of the core overall show steadily increasing LOI, with two pronounced decreased between 6.5-5.0 and 3.0-1.0cm.

Loch Talaheel (TALA)

The lithostratigraphic analysis and appearance of core TALA_BB taken from TALA is shown in Figure 6.4; the core has layers of silt and sand and a clay like substrate at the base. The dry weight and %LOI are relatively stable at the base of the core (48-40cm), however the LOI increases between 40-28cm (from 11% to 34%) whilst the dry weight declines slightly (32% to 14%). Decreases in %LOI associated with the first sandy layer are observed at 19-16cm depth, and is followed by an increase in LOI to reach its highest value (ca. 80%) between 13.0 and 8.5cm depth. The top of TALA_BB is predominantly sandy with little silt and organic material as can be seen in the associated increases in dry weight and decrease in %LOI to less than 5% between 5.0-0.0cm

Core lithostraigraphies summary

- The cores from the four lochs range from 32 to 47cm in length and the sediment are composed of silt, sand and clay. The sediment of TALA_BB is noticeably different to the other three sites being primarily sand rather than silt, particularly towards the surface of the core.
- The stratigraphies of the lochs appear conformable and predominantly silt based, although there are distinct layers of different sediment visible. Sandy layers are visible in three of the four cores (the exception being AMHU). These layers occur at between 25-0cm, but there there is no consistency among cores in the number of or depth at which sandy layers occur.

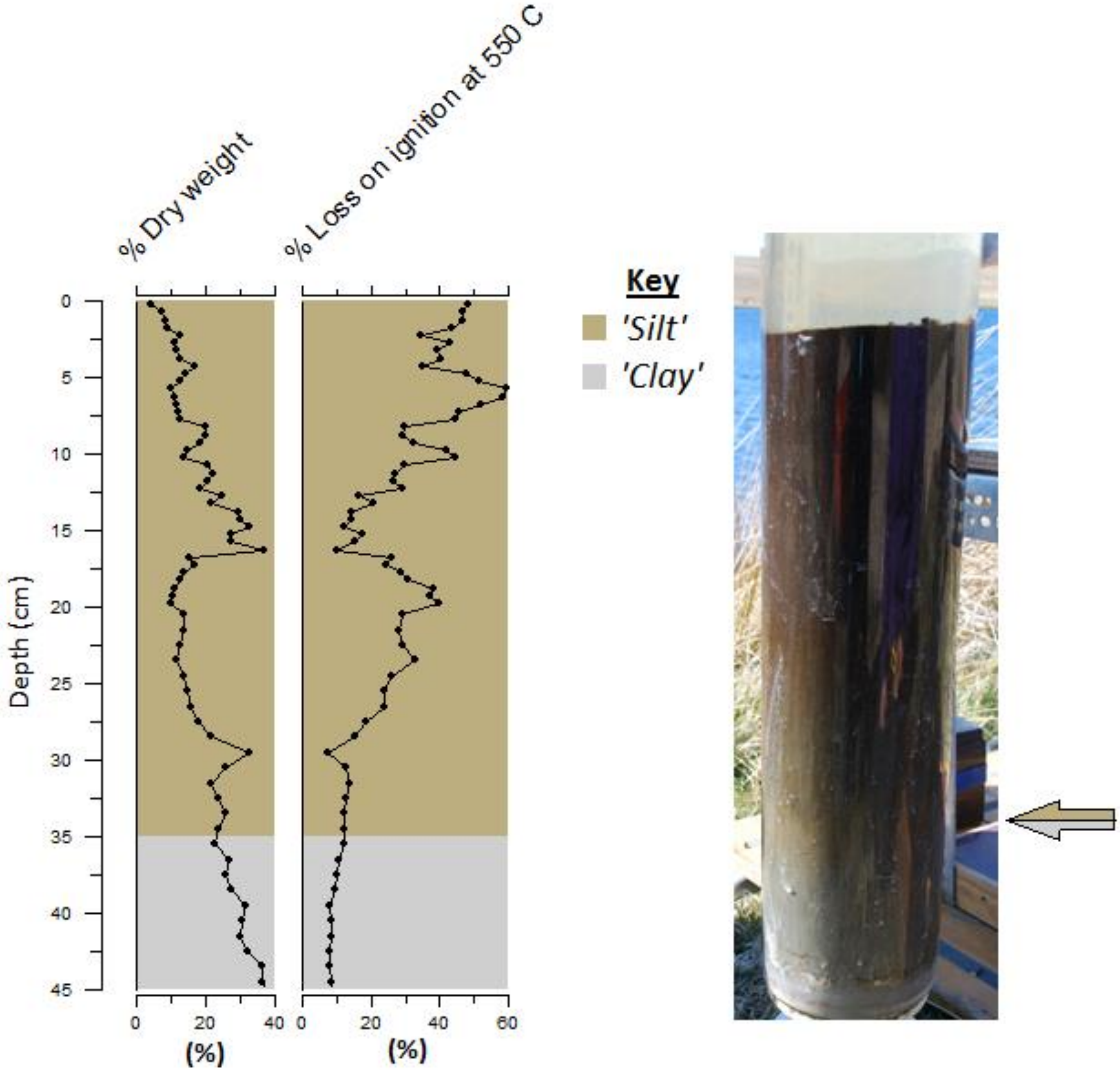


Figure 6.1Lithostratigraphy of core AMHU_BB from Loch a'Mhuillinn (AMHU) and photograph of core intact. Arrows on the core show the visible stratigraphic changes which relate to the %DW and %LOI

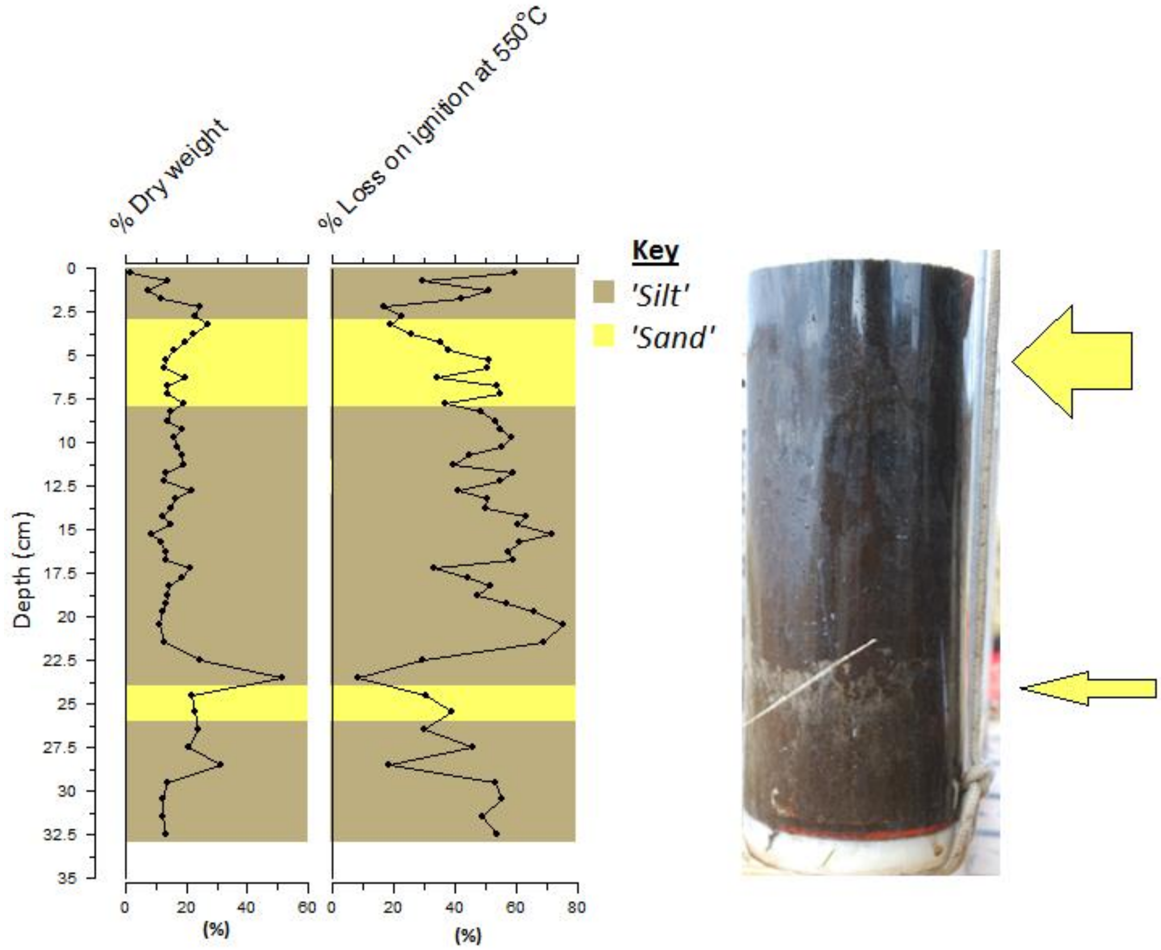


Figure 6.2Lithostratigraphy of core FEAR_BB from Loch nam Fear (FEAR) and photograph of core intact. Arrows on the core show the visible stratigraphic changes which relate to the %DW and %LOI

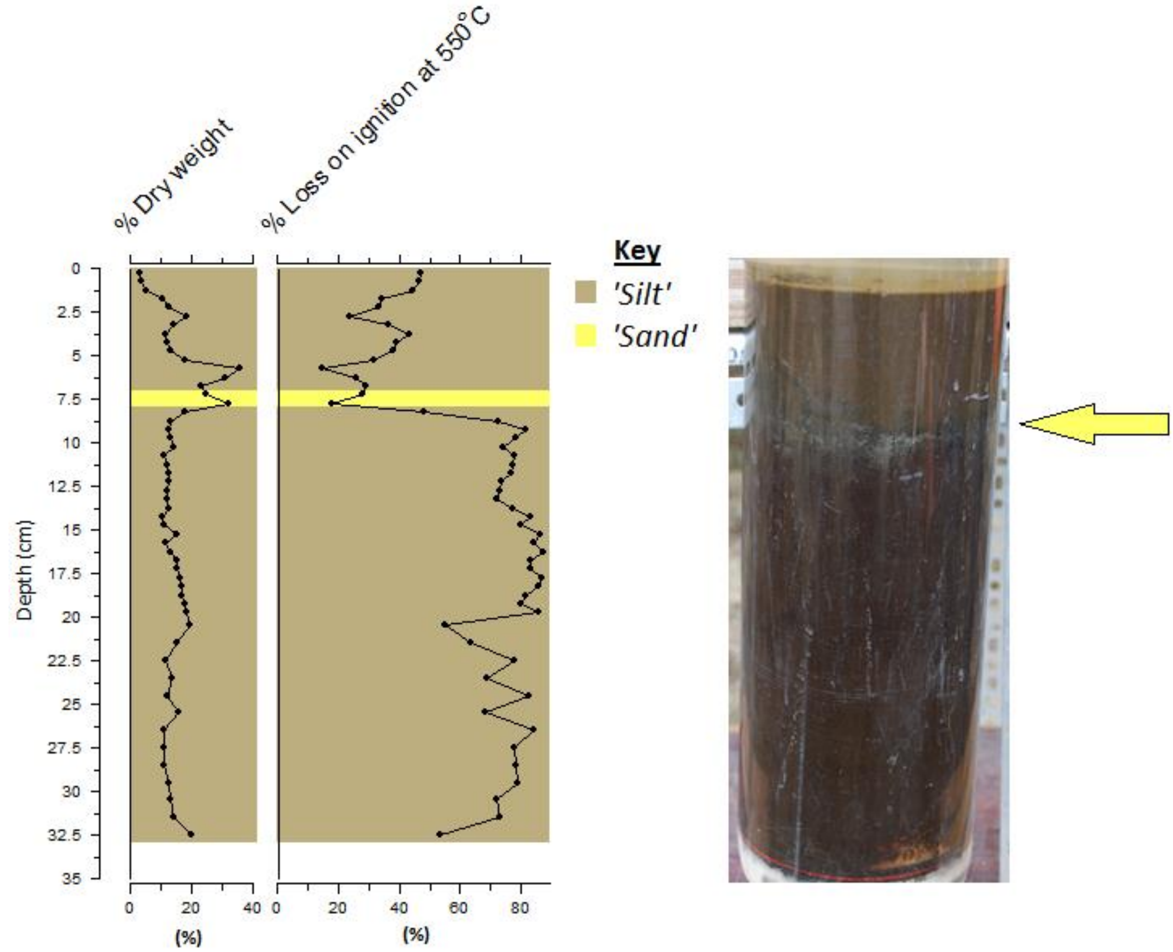


Figure 6.3Lithostratigraphy of core LEIR_BB from Loch Leir (LEIR) and photograph of core intact. Arrows on the core show the visible stratigraphic changes which relate to the %DW and %LOI

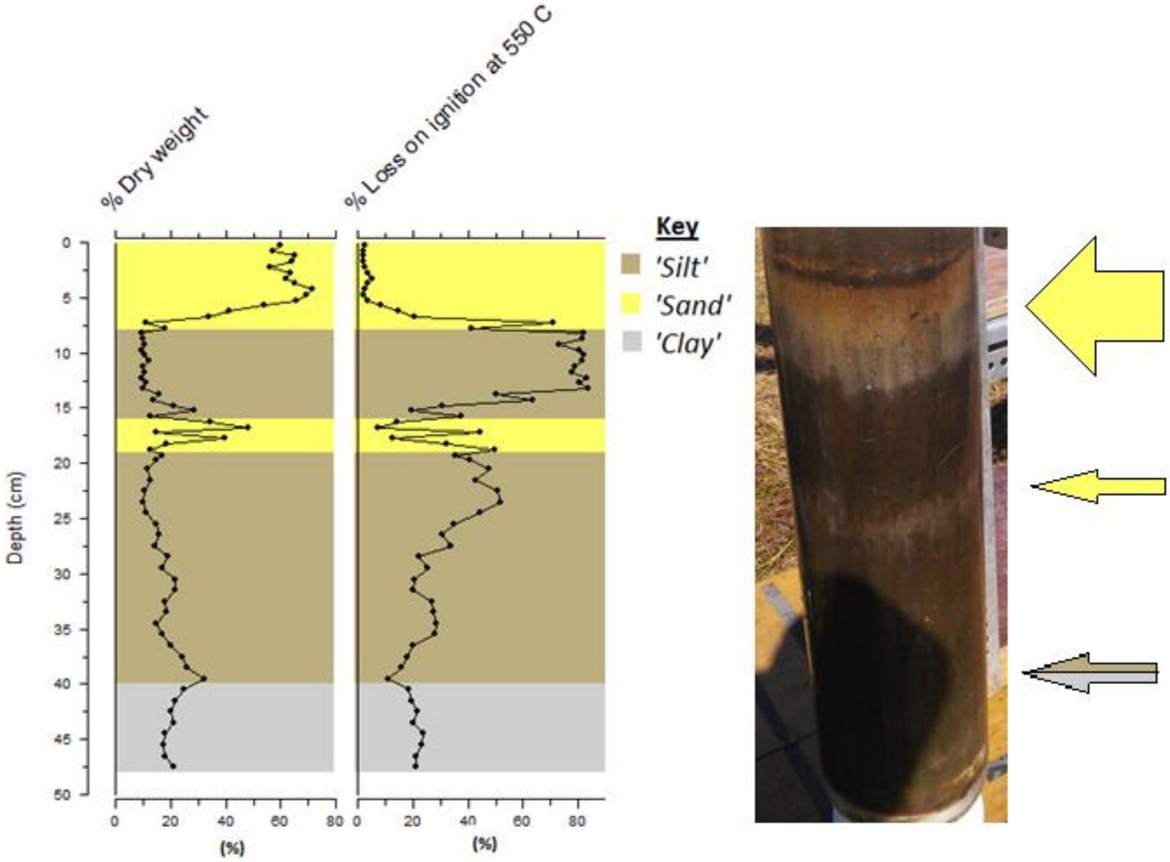


Figure 6.4Lithostratigraphy of core TALA_BB from Loch Talaheel (TALA) and photograph of core intact. Arrows on the core show the visible stratigraphic changes which relate to the %DW and %LOI

6.4.1.2 Core Chronology

Loch a'Mhuillinn (AMHU)

Sediment accumulation rate is relatively stable in the lower part of the core (6.25-4.5cm) but from 4.5cm to the surface, a gradual increase in sediment accumulation rate is observed (Figure 6.6). Total ^{210}Pb and supported ^{210}Pb activity reach equilibrium at ca. 7cm (Figure 6.5). The simple constant rate of ^{210}Pb dating model (CRS) places 1986 at between 2.75 and 3.25 cm which broadly agrees with the ^{137}Cs profile (Table 6.2). However, the ^{137}Cs peak was broad and ^{241}Am peak was absent. There was concern this could have indicated physical mixing and therefore the CRS model was evaluated by aligning peaks in the LOI profiles of AMHU_1 and AMHU_BB, and using the XRF profile from AMHU_1 (detailed in 5.4.2) to estimate the depth of 1980 and 1900 (Figure 6.7). There was good corroboration between the approaches with 1980 calculated as 3.25cm using the CRS model and 2.25cm using the peak of the XRF profile, similarly 1900 was calculated as 5.25cm using the CRS model and XRF approach (Table 6.3). Corroborating dates for the CRS model in this way suggests no physical mixing had taken place in the surface sediments of AMHU. Sediment accumulation rate in AMHU_BB increases gradually from 0.0021 g cm^{-2} yr^{1} in ca. 1850 to 0.0138 g cm^{-2} yr^{1} in 2014, there is no evidence of forestry effecting the sediment accumulation rate in loch AMHU.

Loch nam Fear (FEAR)

Total ^{210}Pb and supported ^{210}Pb reach equilibrium at approximately 8cm (Figure 6.9). The simple CRS model places 1963 and 1986 at 3.5 and 2cm respectively (Table 6.4); however, it was not possible to use the ^{137}Cs record to corroborate as the peak was not distinct rather it continues to increase in the surface sediments. Similarly, it is not possible to use the ^{241}Am associated with nuclear weapons testing as ^{241}Am was not recorded in sufficient quantities at any point along the core. Whilst the lack of a ^{241}Am or ^{137}Cs peak has been attributed to physical mixing elsewhere this does not appear to be the case here. It was possible to align the peaks of the LOI profiles from FEAR_1 and FEAR_BB, and use the XRF derived Pb concentrations (section 5.4.2) to provide an approximate depth for 1980 and 1900. There is good agreement between the depth for 1980 and 1900 generated by the radiometric and XRF analysis (Table 6.5

and Figure 6.10), which suggests physical mixing has not taken place in Loch FEAR. Sediment accumulation rate in FEAR_BB increases from 0.0026 g cm^{-2} yr^{1} to 0.0198 in ca. 1960, with a clear peak at ca. 1920 and between 1940 and 1950. Sediment accumulation remains high between ca. 1960 and 1990 before decreasing in the upper most part of the core (Figure 6.8). There is some evidence that sediment accumulation being higher during the period of forestry planting (ca.1980s) however, there are other peaks in the core which suggest there could be other factors influencing sediment accumulation rate in FEAR.

Loch Leir (LEIR)

The Big Ben core from Loch LEIR was not radiometrically dated using ^{210}Pb, but was analysed for Pb using XRF. A Glew core taken in 2013 was dated using ^{210}Pb (Chapter 5, 5.4.2), and it was therefore possible to cross-correlate the XRF and %LOI profiles of the Glew and Big Ben cores to establish an approximate core chronology. The XRF Pb profile for the Glew core peaks at 3.5cm, the Big Ben peak was at 1.5. Aligning the peaks of the profiles indicates ca. 1970 in the Big Ben core is at 1.75cm and 1900 at 5.5-6.0cm (Figure 6.11).

Loch Talaheel (TALA)

^{210}Pb activities in the TALA_BB core are relatively low with equilibrium being reached at c. 1.5cm (Figure 6.13). Similarly, to AMHU_BB and FEAR_BB, the ^{137}Cs record is of little use for dating as the nuclear weapons testing and Chernobyl peaks could not be identified. The simple CRS model puts the 1960s at 0.5-1cm (Table 6.6, Figure 6.12) and 1900 at ca. 3cm. Similarly, to the other radiometrically dated cores, an attempt was made to align the peaks in the LOI profiles of TALA_1 and TALA_BB with the aim of establishing an estimated date for 1980 and 1900 using the XRF Pb profile of TALA_1. However, this was challenging as the LOI profiles of both TALA_1 and TALA_BB show no distinct pattern or tie points, and consequently it was difficult to confidently align the LOI profiles of the cores (Figure 6.14). There is a large amount of difference between the estimates of 1980 and 1900 from the CRS (ca. 0.75cm 1980 and 1.75cm 1900) and XRF (1.75cm 1980 and 5.75cm 1900) approaches (Table 6.7). Calibrating dating using XRF Pb concentrations from TALA_1 was not feasible because it was not possible to confidently cross correlate the LOI profiles from TALA_1 and TALA_BB. Although the chronology from the CRS model is used for TALA_BB in this chapter the results are considered with some caution, as without ^{137}Cs or ^{241}Am peaks or corroboration from the XRF Pb profile of TALA_1 the dating of the Loch TALA core may not be particularly robust. Sediment accumulation rate increases gradually in TALA_BB from 0.0061 g cm^{-2} yr^{1} in ca.1925 and 0.0216 g cm^{-2} yr^{1} in 2002.

Core chronologies summary

- The chronologies of cores from lochs Loch a'Mhuillinn, Loch nam Fear, Loch Leir and Loch Talaheel were determined using radiometric dating techniques. The ^{137}Cs and ^{234}Am peaks were absent or poorly defined in the cores, and therefore the accuracy of the dates from the CRS models was assessed by cross correlating with the short cores and examining the XRF Pb profiles.
- The chronologies of the cores from Loch a'Mhuillinn, Loch nam Fear and Loch Leir were successfully affirmed by the cross-correlation with Pb XRF profiles. However, it was not possible to corroborate the dates in Loch Talaheel as there seemed to be a large discrepancy between the dating estimates based on the CRS and XRF Pb profiles.

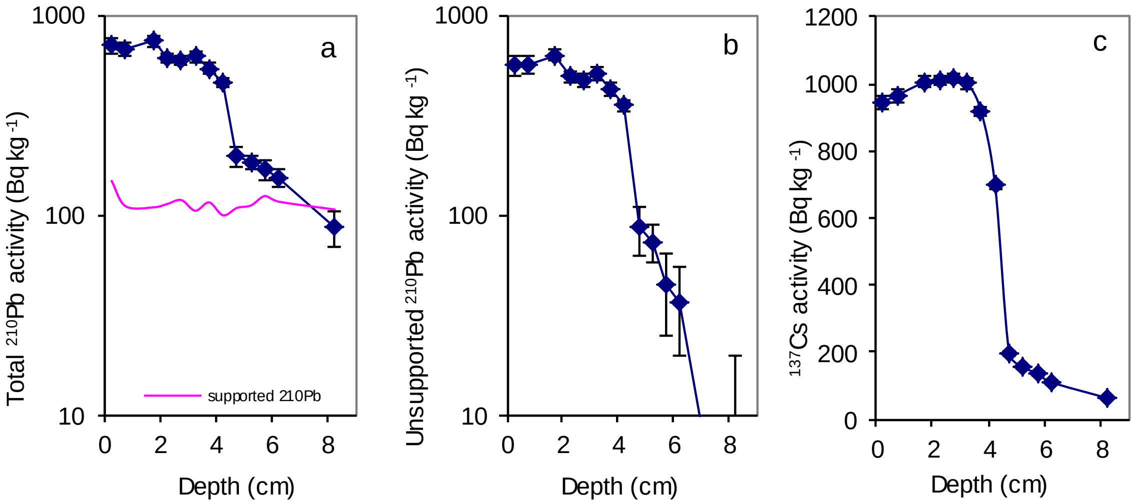


Figure 6.5 Fallout radionuclide concentrations in core AMHU_BB, showing (a) total ^{210}Pb (solid pink line) and unsupported ^{210}Pb (solid blue line) (b) unsupported ^{210}Pb, and (c) ^{137}Cs

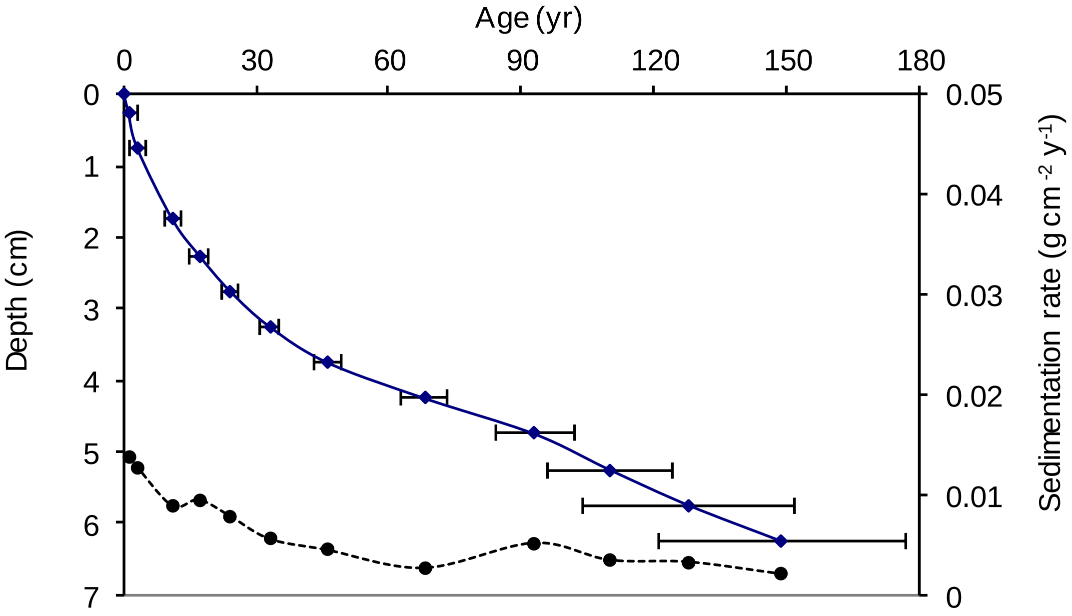


Figure 6.6. Radiometric chronology of core AMHU_BB, showing the corrected CRS dates (solid blue line) and sediment accumulation rates (black dashed line)

Depth	Drymass	Chronology			Sediment Accumulation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2015	0				
0.25	0.0118	2014	1	2	0.0138	0.243	11.9
0.75	0.0427	2012	3	2	0.0128	0.165	10.2
1.75	0.1277	2004	11	2	0.0089	0.095	7.8
2.25	0.1836	1998	17	2	0.0095	0.082	7.7
2.75	0.2445	1991	24	2	0.0079	0.066	9.1
3.25	0.3027	1982	33	2	0.0056	0.046	10.1
3.75	0.3661	1969	46	3	0.0045	0.032	11.6
4.25	0.446	1947	68	5	0.0027	0.016	15.7
4.75	0.5331	1922	93	9	0.0052	0.032	37.8
5.25	0.6085	1905	110	14	0.0035	0.026	48.1
5.75	0.6707	1887	128	24	0.0033	0.028	84.6
6.25	0.7272	1866	149	28	0.0021	0.015	100.7

Table 6.2. ^{210}Pb chronology of core AMHU_BB taken from Loch a'Mhuillinn (AMHU)

Depth (cm)	**Age CRS model**	**Pb concentration from XRF (ug/g)**	**Age estimate from XRF**
0.25	2014	-	2013
1.25	2004	66	-
2.25	1998	118.4	1980
3.25	1982	39.8	-
4.25	1947	25.7	-
5.25	1905	32.2	1900
6.25	1866	27.6	-
7.25	-	66	-
8.25	-	65.7	-
9.25	-	22	-
10.25	-	24.1	-
11.25	-	19.3	-
12.25	-	19.4	-

Table 6.3 Date estimates for AMHU_BB from cross correlation with the XRF Pb profile from AMHU_1

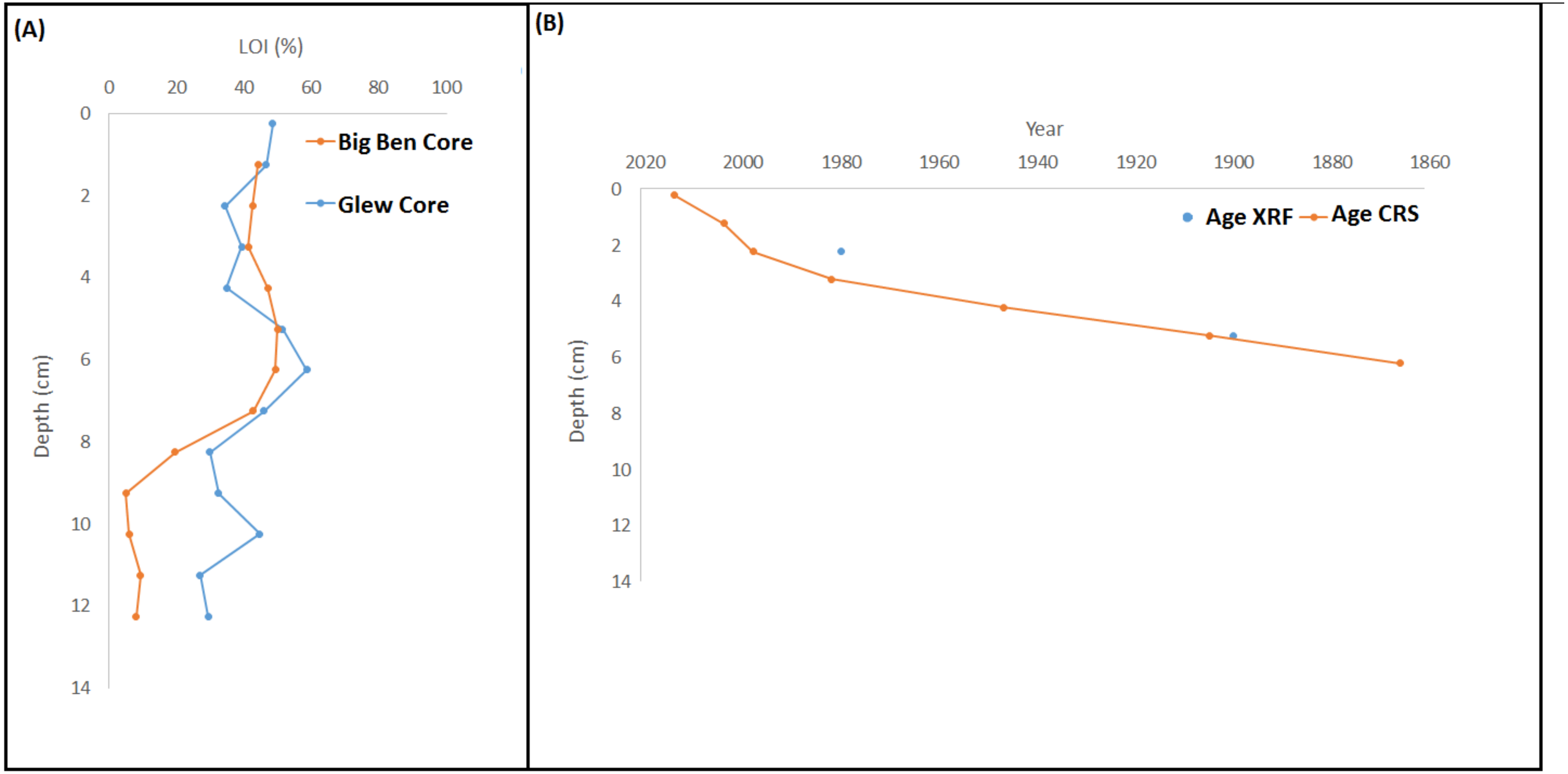


Figure 6.7 (A) Correlation between %LOI from AMHU_1 and AMHU_BB and (B) Dating from CRS model and cross correlation with Pb profile from AMHU_1.

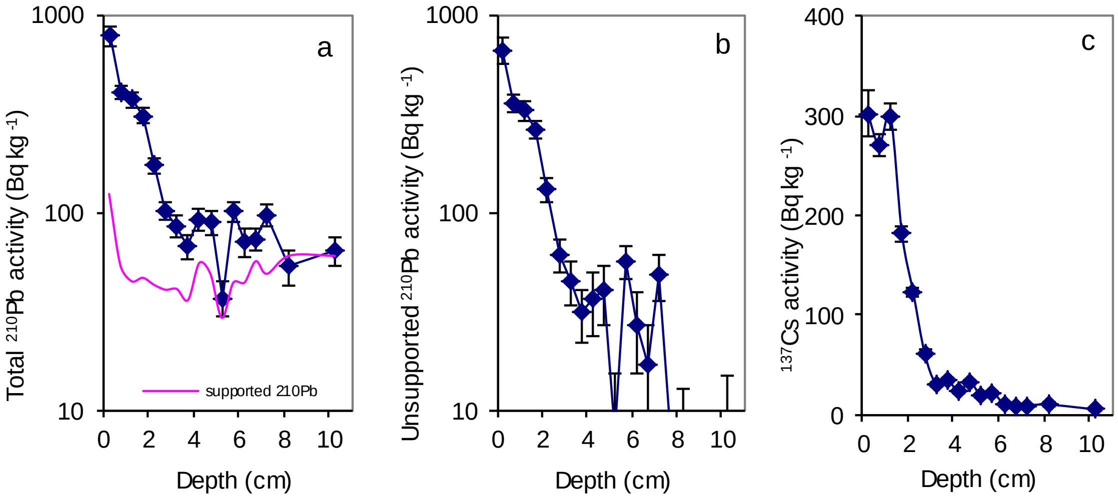


Figure 6.8 Fallout radionuclide concentrations in core FEAR_BB, showing (a) total ^{210}Pb (solid pink line) and unsupported ^{210}Pb (solid blue line) (b) unsupported ^{210}Pb, and (c) ^{137}Cs

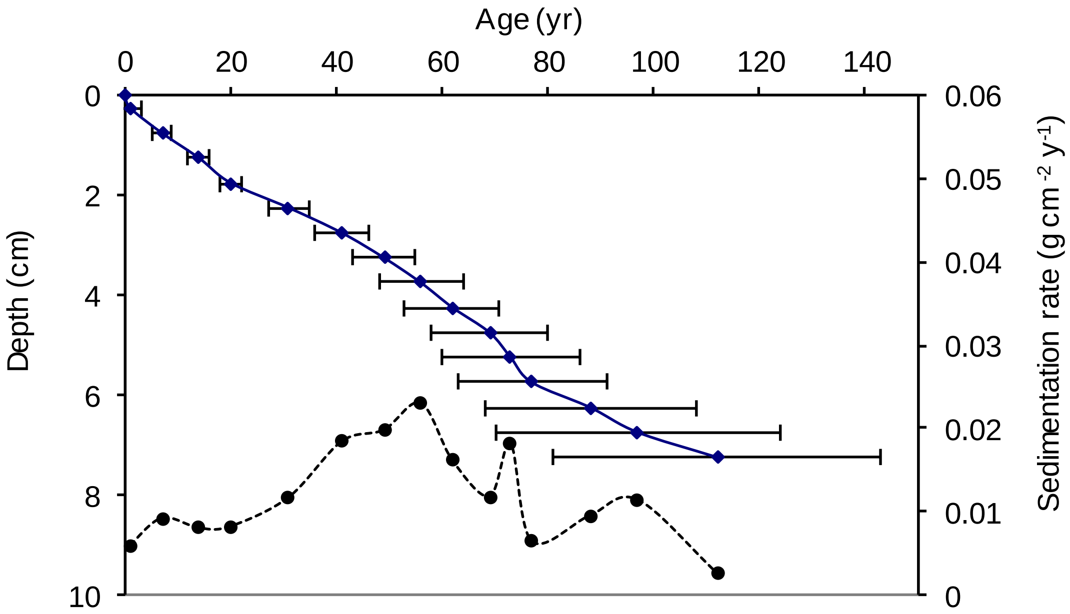


Figure 6.9. Radiometric chronology of core FEAR_BB, showing the corrected CRS dates (solid blue line) and sediment accumulation rates (black dashed line)

Depth	Drymass	Chronology			Sediment Accumulation Rate		
		Date	Age				
Cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2015	0				
0.25	0.0046	2014	1	2	0.0059	0.092	15.7
0.75	0.0483	2008	7	2	0.0092	0.089	12.4
1.25	0.1079	2001	14	2	0.008	0.071	14.5
1.75	0.161	1995	20	2	0.0082	0.051	14.1
2.25	0.2686	1984	31	4	0.0117	0.047	19.1
2.75	0.4094	1974	41	5	0.0184	0.064	25.4
3.25	0.5549	1966	49	6	0.0198	0.068	32.6
3.75	0.6998	1959	56	8	0.023	0.088	39
4.25	0.8177	1953	62	9	0.0161	0.074	45.9
4.75	0.9165	1946	69	11	0.0118	0.065	48.7
5.25	1	1942	73	13	0.0181	0.117	52.6
5.75	1.0705	1938	77	14	0.0064	0.041	50.1
6.25	1.1587	1927	88	20	0.0095	0.052	78.1
6.75	1.2524	1918	97	27	0.0114	0.067	102.4
7.25	1.3283	1903	112	31	0.0026	0.015	118.7

Table 6.4. ^{210}Pb chronology of core FEAR_BB taken from Loch nam Fear (FEAR)

Depth (cm)	Age CRS model	Pb concentration from XRF (ug/g)	Age estimate from XRF
0	2015	-	-
0.25	2014	81	2013
1.25	2001	-	-
2.25	1984	86	1980
3.25	1966	-	-
4.25	1953	50	-
5.25	1942	-	-
6.25	1927	35.9	-
7.25	1903	-	1900
8.25	-	36.6	-
9.25	-	-	-
10.25	-	44.1	-
11.25	-	-	1850

Table 6.5 Date estimates for FEAR_BB from cross correlation with the XRF Pb profile from FEAR_1

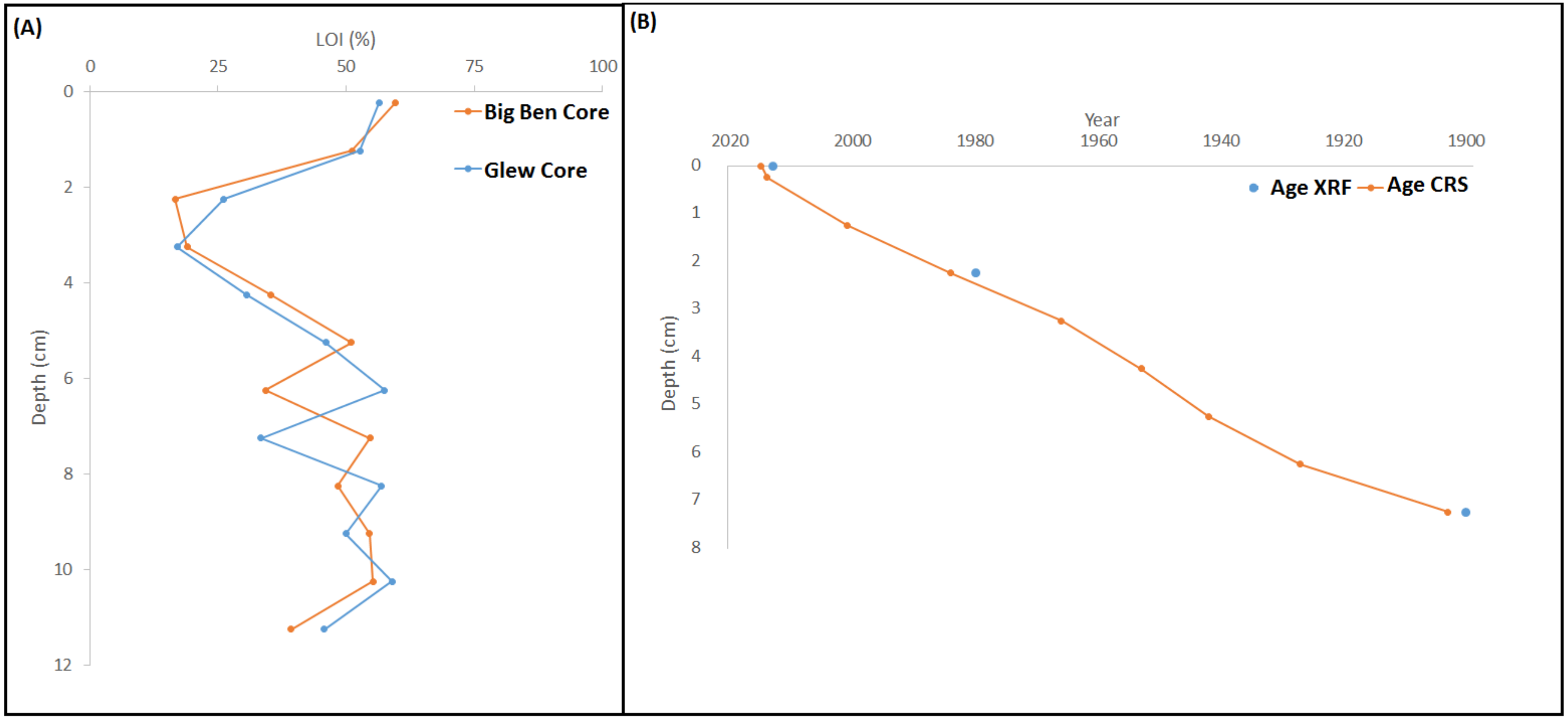


Figure 6.10 (A) Correlation between %LOI from FEAR_1 and FEAR_BB and (B) Dating from CRS model and cross correlation with Pb profile from FEAR_1.

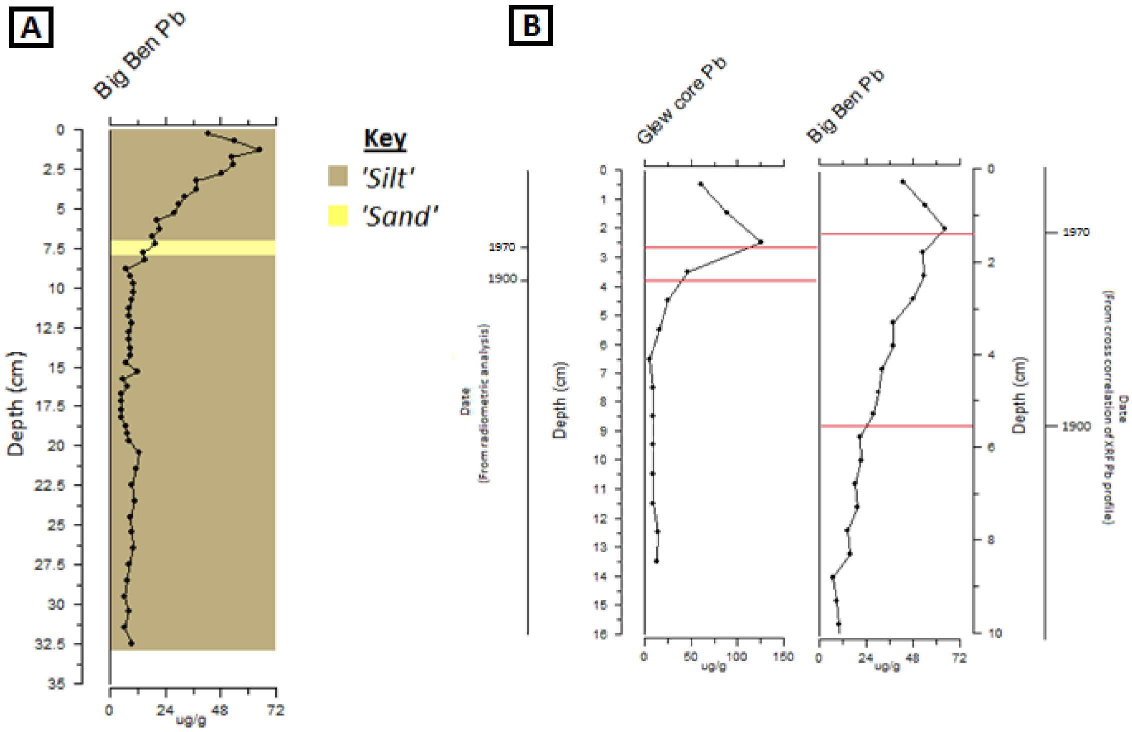


Figure 6.11 (A) The heavy metal lead (Pb) profile from Loch Leir (LEIR) and (B) cross correlation of 1970 and 1900 between the Big Ben and the Glew core

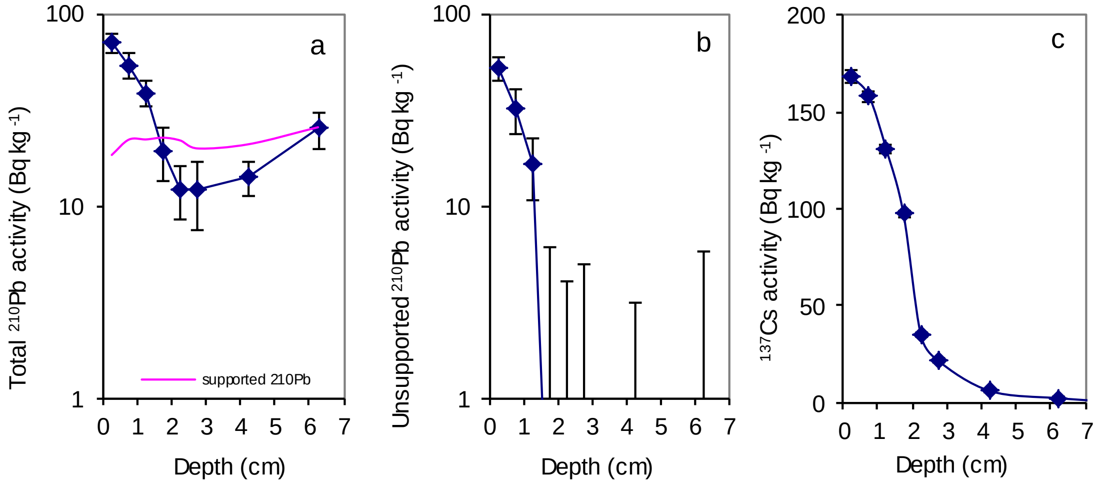


Figure 6.12 Fallout radionuclide concentrations in core TALA_BB, showing (a) total ^{210}Pb (solid pink line) and unsupported ^{210}Pb (solid blue line) (b) unsupported ^{210}Pb, and (c) ^{137}Cs

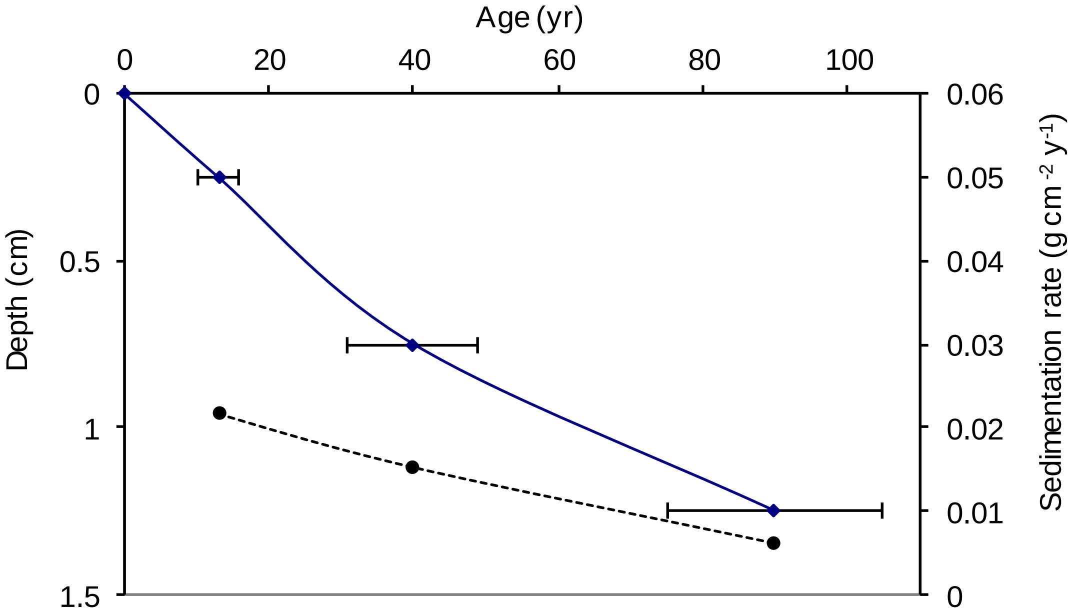


Figure 6.13. Radiometric chronology of core TALA_BB, showing the corrected CRS dates (solid blue line) and sediment accumulation rates (black dashed line)

Depth	Drymass	Chronology			Sediment Accumulation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2015	0				
0.25	0.2485	2002	13	3	0.0216	0.022	24.3
0.75	0.747	1975	40	9	0.0152	0.015	43.5
1.25	1.2745	1925	90	15	0.0061	0.006	63.7

Table 6.6. ^{210}Pb chronology of core TALA_BB taken from Loch Talaheel (TALA).

Depth (cm)	**Age CRS model**	**Pb concentration from XRF (ug/g)**	**Age estimate from XRF**
0	2015	-	2013
0.25	2002	37.1	-
0.75	1975	-	-
1.25	1925	44.6	1980
1.75	-	-	-
2.25	-	42.5	-
2.75	-	-	-
3.25	-	31.6	-
3.75	-	-	-
4.25	-	37.1	-
4.75	-	-	-
5.25	-	44.6	-
5.75	-	-	-
6.25	-	42.5	1900

Table 6.7 Date estimates for TALA_BB from cross correlation with the XRF Pb profile from TALA_1

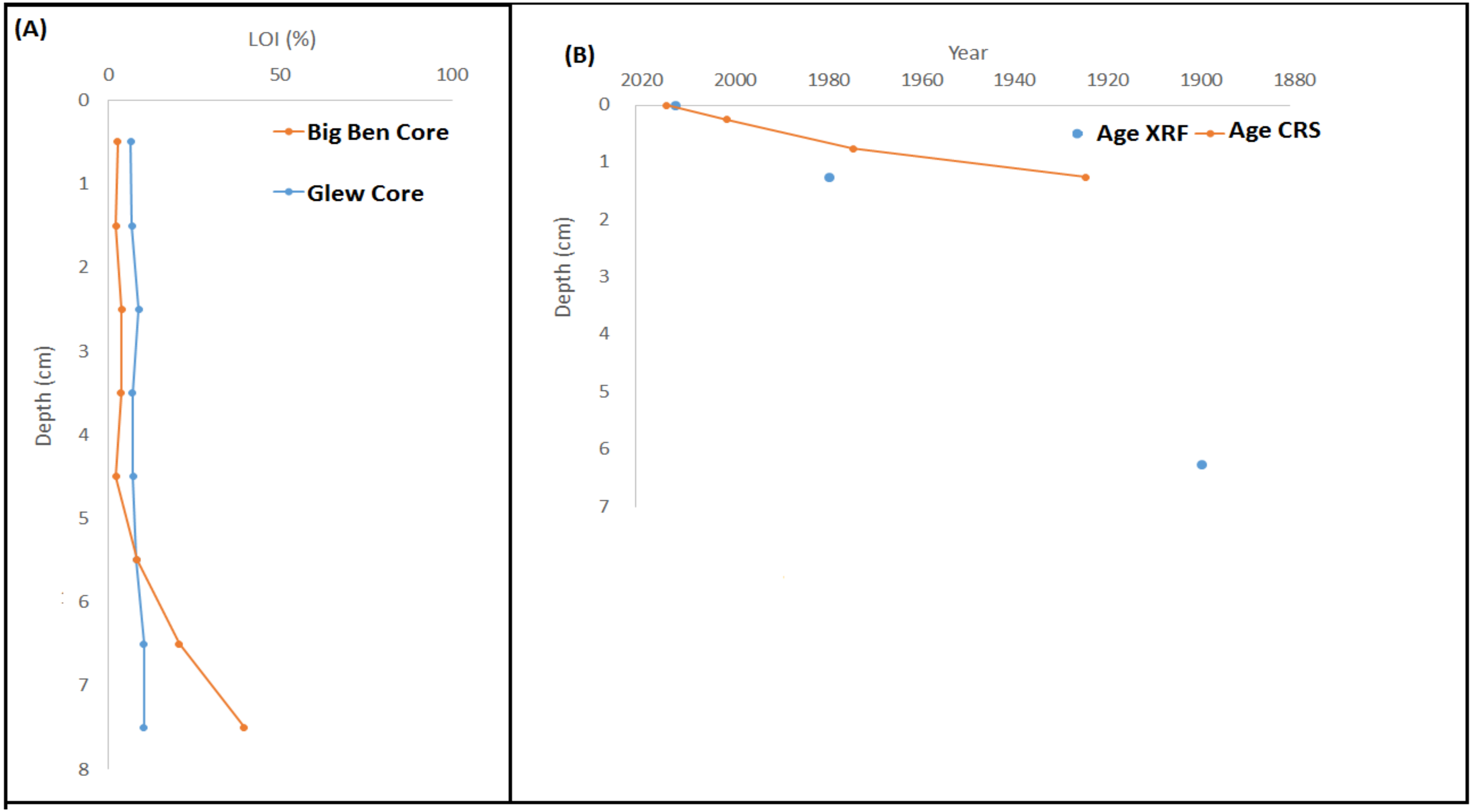


Figure 6.14 (A) Correlation between %LOI from TALA_1 and TALA_BB and (B) Dating from CRS model and cross correlation with Pb profile from TALA 1.

6.4.1.3 Diatoms

6.4.1.3.1 Abundance and composition

Loch a'Mhuillinn (AMHU)

13 samples of AMHU_BB were analysed for diatoms which included every 0.5cm slice down to a depth of 6.5cm which covered the period of the last 150-200years (based on ^{210}Pb dates). The mean number of species recorded per slice was 34. The diatom accumulation increases from 0.37 g cm^{-2} yr^{-1} at 6cm (ca. 1850) to 9.86 g cm^{-2} yr^{-1} at 0-0.5cm (present day) (Figure 6.15). Distinct diatom increases are evident at ca. 1980 (between 3.5-4.0 and 3.0-3.5) and ca. 2006 (between 1.0-1.5 cm and 0.5-1.0 cm) where the diatom accumulation rate almost doubles. AMHU_BB is dominated throughout by benthic diatoms, the mean percentage of benthic diatom in samples along the core is 72.4% (range 66-79%). The dominant taxa in AMHU_BB were *Fragilaria sensu lato*, particularly *Fragilaria exgiua, Pseudostaurosira. brevistriata* and *F. pinnata,* which were present throughout the core (Figure 6.15). *Aulacoseria ambigua* was present in lower numbers throughout the core. *Asterionella formosa* and *Fragilaria virescens* appear in the core between 4-0 cm depth, with the accumulation of *A. Formosa* particularly increasing at 1.5cm depth (2005). CONISS analysis identifies two statistically significant breaks in the AMHU_BB diatom stratigraphy, at ca. 2005-2010 (1 cm) and ca.1970 (4 cm).

Loch nam Fear (FEAR)

13 samples from FEAR_BB were analysed for diatoms which included every 0.5cm slice down to a depth of 8.0 cm which covered the period since ca. 1900 (based on ^{210}Pb dates). The mean number of species in FEAR_BB is 37, which is the highest of any of the four cores. The accumulation rate of diatoms increases up the core from 0.41 g cm^{-2} yr^{-1}at 7.5-8.0cm to peak at 25.2 g cm^{-2} yr^{-1} at 0.0-0.5cm (Figure 6.16). Accumulation doubles at periods dated as ca. 1920, 1940, 1980 and 2000 and there is a substantial increase in diatom accumulation in the surface sediments. Benthic species dominate the diatom record (range along the core length is 62-74%), and although a steady increase in planktonic species is observed towards the surface of the core benthic taxa still dominate. *Fragilaria sensu lato* species are the most prevalent taxa throughout the core (mean 38%) however *Achnanthes* sp. and

Aulacoseira sp. also make up a substantial proportion of the community (27 and 12% respectively). *Eunotia* sp. are present in low abundance between 10-2cm (mean <2%), after which their number decreases further between 2.0 and 0cm. The most frequently occurring *Fragilaria sensu lato* were *F. exigua* and *F. elliptica* which are present throughout the core and *S. construens var venter* which is only absent between 2.0 and 3.0cm. Planktonic *Aulacoseira. ambiugua* are present between 7.5 and 0.0cm with a distinct peak at 2.5-3.0 cm. *Aulacoseira lacustris*, *Navicula radiosa*, *Cycotella sp. and Achnanthes sensu lato* appear in the samples from 5.0 to 0cm. *Asterionella formosa* is present in low accumulation rate throughout the core, with noticeable peaks associated with 1940 and ca. 1995 to 2005. CONISS analysis identifies two statistically significant shifts in FEAR_BB diatom stratigraphy, at ca.1980 (3 cm) and ca. 1925 (7 cm).

Loch Leir (LEIR)

Every slice of the LEIR_BB core was analysed down to a depth of 6cm (12 samples in total) which covered the last 150 years (Figure 6.17). The mean number of species recorded per slice was 26, the lowest recorded at any of the four sites. Diatom accumulation is relatively stable between 6 and 2.5cm (ca. 0.5 valves per g cm^{-2} yr^{-1}), with evidence of a slight increase between 2.5 and 2.0cm (ca. 1950 and 1970). A substantial increase a period estimated at ca. 1970s-1980s occurs with diatom accumulation more than doubling during this time. Following this there is a slight decrease between 1.5 and 0.0cm to mean of 2.8 per g cm^{-2} yr^{-1}, but accumulation remains substantially higher than pre-1980s. Benthic diatoms dominate throughout the core, planktonic species are most prevalent between 5.5-4.0cm, ca. 1900 (mean 23%). *Fragilaria sensu lato* were the most abundant taxa present throughout the core (mean 72%, range 65-76%) followed by *Achnanthes sensu lato* (mean 10%, range 4-14%) and *Aulacoseira* sp. (mean 6%, range 2-11%); *Eunotia* sp. were the least abundant taxa throughout the core (mean <1%). *S. construens var venter*, *F. exigua* and *F. elliptica* are the most prevalent species making up on average 17, 11 and 34% of the species respectively. *T. floculosa* is present at low accumulation rate from 2-0cm and *A formosa* in the top 1.5cm of LEIR_BB (since ca. 1980). CONISS analysis confirms there is a statistically significant shift in the diatom community in LEIR_BB associated with the ca. 1980s (1.5 cm).

Loch Talaheel (TALA)

The diatom analysis of TALA_BB included every 0.5cm slice down to a depth of 2.5cm which covered a time period of 1850-present. The mean number of species recorded per slice was 29. Diatom accumulation increases distinctly between the 1970s and 1990s and remains high in the surface sediments. Benthic diatoms dominate the record, planktonic species made up only 10-20% of the diatoms community along the core length. *Fragilaria sensu lato* dominated the community (27-50%) followed by *Achnanthes* sp. (11-25%); *Aulacoseira* sp. (2-10%), and *Eunotia* sp. (2-9%) which were present in lower numbers (Figure 6.18). *F. exigua* was the most abundant species and was present in all of the samples between 2.5cm and 0cm. *Achnanthes altaica* is only present in the top 1 cm of the TALA_BB core and *Aulacoseira lacustris* in the top 0.0-0.5 cm. CONISS analysis identifies a single statistically significant shift in the diatom stratigraphy of TALA_BB at ca. 1990 (1 cm).

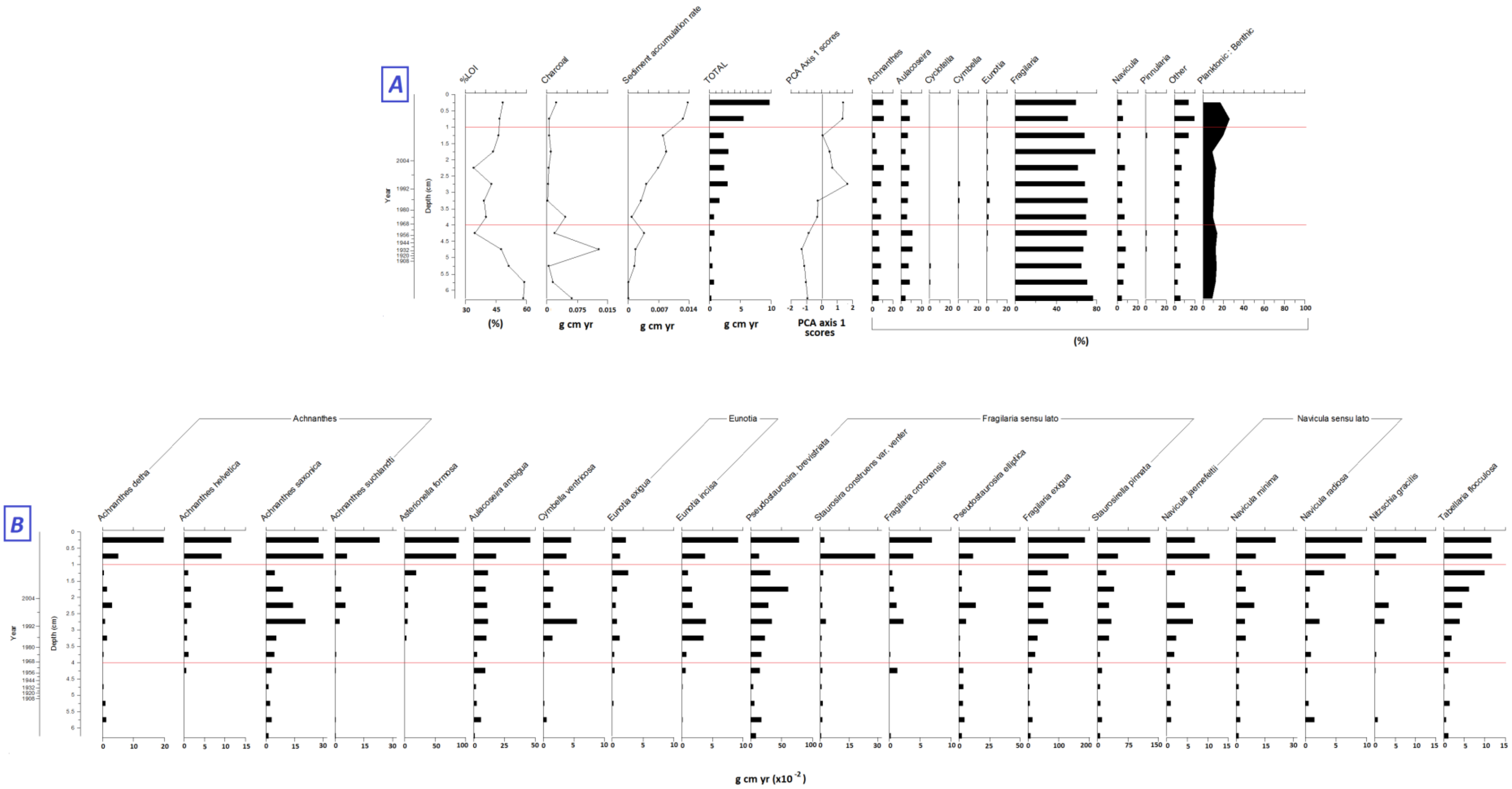


Figure 6.15 Stratigraphic plot of the diatom communities in AMHU_BB. (A) overview of community change. (B) Twenty most frequently occurring species. Red lines indicate the statistically significant splits determined by CONISS analysis.

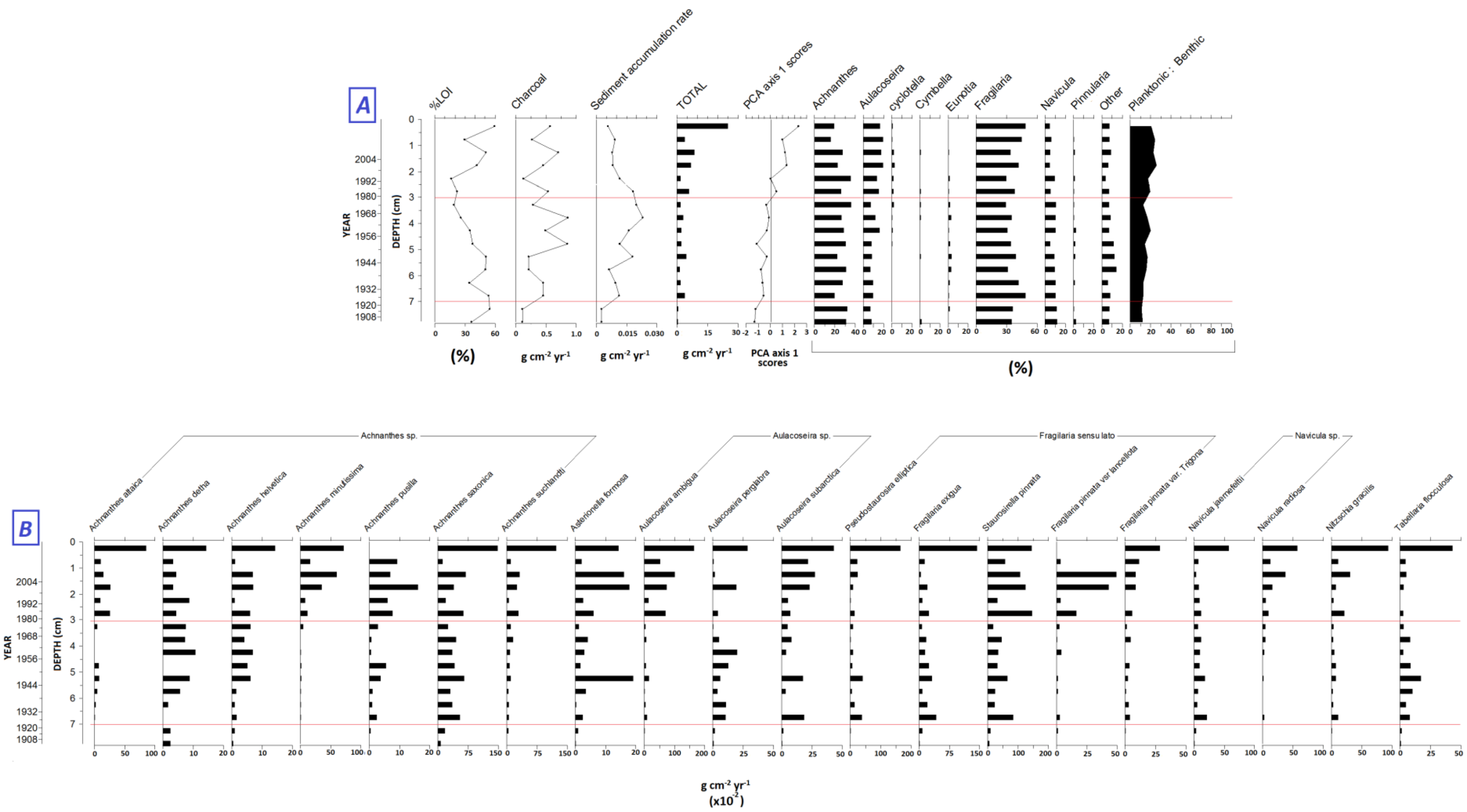


Figure 6.16 Stratigraphic plot of the diatom communities in FEAR_BB. (A) overview of community change. (B) Twenty most frequently occurring species. Red lines indicate the statistically significant splits determined by CONISS analysis.

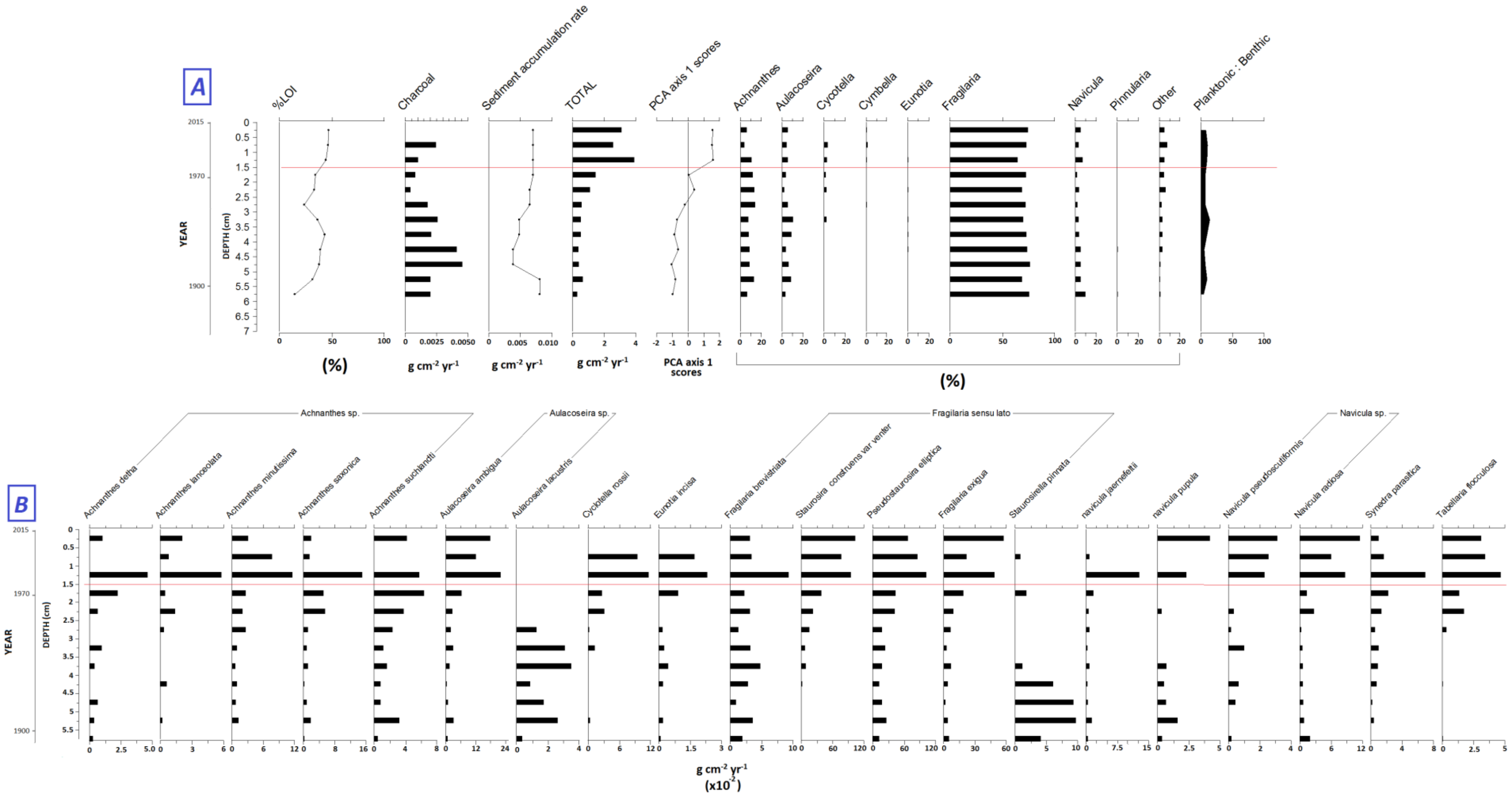


Figure 6.17 Stratigraphic plot of the diatom communities in LEIR_BB. (A) overview of community change. (B) Twenty most frequently occurring species. Red lines indicate the statistically significant splits determined by CONISS analysis.

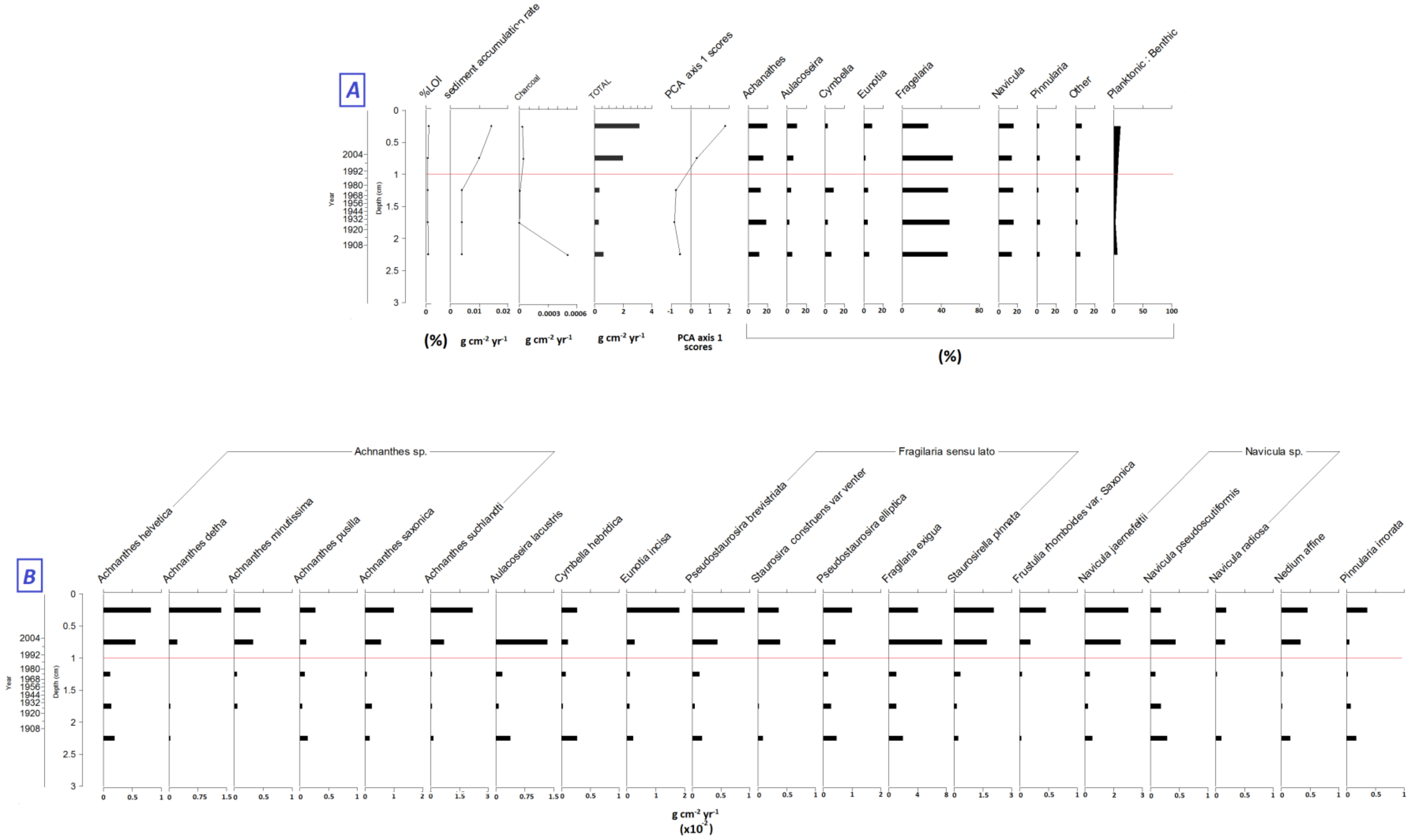


Figure 6.18 Stratigraphic plot of the diatom communities in TALA_BB. (A) overview of community change. (B) Twenty most frequently occurring species. Red lines indicate the statistically significant splits determined by CONISS analysis.

6.4.1.3.2 Change in diatom community composition at all four study sites

The downcore communities of each core are represented in the same ordination space to enable comparisons of diatom communities' composition both down each core (to a depth associated with ca. 150-200 years BP) and between cores. The first two axes of the PCA and account for 28.9 and 12.8% of the variation respectively (Figure 6.19). The community composition in LEIR and TALA was similar along the core length; present day communities are shown to be similar as are the bottoms (both at ca. 1850). Community composition of Loch AMHU and FEAR are distinctly different to LEIR and TALA, and from one another for their entire length. FEAR moves along towards a community dominated by pelagic species of Achnanthes and Aulacoseira (Cambourn and Charles, 2000). The top of AMHU is associated with taxa such as *Asterionella formosa* and *Tabellaria flocculosa,* both species typical of higher nutrient availability. The abundance of diatoms is lower in lochs LEIR and TALA but the direction of change is similar to loch AMHU towards a community with more nutrient tolerant taxa.

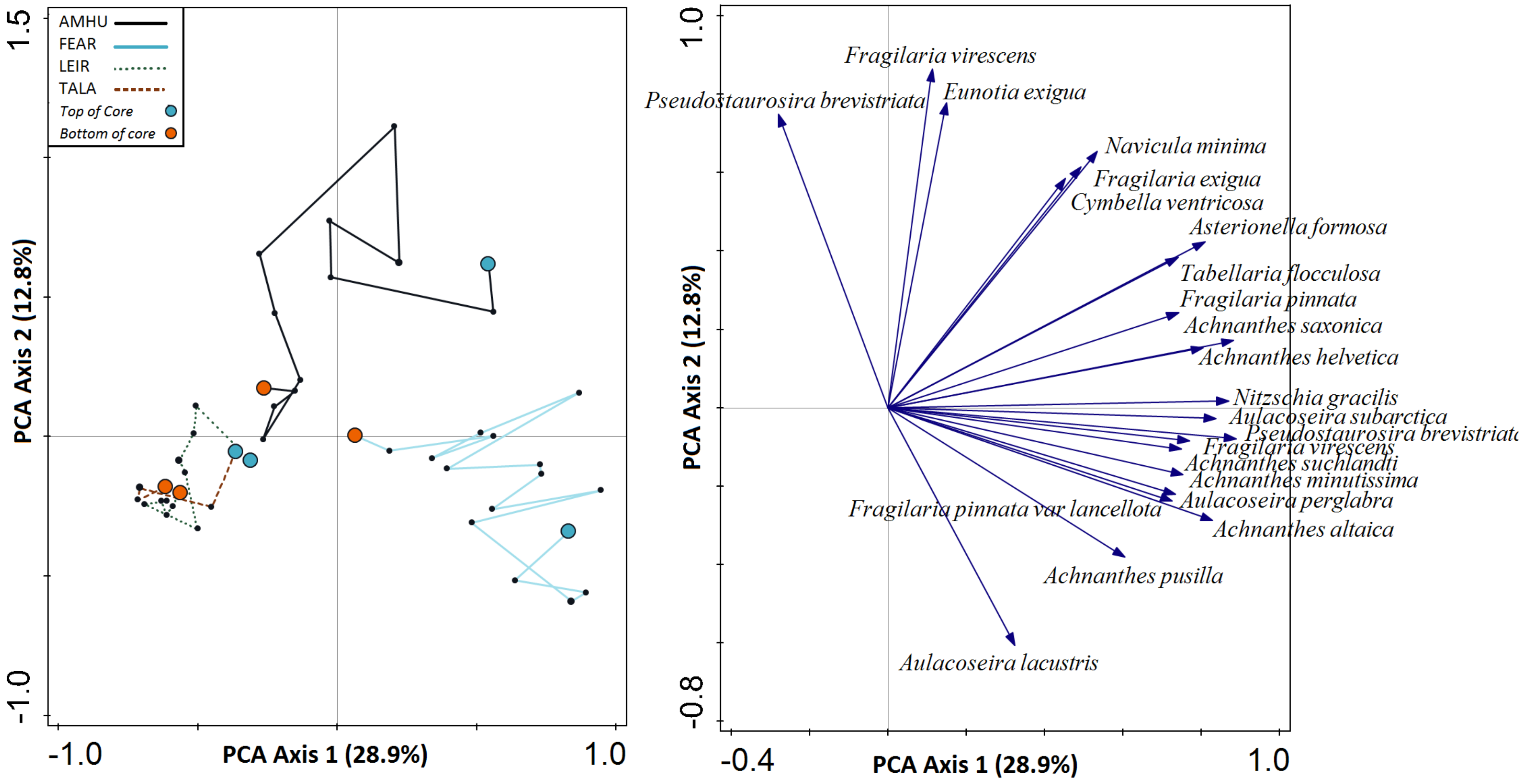


Figure 6.19 Axis 1 and 2 of a PCA of the diatom communities of the four lochs over the last 150-200 years.

Diatoms summary

- The accumulation rate of diatoms has increased steadily at all four sites since 1850, notable increases are evident in the 1980s (lochs FEAR and TALA) and early 2000s (loch AMHU)
- Benthic species dominate the records of all four cores. Although the proportion of planktonic species steadily increases in more recent sediments the overall percentage of planktonic species does not exceed 30% even in the surface sediments.
- *Fragilaria sensu lato* are the most commonly recorded taxa in the sites; followed by *Achnanthes, Aulacoseira, Naviulcae* and *Eunotia.*
- Commonly occurring *Fragilaria sensu lato* species include *S. construens var venter*, *F. exigua* and *F. elliptica*
- There are noticeable increases in nutrient tolerant taxa such as *A. formosa* and *A. ambigua* in the surface sediments of the cores.
- Exploration of community composition at the four lochs using PCA shows the diatom communities of LEIR and TALA to be relatively similar, with much overlap along the core length. The diatom communities in the bottoms of AMHU and FEAR do not overlap with either LEIR or TALA or one another.
- The direction of community change in lochs AMHU, LEIR and TALA is similar, towards a community associated with nutrient tolerant taxa, whereas FEAR moves in a different direction towards a community associated with more planktonic taxa, such as *Aulacoseira* sp.

6.4.1.4 Macrophytes

6.4.1.4.1 Abundance and composition

Macrophyte remains in the cores consisted of leaves, seeds and oospores from aquatic plants. Species level identification was not possible in most cases due to the taxonomic limitations of the groups involved, so taxa were identified to genus level. Five types of seeds were not identifiable to this level and were labelled unidentified seeds 1 to 5.

Loch a'Mhuillinn (AMHU)

10 plant taxa were represented in AMHU_BB during the last 150 years (Figure 6.20) and three distinct phases were identifiable. Pre-1850 to ca. 1900 (7.5-6.0 cm) is characterised by low sediment accumulation rates and charcoal counts. The plant remains of most groups are sparse during this period except the remains of *Isoetes* sp. and unidentified seed (1) which were most numerous during this period. Between 1900 and 2000 (6.0-2.0cm) there are several peaks in charcoal counts, particularly at ca. 1920 and 1970. During this period macrophyte remains were consistently low. *Lobelia* sp. and *Nitella* sp. are each recorded just once in the 1970s (*Lobelia* sp.) and 1990s (*Nitella* sp.). The most recent phase in the AMHU_BB core between 2000 and 2015 (2.0-0.0 cm) charcoal counts drop to their lowest levels. Increases can be observed in all macrophyte taxa during this period, the only exception being *Isoetes* sp. remains which continue to persist but only at low levels. Moss sp. and *Juncus* sp. substantially increase during this period; *Lobelia* sp. continues to appear sporadically and *Nitella* sp. is absent. CONISS analysis identifies a single statistically significant break in the macrophyte stratigraphy of AMHU_BB in the mid to late 2000s (1 cm).

Loch nam Fear (FEAR)

A total of 16 plant taxa were identified in FEAR_BB, and three phases are identifiable and charcoal remains show several peaks between the ca. 1940s and 2000. (Figure 6.21). Pre-1900 (10-7.5 cm) is characterised by a comparatively low abundance of charcoal as well as the remains for most groups. There is a stepped increase in most taxa at 1940 (ca. 6.0cm), remains continue to be recorded at this elevated level until ca. 1980 (2.5cm), when a distinct decline occurs. Between 1940 and 1980 (ca. 6.5 - 2.5 cm) most groups are relatively stable, slight declines occur in unidentified seed

(1) and Moss sp. (1). Between 1980 and 2015 (2.5-0.0cm) the accumulation of macrophyte remains increase steadily however for most groups (except unidentified seed (1) and *Juncus*) the accumulation rate of remains does not exceed those recorded between 1940 and 1980. Two statistically significant shifts can be identified in the FEAR_BB macrophyte stratigraphy at 1990 (2.5 cm) and ca. 1920 (7.0 cm).

Loch Leir (LEIR)

The last 150 years are represented in the top 5.5cm of LEIR_BB, 10 plant taxa were identified to at least genus level (Figure 6.22). Seeds from the slender Naiad, *Najas flexilis*, were recorded in LEIR_BB. The species was not found in the macrophyte surveys (Chapter 3) or in the previous macrophyte surveys (in the late 1980s) by SNH and constitutes the first record of the species for the area. Charcoal counts in LEIR_BB are highest in the lower part of the core between ca. 1900 and 1940 after which they decline throughout the 20th century.

There are two distinct phases in the LEIR_BB macrofossil record. During the first phase, from pre-1850 to ca. 1980 (5.5 – 1.5 cm), *Isoetes* sp. are the most abundant type of remains, and accumulation rate of remains also increases during this period, approximately double between ca. 1850 (5.5-6cm) and 1980 (1.5-2.0cm). Other plant remains during this phase are low; moss sp. occurs only in low levels and *Najas flexilis*, *Potomogeton* sp. and *Juncus* sp. only occur sporadically. The second period in LEIR_BB is from 1980 to 2015 (1.5-0.0 cm) and is characterised by a distinct shift in macrophyte taxa. The abundance of *Isoetes* sp. drops substantially; *Nitella* sp. and *Potamogeton* sp. both appear for the first time in the ca. 1980s (2cm). Between ca. 1980s and 2015 all moss taxa increase; *Isoetes* sp. also increase but do not reach levels recorded prior to 1980. CONISS analysis confirms there is a statistically significant shift in the macrophyte stratigraphy of LEIR_BB associated with the 1980s.

Loch Talaheel (TALA)

The last 150 years are represented in the top 2.5cm deposited in Loch TALA, and seven macrophyte taxa were identified and charcoal remains are very low throughout the core. Between 1850 and 1950 (1.5-2.5cm) sediment accumulation rate is low (0.0061-0.015 g cm^{-2} yr^{-1}) and taxa prevalent during this period were

Juncus sp., *Isoetes* sp., *Nitella* sp. and *Lobelia* sp., Moss sp. in TALA_BB were not recorded during this period. Between 1950 and 2015 (1.5cm-0.0cm) Moss sp. also increase. The abundance of *Juncus* sp., *Isoetes* sp. and *Nitella* sp. all decrease between 1950 and 2015, and *Lobelia* sp. does not occur. CONISS identifies a single statistically significant split in the TALA_BB macrophyte stratigraphy at ca. 1990 (1.0 cm).

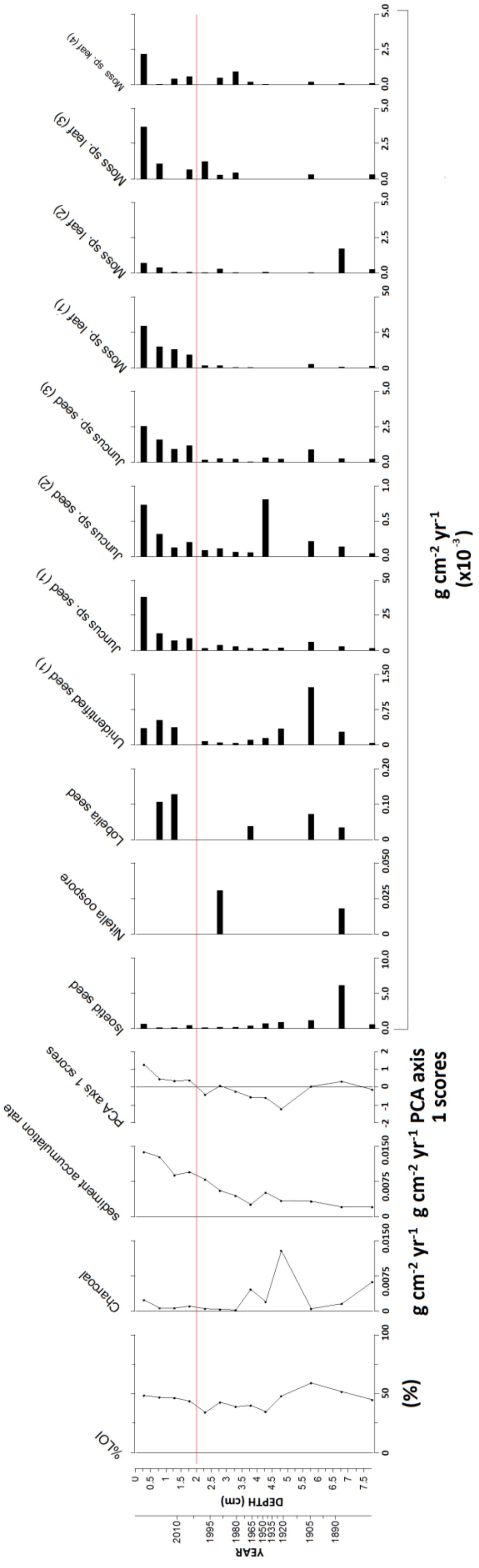


Figure 6.20 Stratigraphic plot of the macrophyte remains in AMHU_BB. Red lines indicate the statistically significant splits determined by CONISS analysis

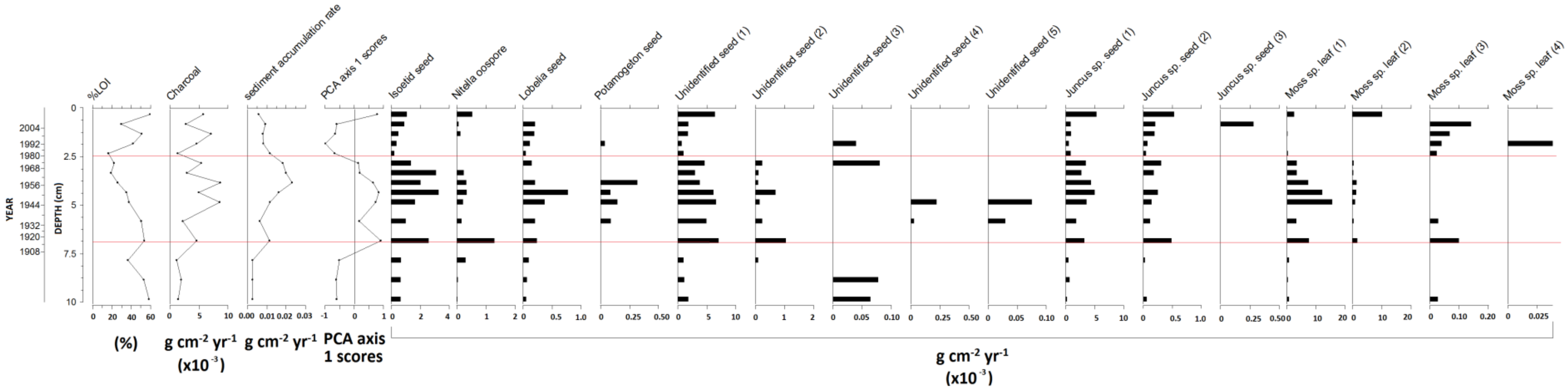


Figure 6.21 Stratigraphic plot of the macrophyte communities in FEAR_BB. Red lines indicate the statistically significant splits determined by CONISS analysis

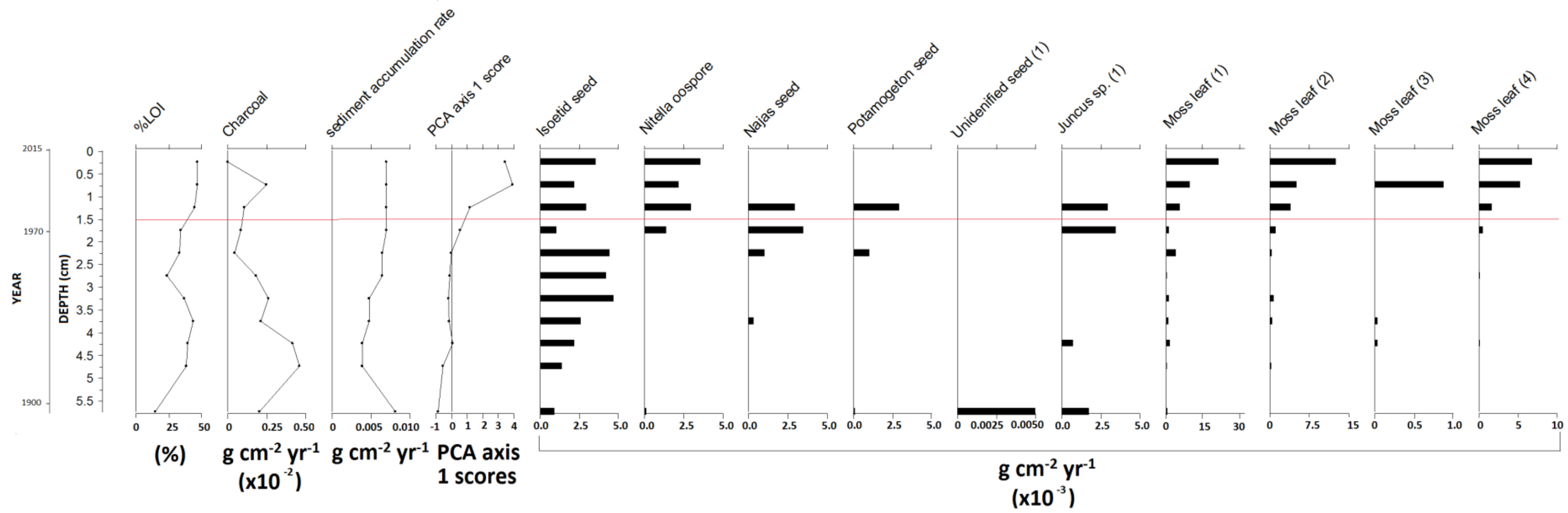


Figure 6.22 Stratigraphic plot of the macrophyte communities in LEIR_BB. Red lines indicate the statistically significant splits determined by CONISS analysis

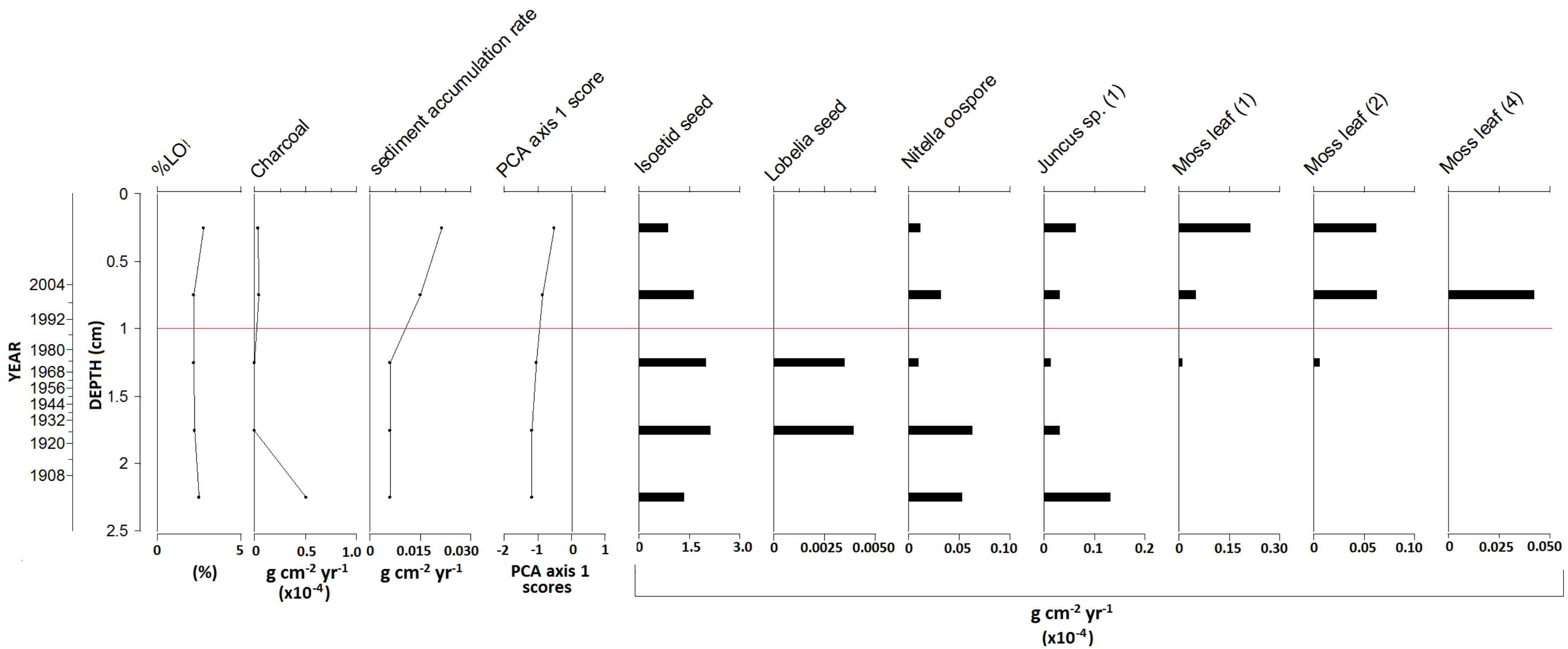


Figure 6.23 Stratigraphic plot of the macrophyte communities in TALA_BB. Red lines indicate the statistically significant splits determined by CONISS analysis

6.4.1.4.2 Change in macrophyte community composition at all four study sites

The similarities and differences in the macrophyte communities of AMHU_BB, FEAR_BB, LEIR_BB and TALA_BB was explored by displaying multiple cores on a single ordination space (Figure 6.24). PCA axis 1 accounts for 48.5% of the variability and PCA axis 2 29.4.0%. The macrophyte communities of the cores are primarily distinct from one another, with only a small period of overlap between the bottom of AMHU_BB and parts of FEAR_BB, indicating the macrophyte community of loch AMHU was historically more similar to loch FEAR. Whilst FEAR_BB shows signs of remaining fairly stable over the last 150-200 years, loch AMHU moves towards a community characterised by species of *Juncus*. TALA_BB and LEIR_BB are distinctly separate from both one another and from AMHU_BB and FEAR_BB. The base of loch LEIR shows relatively little changes, but a substantial change in community composition occurs post 1995. After this, the community is characterised by moss sp. and *Nitella* sp. Loch TALA is characterised through by low abundance of macrophyte remains and shows relatively little change over the last 150 years.

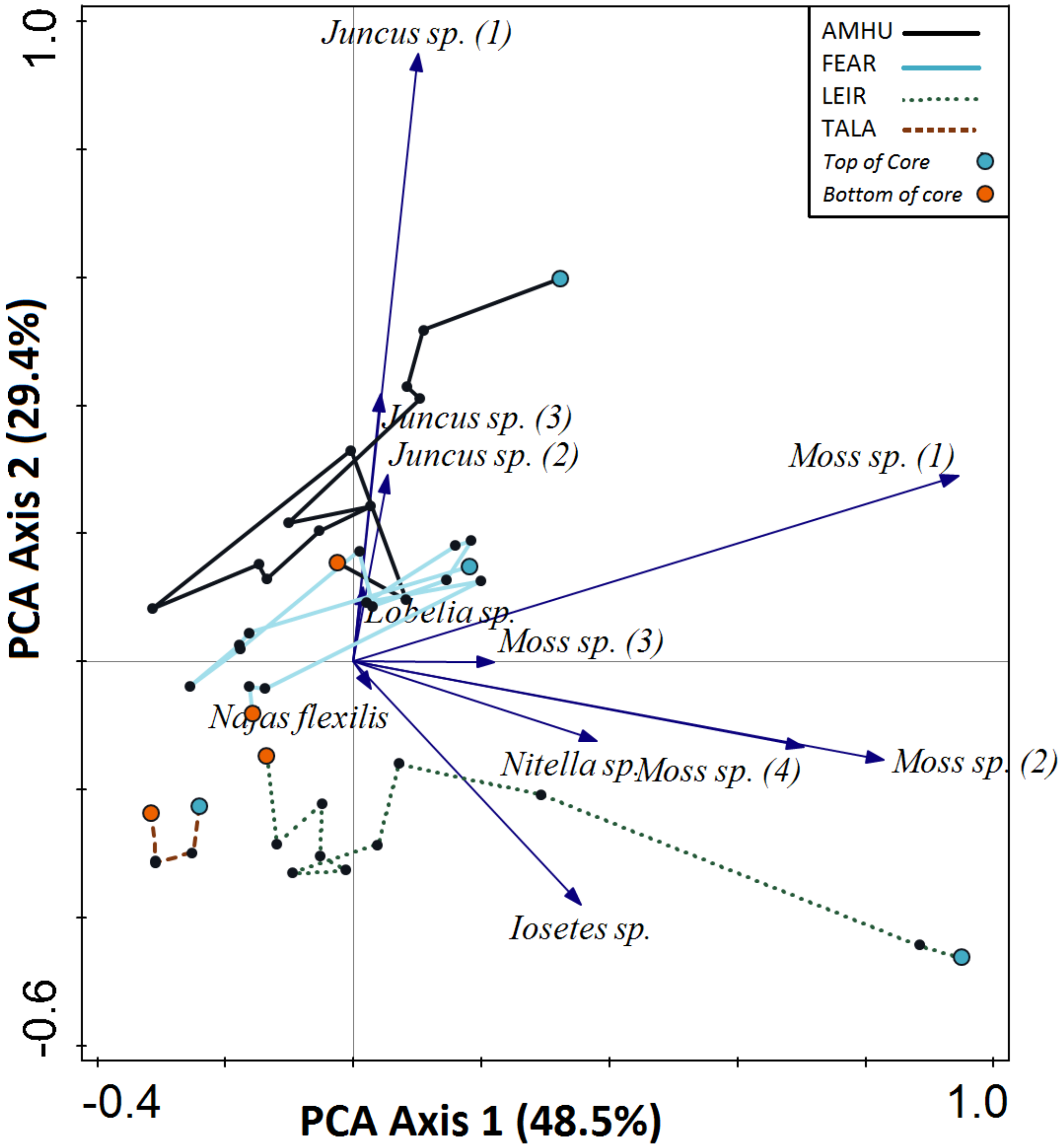


Figure 6.24 Axis 1 and 2 of a PCA of the macrophyte communities of the four lochs over the last 150-200 years.

Macrophyte summary

- Between 7 and 16 macrophyte taxa were recorded in the lochs, all species that are typically associated with oligotrophic lochs
- All of the species were recorded in the contemporary macrophyte surveys with the exception of *Najas flexilis* in Loch LEIR which is a new record for the area.
- Both Loch LEIR and Loch FEAR show distinct shifts in the 1980s and in both cases there is a decline in *Isoetes* sp. In Loch FEAR several other species decline at the same time whilst in Loch LEIR Moss sp. and *Juncus* sp. increase.
- In Loch AMHU the same pattern occurs of a decline, followed by an increase. However the timing is slightly later (early 2000s)
- The small number of samples covering the last 150 years in Loch TALA make patterns difficult to identify. However there appears to be shift in the middle of the twentieth century.
- PCA indicates the base of AMHU_BB overlaps with FEAR_BB, whilst the community of FEAR_BB shows realtively little change, loch AMHU changes to become more dominated by species of *Juncus*. Loch LEIR and TALA are separate from FEAR and AMHU and one another. LEIR is relatively stable for the early part of the record. However, substantial changes are observed post 1980s. TALA is characterised by a low abundance of macrophyte taxa and shows little overall change relative to the other sites.

6.4.1.5 Zooplankton

The zooplankton picked from the Flow Country cores consisted of cladocera ephippia (*Alona* and *Daphnia* sp.), and the headshields of the large species of *Eurycercus lamellatus* which have been shown to be an important food resource for common scoters in other parts of their range (Bengtson, 1971).

6.4.1.5.1 Abundance and composition

Loch a'Mhuillinn (AMHU)

Accumulation of cladocera remains increases over the last 150 years from 0.004 g cm^{-2} yr^{-1} at 1985 (ca.3.0cm) to 0.05 g cm^{-2} yr^{-1} in 2015 (0.0cm). *Daphnia* sp. and *Alona* sp. were the most dominant groups of cladocera present in the AMHU_BB core between 1850 and 1900 (Figure 6.25). Low levels of both taxa were recorded between 1900 and 1990s (5.5-2.5cm) following which the abundance of both groups increases to levels higher than at any other time over the last 150 years. *Eurycercus* sp. were present in very low abundance between 1850 and 1980s, however between 1980s and 2010 the abundance of *Eurycercus* sp. increases. CONISS analysis identified a single statistically significant break in the AMHU_BB for cladocera remains at ca. 2004 (2.0 cm).

Loch nam Fear (FEAR)

Low levels of cladocera were present at the base of FEAR_BB (10-7cm, pre-1900) and the accumulation rate of remains increases up the core with a total of 0.01 g cm^{-2} yr^{-1} recorded in the surface sediments (Figure 6.26). There is a noticeable increase, particularly in *Alona* sp. at ca. 1920 (6.5-7.0 cm) and then a decrease in all taxa in ca. 1980s (2.5cm), followed by a steady increase to the surface sediments. Accumulation of cladocera does not reach pre-1980 levels until the surface sediments (0.5-0.0cm). There are three statistically significant shifts in the cladocera remains present in FEAR_BB at ca. 1990 (2.5 cm), 1960 (4.5 cm) and 1920 (7.0 cm).

Loch Leir (LEIR)

The accumulation of cladoceran remains in Loch LEIR was low until ca. 1990-2000 (1.0-0.5cm) when there is a distinct increase (from 0.002 g cm^{-2} yr^{-1} to 0.007 g cm^{-2}

yr^{-1}). *Daphnia* sp. were the most abundant cladocera taxa in the first phase of the LEIR_BB core (between 6.0-2.0cm), but were only present in low accumulation rate (Figure 6.27). *Eurycercus* sp. and *Alona* sp. were present in very low accumulation rate during this phase. A distinct shift is observed in the cladocera community at ca. 1990 (1.0-1.5cm), with all groups increasing in abundance, a trend which continues in the surface sediments. CONISS identifies two statistically significant shifts in the cladocera remains present in LEIR_BB, one associated with ca. 1960 (2.0 cm) and one with ca. 1980 (1.5 cm)

Loch Talaheel (TALA)

Despite a small number of samples being examined for cladocera remains in TALA_BB, a distinct shift is evident at ca. 1970-80s (1.5-2.0 cm) with total remains increasing from 7 x10^{-5} g cm^{-2} yr^{-1} to 0.0004 g cm^{-2} yr^{-1} (Figure 6.28). Between 1850-1950 (2.5-1.5 cm) cladocera remains were very sparse in TALA_BB. Increases in the accumulation rate of remains is observed between 1950-1970 (1.5-1.0cm) and again between ca. 1970 and present day (1.0-0.0cm). CONISS analysis confirms the observed shift in cladocera remains at ca. 1970 (1.0 cm) is statistically significant.

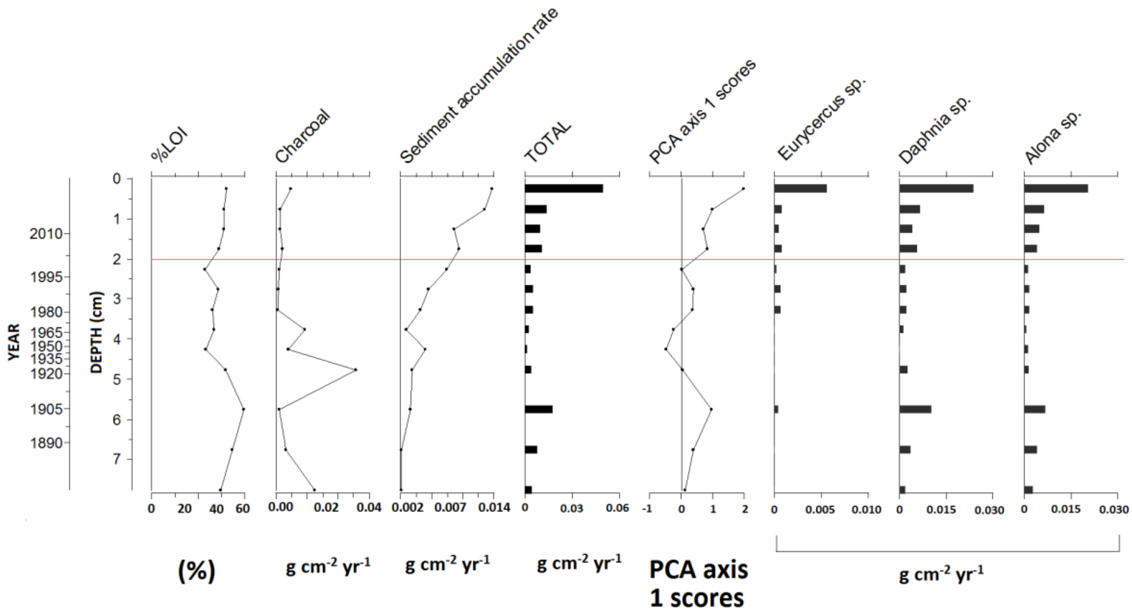


Figure 6.25 Stratigraphic plot of the cladocera remains in AMHU_BB. Red line indicate the statistically significant splits determined by CONISS analysis

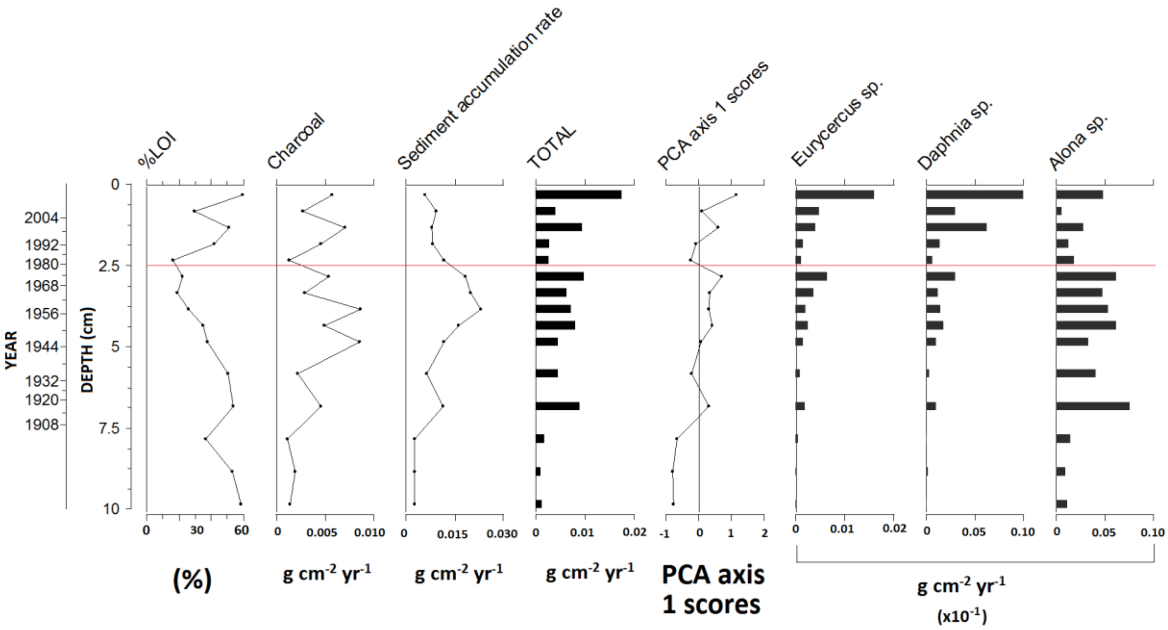


Figure 6.26 Stratigraphic plot of the cladocera remains in FEAR_BB. Red line indicates the statistically significant splits determined by CONISS analysis

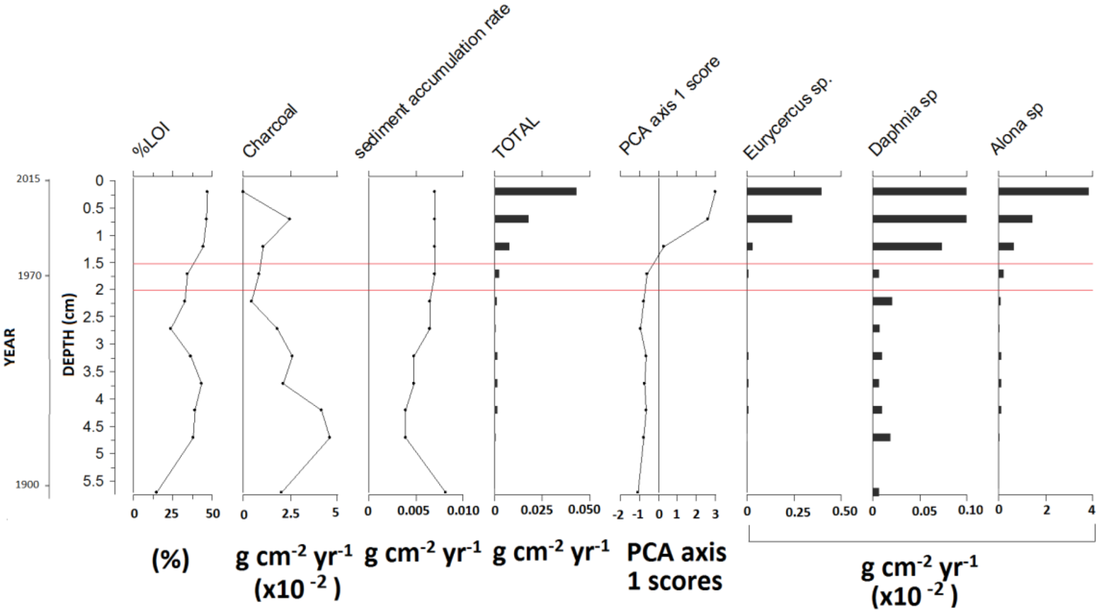


Figure 6.27 Stratigraphic plot of the cladocera remains in LEIR_BB. Red line indicates the statistically significant splits determined by CONISS analysis

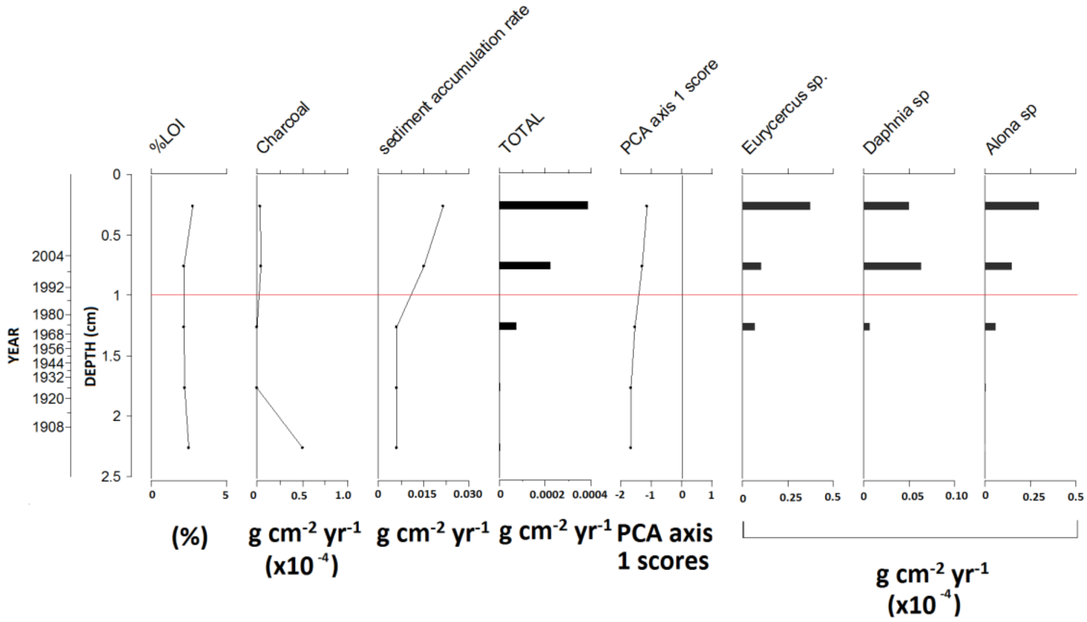


Figure 6.28 Stratigraphic plot of the cladocera remains in TALA_BB. Red line indicate the statistically significant splits determined by CONISS analysis

6.4.1.5.2 Change in community composition at all four study sites

PCA was used to explore the similarities of cladoceran remains between cores (Figure 6.29); PCA axis 1 accounts for 86.3% of the variation, whilst PCA axis 2 accounts for 1.6%. LEIR_BB overlaps with the base of FEAR_BB and the top of TALA_BB. AMHU_BB is similar to the surface samples from FEAR_BB. The direction of change in LEIR and TALA is the same both moving towards a community more strongly dominated by *Alona* sp. Conversely FEAR and AMHU are both progressing towards communities in which *Daphnia* sp. are the most prevalent taxa.

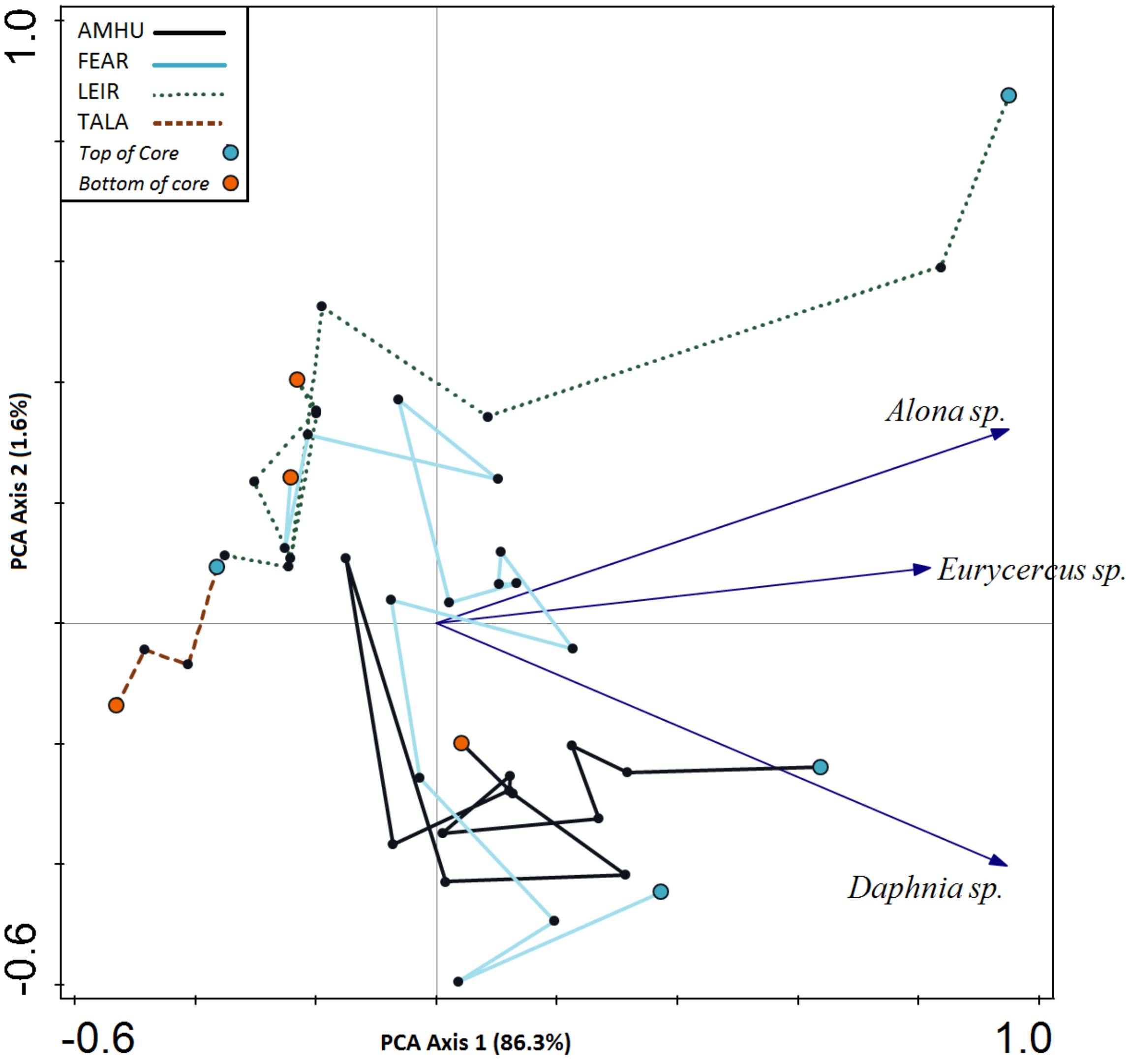


Figure 6.29 Axis 1 and 2 of a PCA of the zooplankton communities of the four lochs over the last 150-200 years.

Zooplankton summary

- The accumulation of cladocera remains in all four cores increases over the last 150-200 years. In Lochs AMHU and LEIR there is a distinct increase post 1980. In Loch FEAR, similarly to the macrophytes, there is a period of increased remains between 1940 and 1980, and a drop at ca. 1980 which is followed by a slow increase towards the top of the core.
- Mean accumulation rate of remains per sample was lowest at Loch TALA (0.00001 g cm^{-2} yr^{-1}), followed by Loch LEIR (0.007 g cm^{-2} yr^{-1}), Loch FEAR (0.006 g cm^{-2} yr^{-1}), and was highest at Loch AMHU (0.01 g cm^{-2} yr^{-1})
- Comparison of community change between sites indicates that loch LEIR and TALA are moving towards and community more dominated by *Alona* sp., whilst in FEAR and AMHU there is a change towards a community characterised by *Daphnia* sp.

6.4.1.6 Invertebrates

The invertebrate remains represented in the Big Ben cores were Trichoptera, Coleoptera, Ephemeroptera and Diptera. Trichoptera cases were categorised into four types and fronto-clypeal apotomes (structures from the dorsal part of the head) were also counted. Coleoptera elytra were enumerated, as were the mandibles of Ephemeroptera. *Sialidae* were represented by their labrum. Six types of invertebrate mandible were identified, most likely from Tricoptera and Coleoptera groups. *Chaoboridae* mandibles were picked with the other macrofossil remains, and were identified as *Chaoburus flavicans*. Chironomid head capsules were picked from a smaller amount of material following the method of (Brooks *et al.,* 2007) Chironomids were identified to sub-family. The number of macrofossil remains recorded was corrected for sediment accumulation rates.

6.4.1.6.1 Abundance and composition

Loch a'Mhuillinn (AMHU)

Nine types of invertebrate remain were recorded at AMHU, representing at least five orders (Figure 6.30). Between 1890-1980 (7.5-3.5cm) the accumulation rate of invertebrate remains in AMHU_BB was predominantly low; the most abundant group was Trichoptera case type 2. The accumulation rate of Ephemeroptera, Trichoptera and Mandibles type 1 and 2 all increase between 1990s and 2015 (2.0-0.0cm). Coleoptera increases occur slightly later (ca. 2000) and *Sialidae* only occurs sporadically at 3 and 5.5cm. *Chaoborus flavicans* mandibles were only found in one slice of AMHU_BB and then only in very small numbers. Overall the accumulation rate of remains in the cores was highest in the surface samples, the only exceptions being Trichoptera case type 2 which peaks at 4.5cm. CONISS identifies two statistically significant breaks in the invertebrate stratigraphy of AMHU_BB at ca. 1960 (4.0 cm) and ca. 2014 (0.5 cm).

There are two phases in the chironomid counts over the top 10cm of AMHU_BB (Figure 31), confirmed by CONISS analysis which identifies a statistically significant split at ca. 2000 (2.0 cm). Between 1850 and 2000 (10-2.0cm) the total accumulation rate of chironomids increases gradually, whilst. between 2 and 0 cm (2000-2015) there was a distinct increase in total chironomid accumulation rate, the accumulation rate of heads is higher than at any period between 1850 and 2000. The relative proportions of different chironomid groups between 2-0cm are relative stable orthocladiinae mean 49% (range 39% to 54%), tanytarsini mean 29% (range 28-32%), chironominae mean 9% (range 6-13%) and tanypodinae mean 12% (range7-20%). However, diamesinae are not recorded in this most recent phase.

Loch nam Fear (FEAR)

14 different types of invertebrate remains were found in FEAR_BB (Figure 32). Between 1850 and 1940 the accumulation rate of remains was low, the most frequently occurring group was Ephemeroptera. Similarly, to the macrophyte taxa, invertebrate remains in FEAR_BB were most abundant between 1940 and 1980 (6.5-2.5cm). At ca.1980 (2.5) a stepped decline occurs in Ephemeroptera and Trichoptera case type 2 and *Chaoborus flavicans* disappears from the core. Between 1980 and 2015 (2.5-0.0cm) the accumulation rate of remains increases, Trichoptera fronto cylpeal apertomes, Coleoptera and Ephemeroptera remain low until the mid-2000s before increasing noticeably in the surface sediments. Bivalves also occur in the surface samples for the first time. One statistically significant break in the stratigraphy is identified using CONISS at ca. 1990.

Similarly, to the macroinvertebrates, chironomid accumulation rate was low from pre-1900 to 1940 (10 -5.0cm) but with a distinct peak at ca. 1940 (Figure 33). Between 1940 and 1980 there is a noticeable increase in total chironomid accumulation rate and particularly in *Diamesinae* group. Total accumulation rate remains relatively stable from 1980-2015 (2.5-0cm) but with two distinct peaks at ca. 2000 (1.0-1.5) and ca. 2010-2015 (0.5-0.0cm) where the accumulation rate of remains more than doubles. *Diamesinae* occur in all the samples at the base of the core but are not present between ca. 1950-present (4.0-0.0 cm). Slight declines in *Tanypodinae* and *Chironominae* groups occur between 3.0 and 1.5cm. *Orthocladiinae* are the most dominant group from 10-2.0cm (range 41-60%), however between 2.0-2.5 (1980-1990) *Tanytarsini* are the most abundant taxa (range 47-48%). In the surface sediments (0.0-0.5cm) *Orthocladiinae* are again the most common taxa making up 48% of the chironomid remains. The proportion of *Chironominae* were roughly stable throughout the core, making up 6-20% (mean 11%) of the total heads.

Tanypodinae made up on average 8% of the total heads throughout the core, making up a distinctly smaller proportion of the total heads at 2-3cm (ca. 1980s). CONISS analysis identifies two statistically significant shifts in the chironomid stratigraphies of FEAR_BB, at 2000 (1.5 cm) and 1915 (7.0 cm)

Loch Leir (LEIR)

A total of 11 invertebrate groups were recorded in Loch LEIR (Figure 34). The most frequently occurring groups in the base of the core (ca.pre-1900-1930s, 6.0-4.0cm) were Coleoptera*,* Trichoptera case type 2 and Mandible type 3. Coleoptera and Mandible type (2) remains increase gradually up the core. The accumulation rate of Ephemeroptera*,* Trichoptera and *Sialidae* all show stepped increases associated with a period dated as approximately 1970-80 (2.0-1.0 cm). The accumulation rate of Ephemeroptera*, Sialidae* and mandible type 2 is highest in the surface sediments; at this point they are all higher than at any other point down the core. A single statistically significant shift in the macroinvertebrate stratigraphy is identified by the CONISS analysis, in ca. 1990 (1.0 cm)

11 samples were examined for chironomid remains covering the top 6.5cm of the LEIR_BB core (Figure 35). Between 1850 and present there are two distinct phases in LEIR_BB, that are confirmed by the CONISS analysis. Total chironomid concentrations between 1900 and ca. 1970 are stable or slightly declining. Similarly, to macrofossil analysis a shift can be seen in the chironomid abundance at ca. 1970-1980 (1.5-2.0cm), a distinct increase in chironomid abundance is observed. Total heads almost double from 2.5-3.cm to 2.0-2.5cm. Increases are seen in all taxa (except *Diamesinae*) and particularly in *Tanypodinae* at 2.0cm. *Tanytarsini* are the most prevalent group in the LEIR_BB core, making up on average 40% of the community. *Orthocladiinae* are more prevalent in the bottom of FEAR_BB whilst *Tanypodinae* reach their highest levels at 2.0-0.0cm depth (mean 20% of the community composition compared to mean 7% for 2-7cm).

Loch Talaheel (TALA)

Nine types of invertebrate remains were recorded in TALA_BB (Figure 36); the limited number of samples representing the last 150-200 years makes it difficult to be confident about patterns or trends. Generally, remains are low in the base of TALA_BB between ca. 1900-1950. Ephemeroptera*,* Trichoptera and mandibles types (2) and (5) increase from ca. 1980 (1.5-1.0cm). CONISS analysis identifies a single statistically significant shift in TALA_BB at ca.2005 (0.5 cm).

Chironomid remains in TALA_BB were extremely low compared to other Big Ben sites, a very large amount of sediment needed to be examined in order to locate 50 heads; between 2 and 64 grams of sediment was analysed from TALA_BB compared to means of 1.2, 1.3 and 2.5 from AMHU_BB, FEAR_BB and LER_BB respectively. Between the pre-1850 and 1980s period (at 2.5-1.5cm) chironomid accumulation rate in TALA_BB are consistently low (0.09-2.1 heads per g w/w, Figure 37). At ca. 1980-1990 (1.5cm) there is a distinct shift in TALA_BB as sediment accumulation rate increases (from 0.0061 g cm^{-2} yr^{-1} to 0.0152 g cm^{-2} yr^{-1}), concurrent increases in all chironomid taxa are observed (from a total mean of 0.85 heads per g w/w in 2.0-4.0cm to 6.87 heads per g w/w in 2.0-0.0cm) with the exception of *Diamesinae*, which are no longer present. A single statistically significant shift in the chironomid stratigraphy is identified at ca. 1990 (1.0 cm).

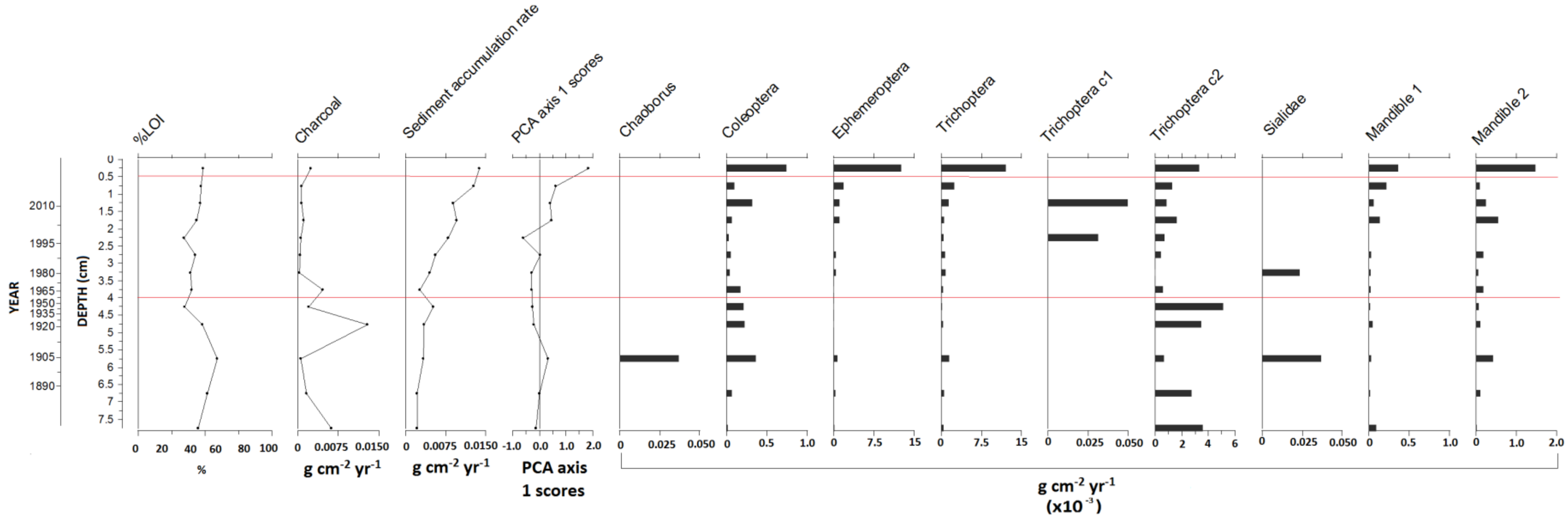


Figure 6.30 Stratigraphic plot of the invertebrate remains in AMHU_BB. Red line indicates the statistically significant splits determined by CONISS analysis

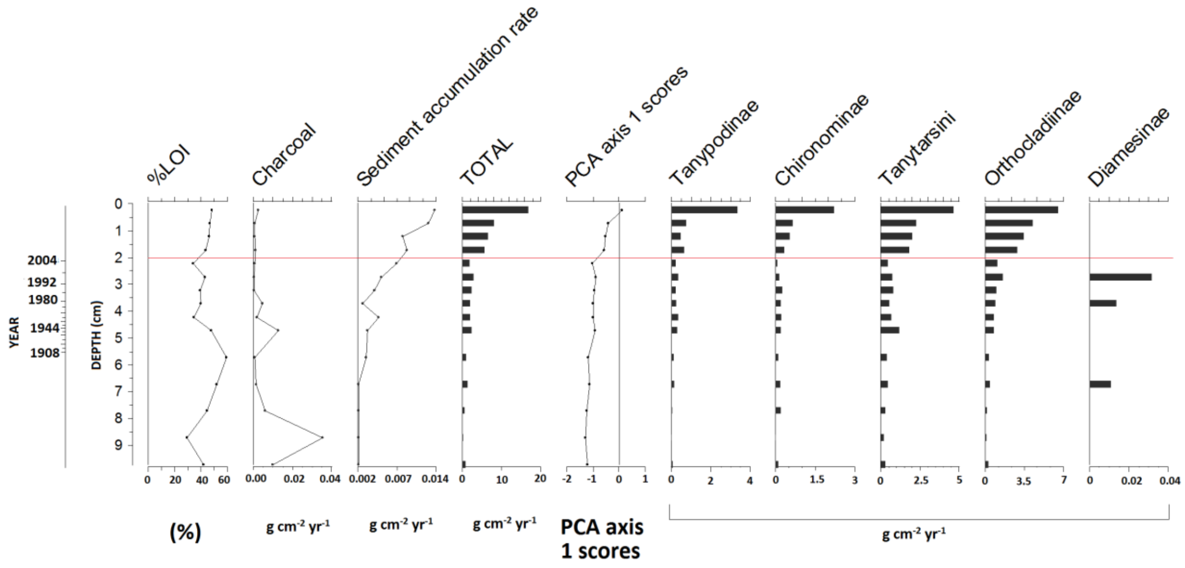


Figure 6.31 Stratigraphic plot of the chironomid remains in AMHU_BB. Red line indicates the statistically significant splits determined by CONISS analysis

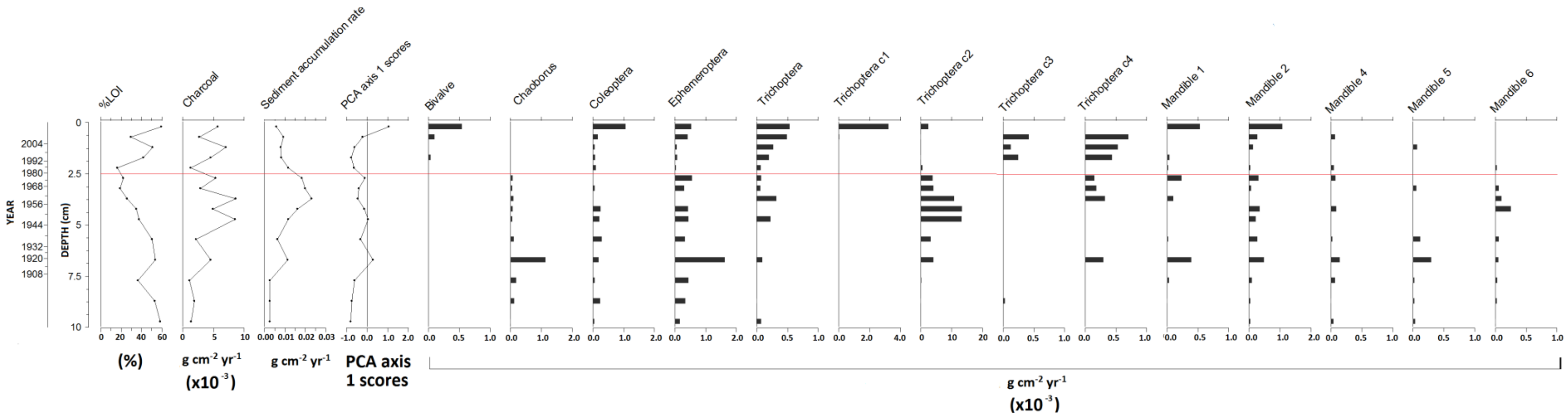


Figure 6.32 Stratigraphic plot of the invertebrate remains in FEAR_BB. Red line indicates the statistically significant splits determined by CONISS analysis

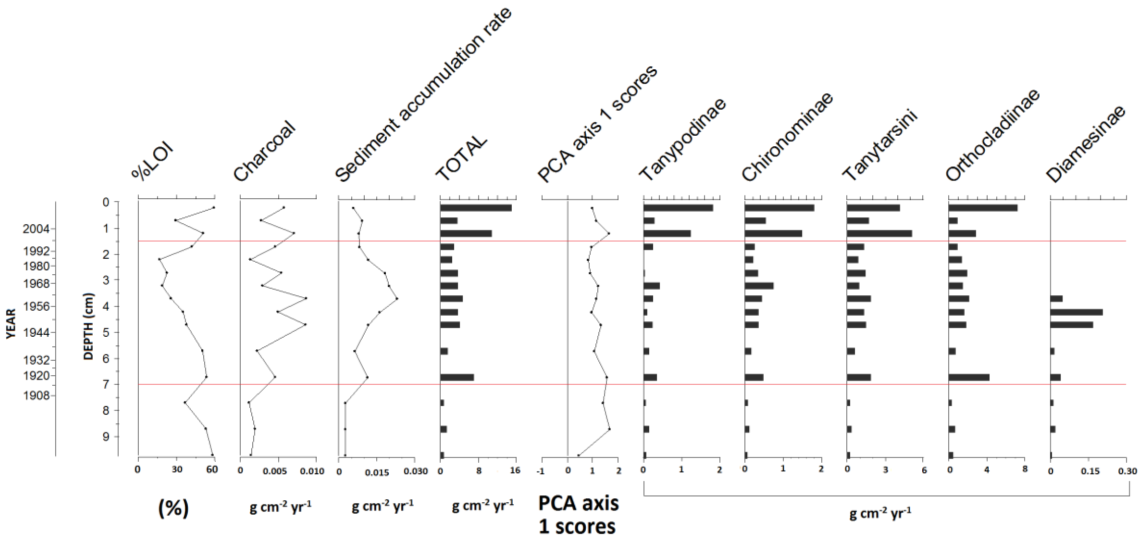


Figure 6.33 Stratigraphic plot of the chironomid remains in FEAR_BB. Red line indicates the statistically significant splits determined by CONISS analysis

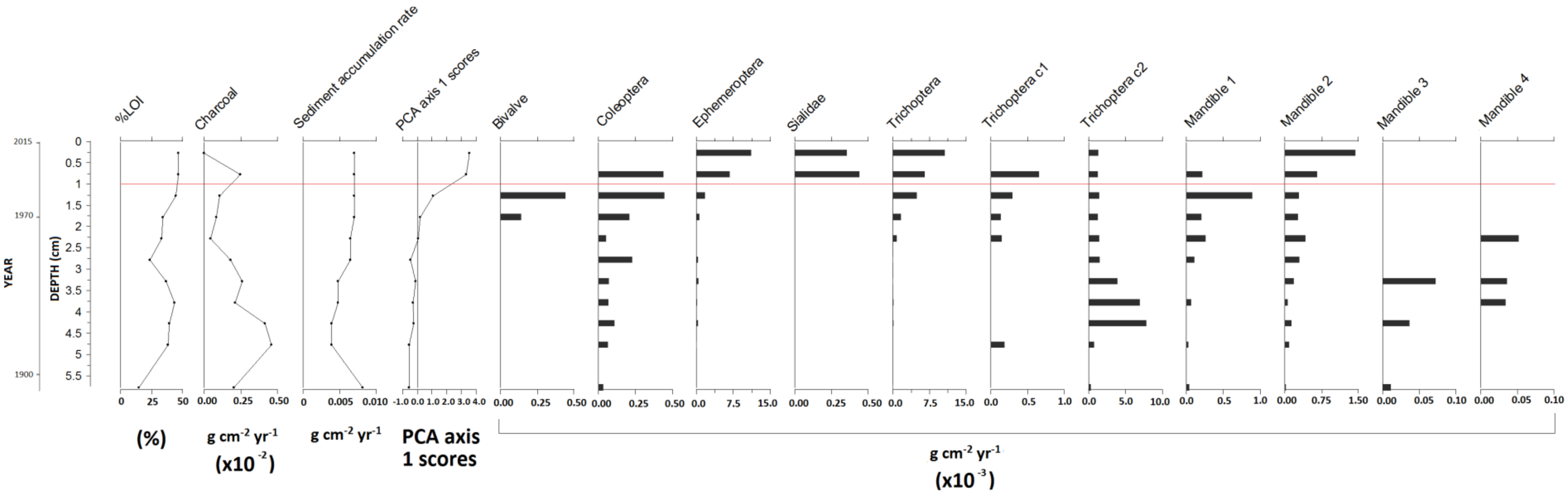


Figure 6.34 Stratigraphic plot of the invertebrate remains in LEIR_BB. Red line indicates the statistically significant splits determined by CONISS analysis

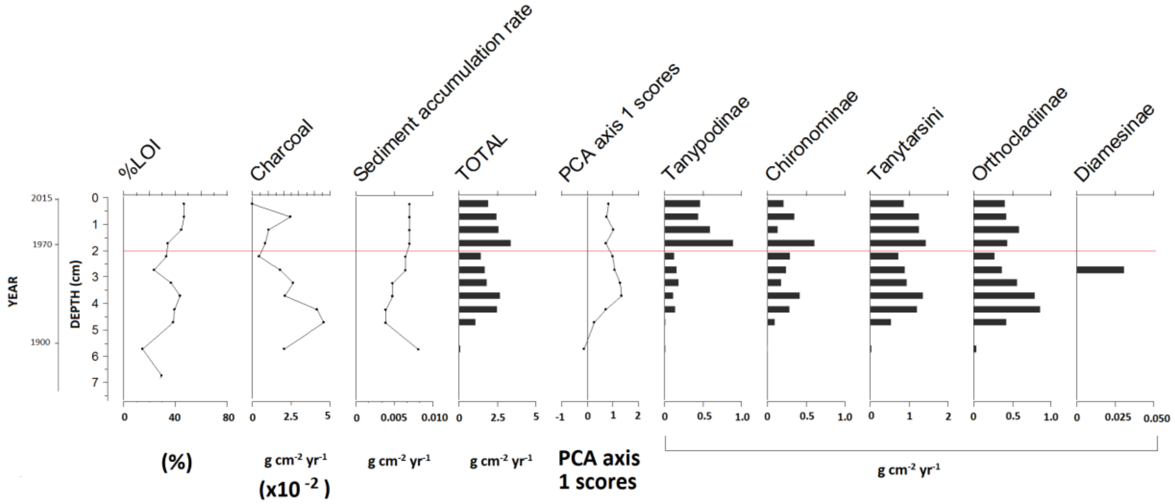


Figure 6.35 Stratigraphic plot of the chironomid remains in LEIR_BB. Red line indicates the statistically significant splits determined by CONISS analysis

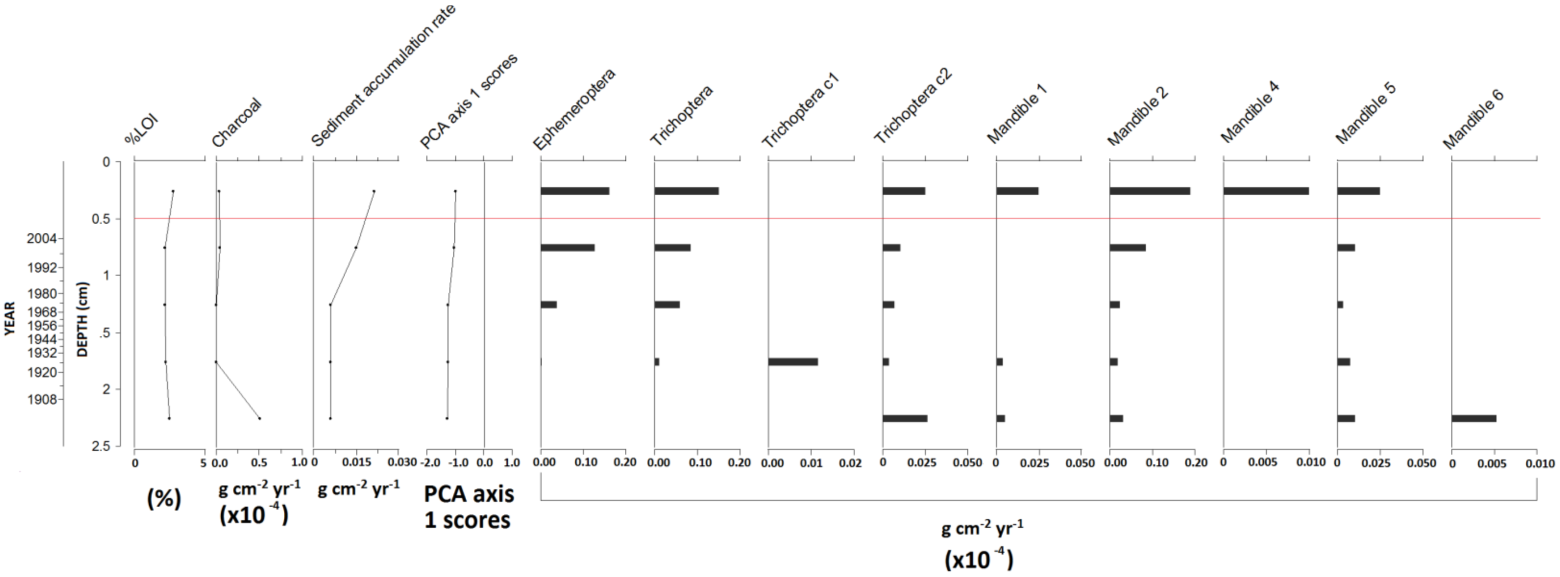


Figure 6.36 Stratigraphic plot of the invertebrate remains in TALA_BB. Red line indicates the statistically significant splits determined by CONISS analysis

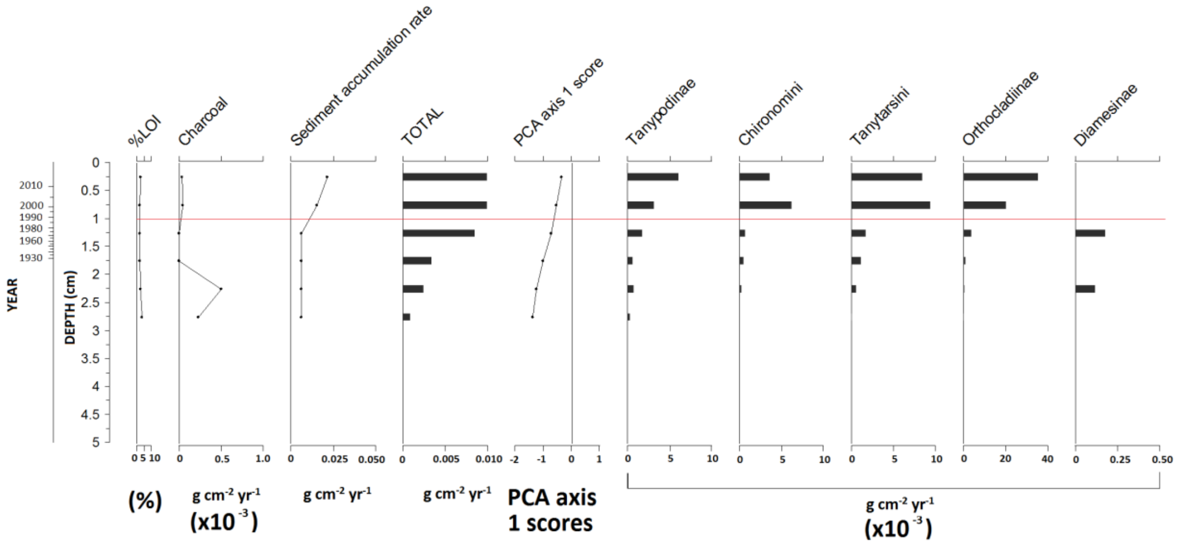


Figure 6.37 Stratigraphic plot of the chironomid remains inTALA_BB. Red line indicates the statistically significant splits determined by CONISS analysis

6.4.1.6.2 Change in invertebrate community composition at all four study sites

PCA of the invertebrate and chironomid communities was used to explore the similarities between sites (Figures 6.38 and 6.39). The first two PCA axis of the macroinvertebrate ordination account for a total of 70.5% of the variation (56.9% PCA 1 and 13.6% PCA 2). There is much overlap in the progression of AMHU_BB, FEAR_BB and LEIR_BB, whilst TALA_BB is distinctly separate, being characterised by a low abundance of all invertebrate groups. AMHU_BB and FEAR show a relatively small amount of change towards communities characterised by Coleoptera and bivalves, whilst LEIR_BB shows a more substantial change, particularly in the post 1980s period. The trajectory of LEIR_BB is similar to AMHU and FEAR during the 1980s and 1990s but post ca. 2000 the invertebrate community of LEIR_BB becomes less similar, being characterised by Ephemeroptera and Trichoptera.

The chironomid communities of the four lochs show some overlap in their tracks, however both FEAR and LEIR are clearly associated with higher abundances of chironomids than AMHU and TALA. The direction of community change is similar in TALA_BB and AMHU_BB, being associated with increasing abundance, whilst LEIR and FEAR move more strongly along PCA axis 2, towards communities associated with *Tanypodinae* sp.

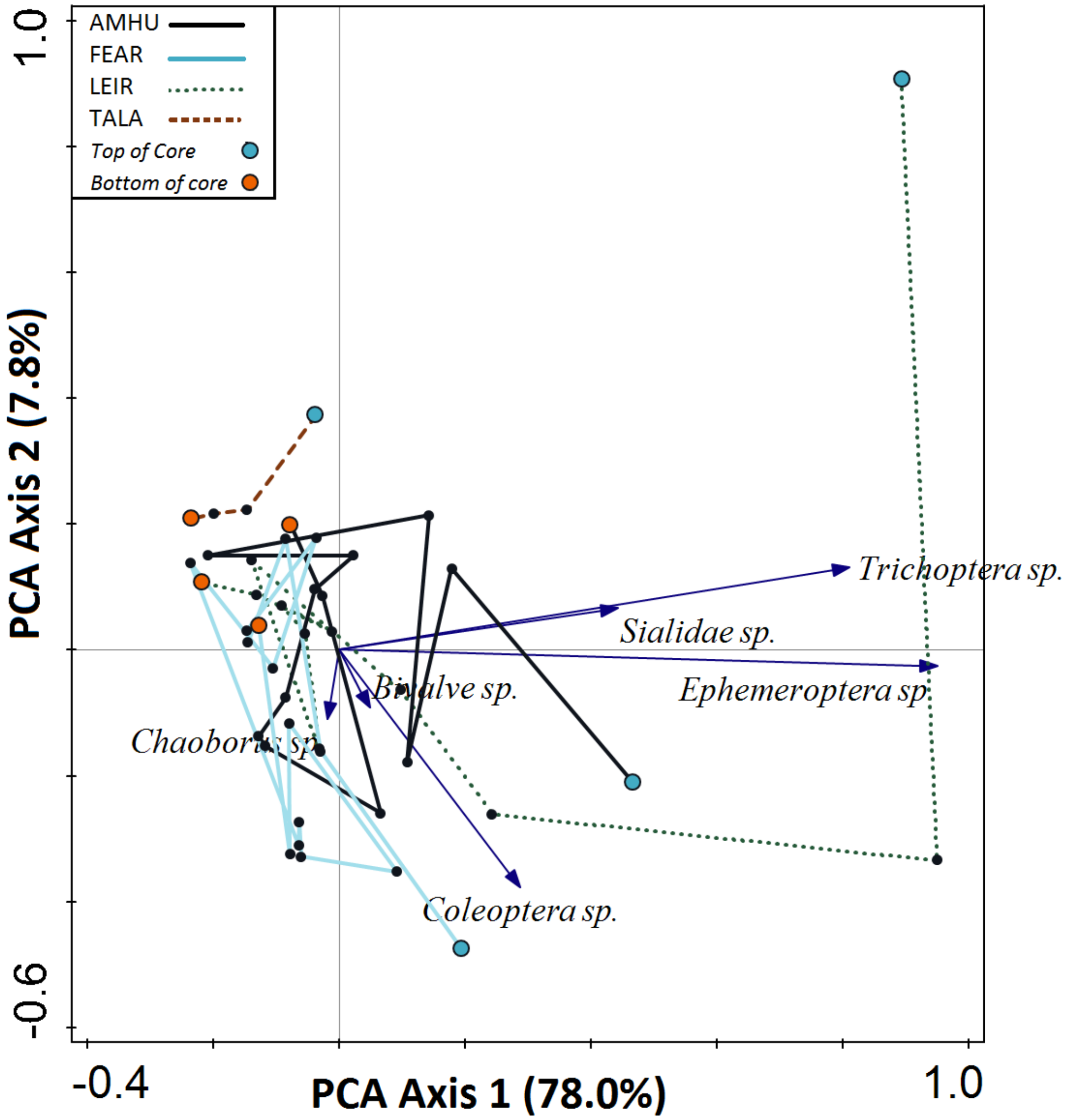


Figure 6.38 Axis 1 and 2 of a PCA of the macroinvertebrate communities of the four lochs over the last 150-200 years.

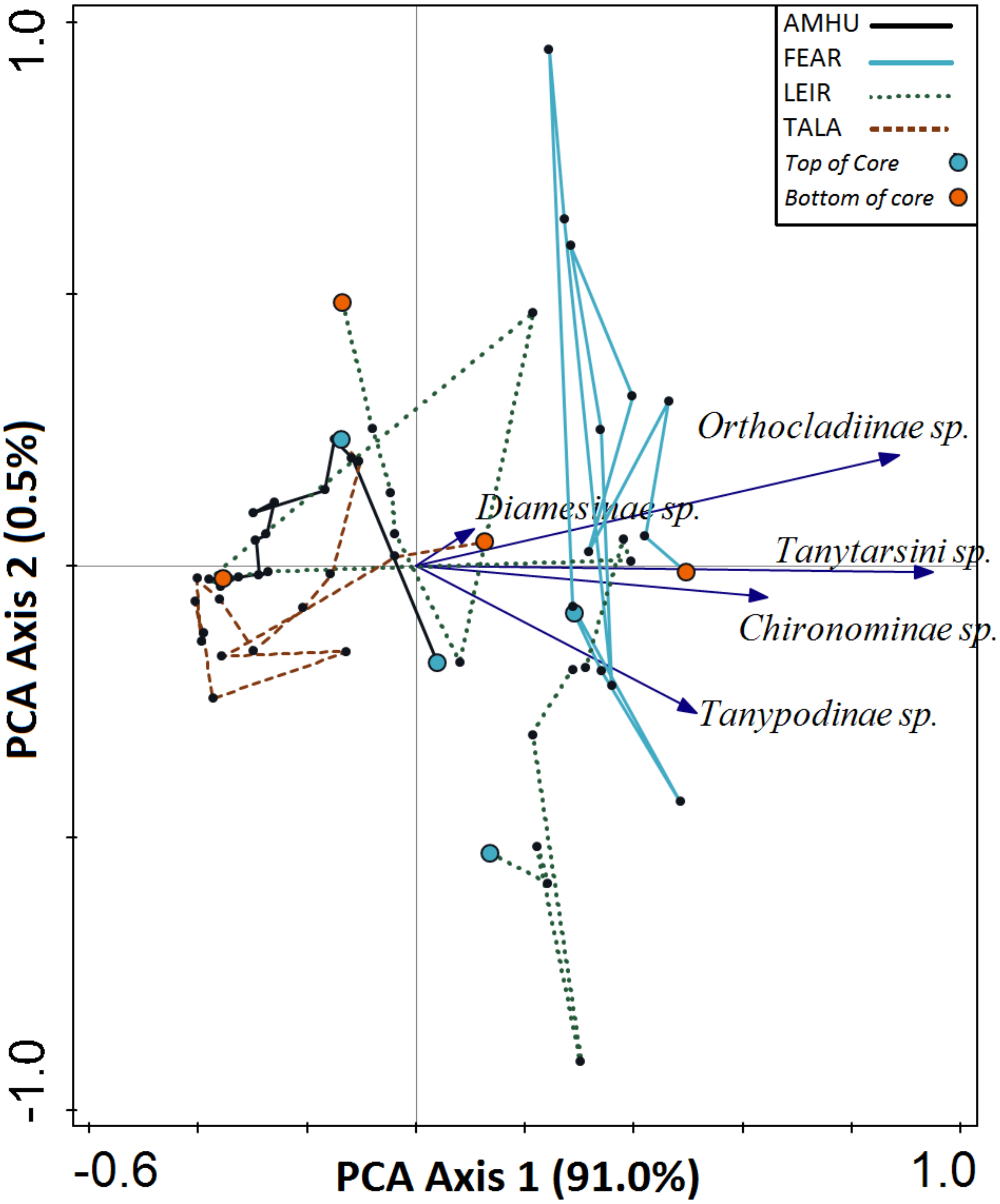


Figure 6.39 Axis 1 and 2 of a PCA of the chironomid communities of the four lochs over the last 150-200 years.

Invertebrate summary

- Between 9 and 14 invertebrate taxa were recorded in the lochs. Bivalves were only recorded in lochs FEAR and LEIR. *Chaoborus flavicornis* was only recorded in Lochs AMHU and FEAR
- Increases in the abundance of most invertebrate taxa were observed at all sites between 1850 and 2015, and typically the number of remains in the surface sediments were substantially higher than at any other point in the cores.
- Ordination of invertebrate communities suggests much similarity in the progression of AMHU_BB, FEAR_BB and LEIR_BB, whilst TALA_BB is somewhat separate and characterised by low abundance of invertebrate remains.
- Generally, increases are observed in the total numbers of chironomids at the sites over the last 150-200 years, with marked increases associated with the 1980s evident in the sites. There is some evidence of a reduction in *Diamesiene* taxa in the surface of the cores.
- PCA analysis of chironomid communities revealed that lochs FEAR and LEIR are associated with higher abundances of chironomids than TALA and AMHU for much of the core length. The direction of change in TALA and AMHU is similar and characterised by increased abundance, whilst the change is also similar at LEIR and FEAR.

6.4.1.7 Site summaries

This section provides an overview of the recent environmental change at each of the four sites. Results of the radiometric dating and timescales covered by the cores are reviewed. Summary stratigraphic plots provide an overview of change for key taxa at each site.

6.4.1.7.1 Loch a'Mhuillinn (AMHU)

- Radiometric dating of AMHU_BB indicates that the last 150 years are represented in the top 7cm. Although the ^{137}Cs profile displays a broad (rather than distinct) peak, it is possible to corroborate the dates from the CRS model using the Pb profile from the XRF analysis of AMHU_1.
- A summary stratigraphic plot of AMHU_BB is shown in Figure 6.40, it shows that:
    i. Total diatom accumulation rate increases steadily from 1900 to ca. 1970. There is a distinct increase in diatom accumulation at ca. 1980s, and between the 1990s and 2015 diatom accumulation rate increased more rapidly almost doubling between 2-1cm (ca. 2005).
    ii. Benthic taxa dominate the diatom species; nutrient tolerant species such as *A. formosa* appear in low numbers between 4.0-0.0 cm depth (1960s to present) and increase towards the top of AMHU_BB, particularly post 2000.
    iii. The remains of all macrophyte taxa increase between 1850 and 2015 with the exception of *Isoetes* sp. which decreases and is only present in low numbers between ca. 1980s and 2015 (3.0 - 0.0cm).
    iv. The accumulation rate of cladocera in samples between 8.0cm and 2.0 cm is low. Between 2.0-0.0 the total accumulation of cladocera is increases distinctly, particularly post 2000.
    v. Most invertebrate groups increase steadily between 1850 and present; at 2cm (post 2000) total chironomid accumulation rate doubles.

6.4.1.7.2 Loch nam Fear (FEAR)

- Radiometric dating was unable to establish clear ^{137}Cs or ^{241}Am peaks, but cross correlation with the Pb profile of FEAR_1 establishes that the age estimates from the CRS model were correct. 1850 was placed at 7.25cm and 1980 at 2.25cm.
- A summary stratigraphic plot of FEAR_BB is shown in Figure 6.41, it shows that:
    i. The total accumulation rate of diatoms increases slightly between 1850 and 2015, with the largest increase in the surface sediments.
    ii. Benthic taxa dominate in FEAR_BB. Nutrient tolerant taxa, such as *A. formosa* are present throughout the period of 1850-2015; distinct peaks occur at ca. 1900, 1970-1980 and the surface sediments.
    iii. The accumulation rate of macrophyte remains in FEAR_BB is highest between 1940-1980s. At 2.5cm (1980s) there is a distinct decline in all macrophyte groups, *Juncus* sp. and Moss sp. are the most prevalent groups in the surface sediments (Figure 42).
    iv. The accumulation rate of cladocera remains are highest between 1940-1980, during this period *Alona* sp. are the most commonly recorded cladoceran remains. At ca. 1980 there is a distinct decline in all taxa.
    v. The majority of invertebrate remains in FEAR_BB follow the same pattern as the macrophytes and cladocera with increases in accumulation rate between 1940 and 1980, however the pattern is not evident for all groups. *Chaoborus flavicans* disappear from FEAR_BB at 2.5cm (1980), similarly *Diamesinae* chironomids are not recorded between 3.5-0.0cm. Conversely *Bivalve* sp., which were not apparent in the lower part of the core, are found between 2.0-0.0cm. Trichoptera sp., Ephemeroptera sp. and Coleoptera sp. all increase between 1980 and 2015, commonly to levels greater than at any other point down core.

6.4.1.7.3 Loch Leir (LEIR)

- Dates for LEIR_BB was established by correlation with LEIR_1 which was ^{210}Pb dated. The cross correlation estimated 1900 at 6.25 and 1970 at 1.75cm.
- A summary stratigraphic plot of LEIR_BB is shown in Figure 6.42, it shows that:
    i. Total diatom accumulation rate increases up the length of LEIR_BB. There is a distinct increase in diatom accumulation rate at 1.5cm (1980s).
    ii. Benthic taxa dominate the core. Nutrient tolerant species such as *A. formosa* and *C. rossi* increase in the surface sediments, particularly between 1.5-0.0 cm (1980).
    iii. *Isoetis* sp. are the most dominant taxa between 6-2 cm, a distinct decline is evident at 1.5-2.0cm. Moss species increase in accumulation rate, particularly at 1.5-2.0cm (1980s-2015). *Najas flexilis* is not present between 1.0-0.0cm.
    iv. Cladocera accumulation rate is low in LEIR_BB between 5.0 and 1.5cm at 1.5cm (1980) there is a substantial increase in cladocera remains.
    v. In the lower part of LEIR_BB the most prevalent invertebrate group is Coleoptera sp. Bivalvia sp. occur between 2.0 and 0.0cm (1970-2015). Between 1980 and 2015 (1.5-0.0cm) Ephemeroptera sp., Coleoptera sp., and Trichoptera sp., all increase substantially. *Chironomid* sp. are low in the base of the core, at ca. 1990 a stepped increase occurs.

6.4.1.7.4 Loch Talaheel (TALA)

- Radiometric dating of TALA_BB was hampered by an absence of a ^{137}Cs peak. Unlike FEAR_BB and AMHU_BB corroboration with the XRF Pb profile from TALA_1 did not provide robust evidence to support the CRS dates and interpretation of findings from TALA_BB must therefore be considered with caution.
- A summary stratigraphic plot of LEIR_BB is shown in Figure 6.43, due to the small number of samples representing the last 150-200 years in TALA_BB is difficult to distinguish trends and/or patterns but in general the results indicate that:
    i. Overall diatom accumulation rate has increased between 2.5-0.0cm. *Fragilaria sensu lato* species dominated the community of TALA_BB and benthic taxa are more prevalent than planktonic species throughout the core.
    ii. *Isoetis* sp.*,* *Lobelia* sp.*,* *Nitella* sp. and *Juncus* sp. are the dominant macrophyte taxa between 2.5-1cm, at 1cm (ca. 1990) *Lobelia* sp. disappears, *Nitella* sp. and *Isoetes* sp. decline and Moss sp. species increase.
    iii. Cladocera remains are low between 2.5-1.5cm; there is a substantial increase in all cladocera taxa at 1.0-1.5cm (ca. 1980s-1990s).
    iv. All invertebrate groups are low between 1.5-2.5cm, increases in all groups occur at 1.0-1.5cm.

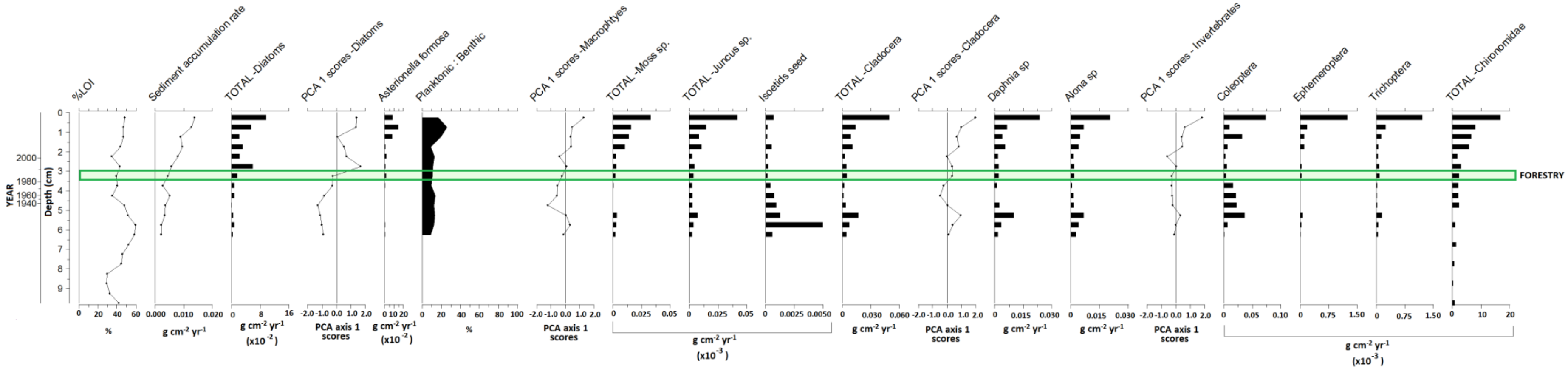


Figure 6.40 Summary stratigraphic plot from AMHU_BB. Green horizon indicates the period of forestry planting.

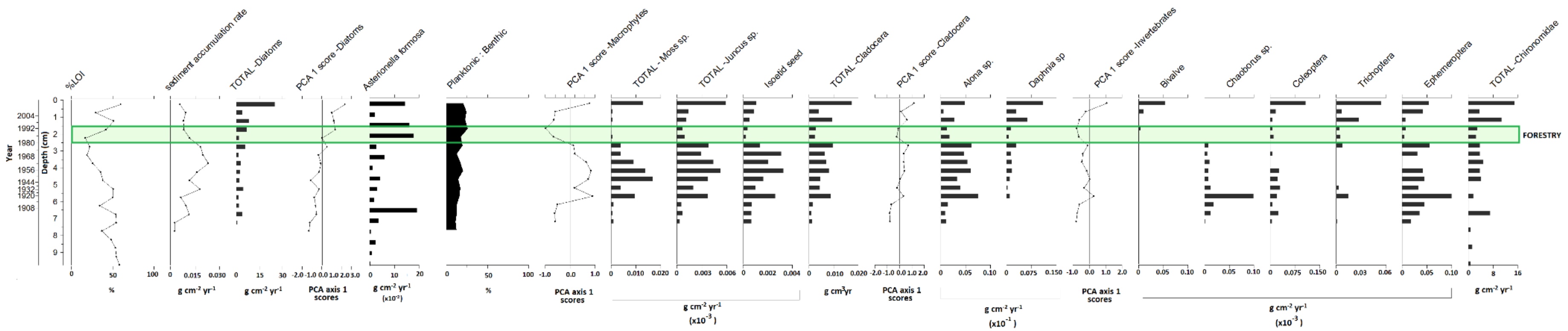


Figure 6.41 Summary stratigraphic plot from FEAR_BB. Green horizon indicates the period of forestry planting.

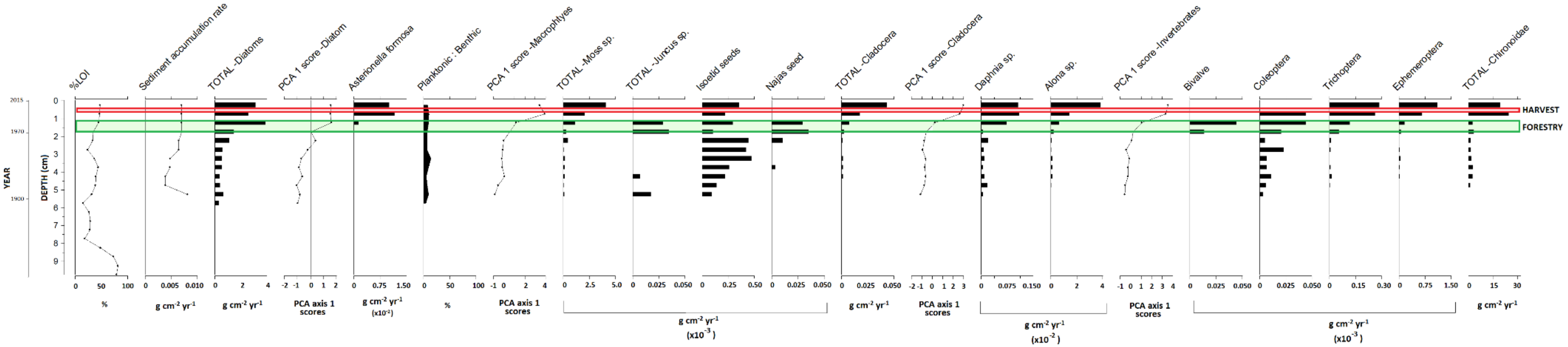


Figure 6.42 Summary stratigraphic plot from LEIR_BB. Green horizon indicates the period of forestry planting. Red horizon indicates timing of forest harvesting

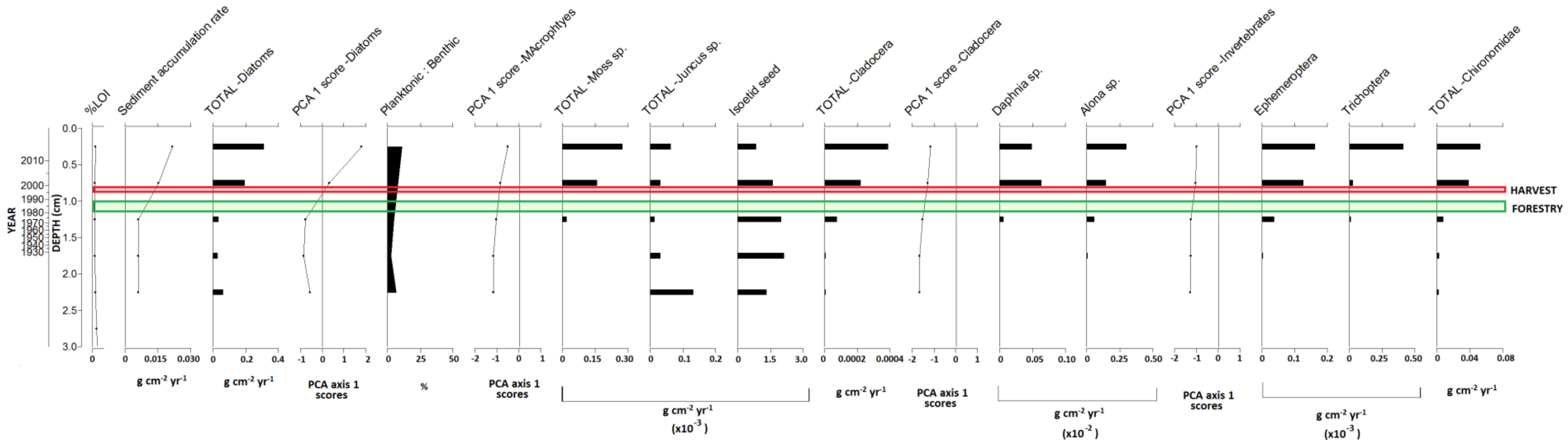


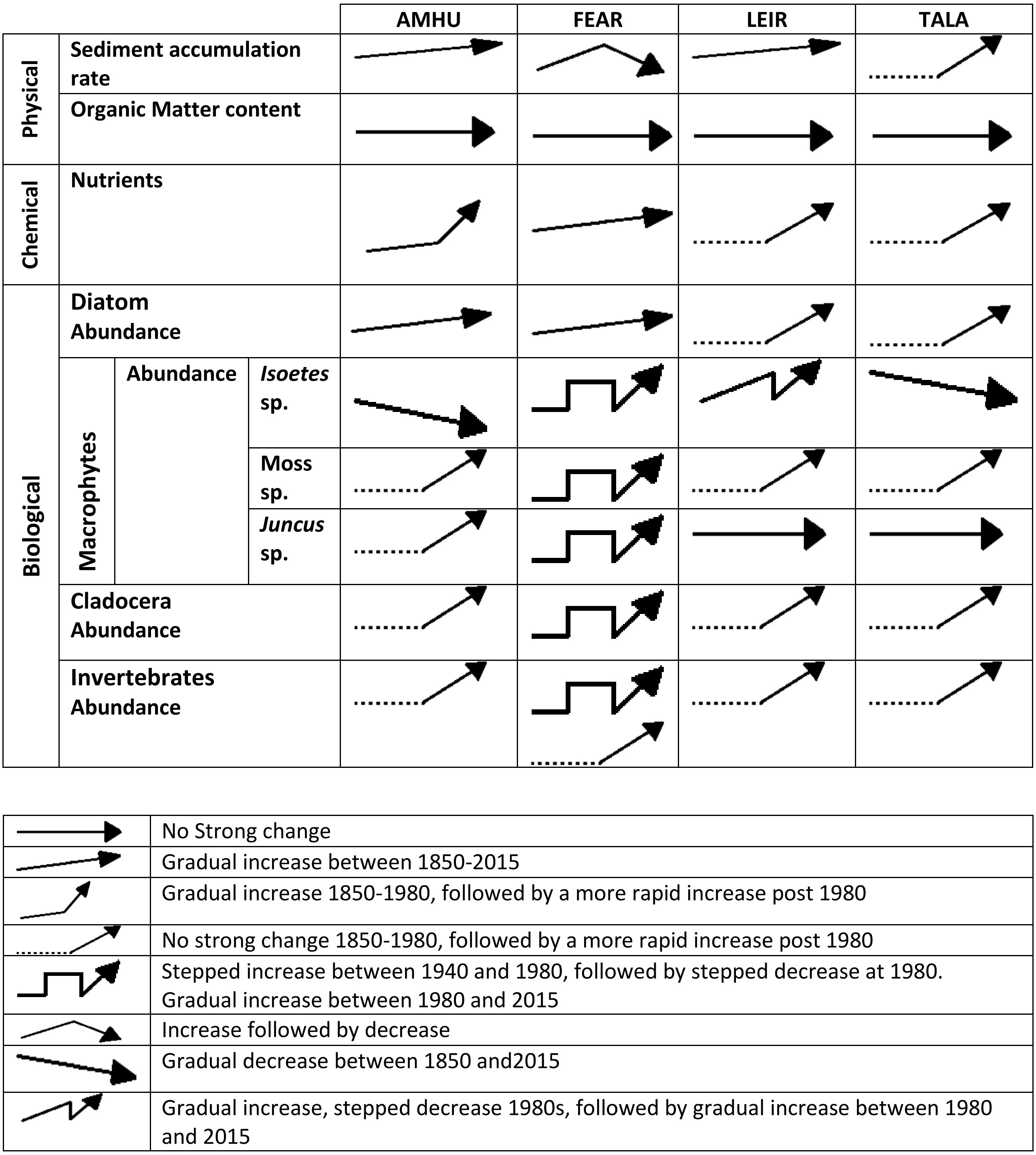
Figure 6.43 Summary stratigraphic plot from TALA_BB. Green horizon indicates the period of forestry planting. Red horizon indicates timing of

6.4.2 Interpretation of palaeolimnological data in the context of common scoter decline

The first aim of this chapter was to provide palaeolimnological evidence of recent environmental change at four Flow Country lochs. Secondly this chapter aims to use these palaeolimnological data to examine two theories for common scoter decline in the Flow Country. A summary of the overall trends observed in the palaeolimnological data are provided in Figure 6.44 and statistically significant splits in the stratigraphic data (identified using CONISS) are illustrated in Figure 6.45.

It has been suggested that brown trout introductions to the lochs or changes in the structure of the brown trout populations already populating the lochs may reduce invertebrate food availability for common scoter. Palaeolimnological evidence will be used to examine the validity of this theory by determining whether there is evidence of fish introductions or change to fish population structure (section i)a and i)b below) and whether consequent reductions in macroinvertebrate abundance occur (section i)c).

Existing literature indicates that coniferous forestry plantations on blanket bog can influence the physical, chemical and biological characteristics of nearby waterbodies. It has therefore been postulated that forestry plantations in the Flow Country may have resulted in changes to physico-chemistry of nearby lochs and that this has resulted in changes to the biological communities that are detrimental to feeding scoter. Section ii) below uses the palaeolimnological evidence to explore the effects of coniferous forestry planted during the 1980s on the lochs.



				AMHU	FEAR	LEIR	TALA
Physical	**Sediment accumulation rate**			↗	⤵	↗	⋯↗
	Organic Matter content			→	→	→	→
Chemical	**Nutrients**			⤴	↗	⋯↗	⋯↗
Biological	**Diatom Abundance**			↗	↗	⋯↗	⋯↗
	Macrophytes	**Abundance**	***Isoetes* sp.**	↘	⎍↗	↗↓↗	↘
			Moss sp.	⋯↗	⎍↗	⋯↗	⋯↗
			***Juncus* sp.**	⋯↗	⎍↗	→	→
	Cladocera Abundance			⋯↗	⎍↗	⋯↗	⋯↗
	Invertebrates Abundance			⋯↗	⎍↗ ⋯↗	⋯↗	⋯↗

→	No Strong change
↗	Gradual increase between 1850-2015
⤴	Gradual increase 1850-1980, followed by a more rapid increase post 1980
⋯↗	No strong change 1850-1980, followed by a more rapid increase post 1980
⎍↗	Stepped increase between 1940 and 1980, followed by stepped decrease at 1980. Gradual increase between 1980 and 2015
⤵	Increase followed by decrease
↘	Gradual decrease between 1850 and2015
↗↓↗	Gradual increase, stepped decrease 1980s, followed by gradual increase between 1980 and 2015

Figure 6.44 A summary of the findings from Chapter 6, showing the predominant trends.

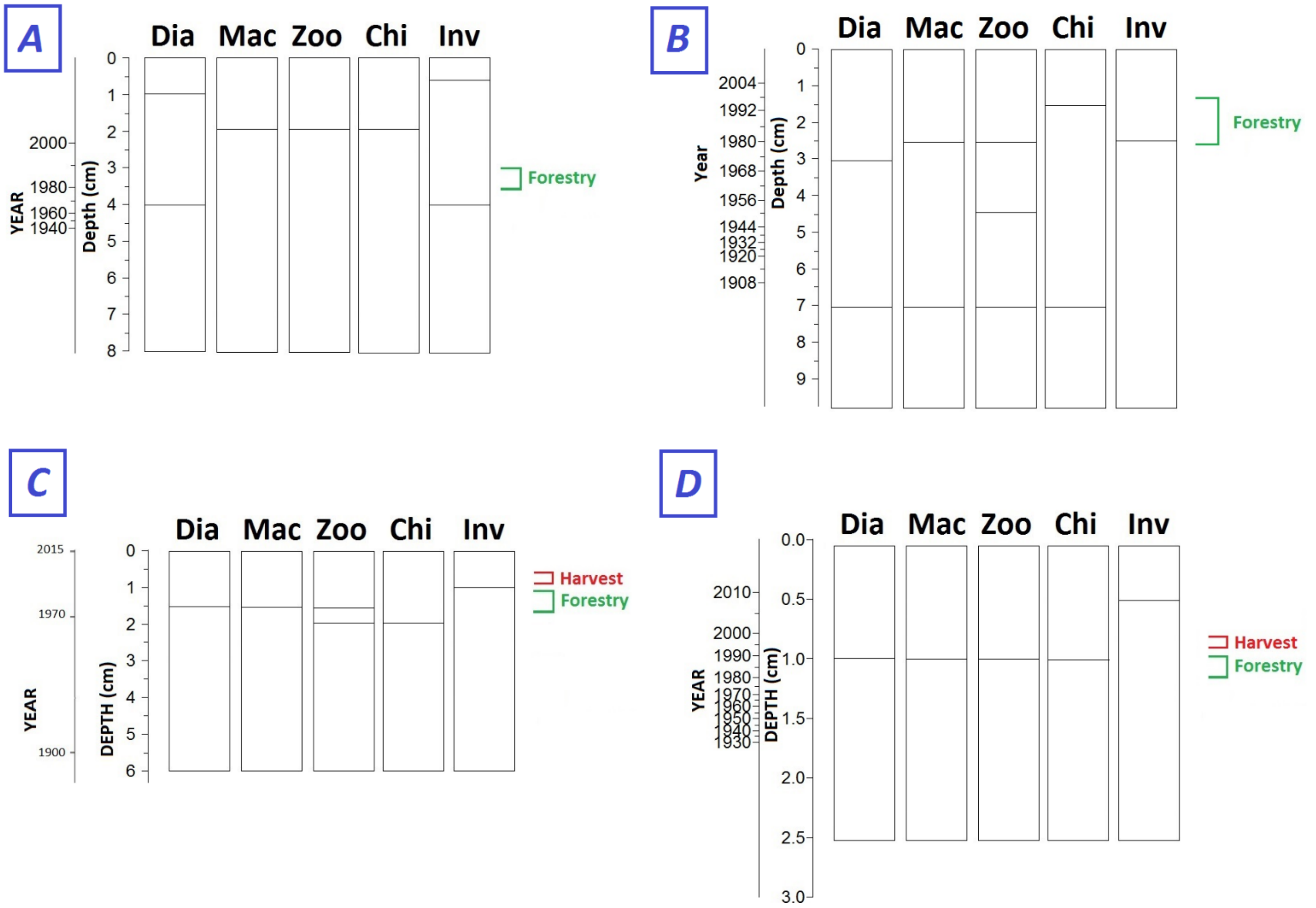


Figure 6.45 Summary of statistically significant splits in the stratigraphies of diatom (DIA), macrophyte (MAC), zooplankton (ZOO), chironomid (CHI) and macropinverterbate (INV) groups at AMHU (A), FEAR (B), LEIR (C) and TALA (D). Periods of forestry planting (Forestry) and harvesting (Harvest) are indicated.

i) *Is there evidence of change in the fish (brown trout) populations at the four lochs, and if so what are the implications for macroinvertebrate abundance?*

It has been suggested that brown trout populations in Flow Country lochs have been altered in recent times. This alteration is thought to be due to either brown trout introductions at previously fishless sites or because of decreased fishing pressure from anglers. In either scenario, the result could be decreased invertebrate food availability as a consequence of trophic cascade effect. It is theorised that this could be detrimental to common scoter who are relying on the same invertebrate food resources.

a. *Can fish scale evidence be used to determine whether fish introductions have occurred at the lochs?*

No historic records documenting fish introductions could be identified to establish the dates of fish stocking events in Flow Country lochs, therefore palaeolimnological data were used to determine whether fish introductions had taken place and when. A wide bore Big Ben corer was used to attempt to establish the presence of fish from scale remains; the technique has successfully demonstrated changes in fish populations in shallow lakes, for example in the case of fish kill events (Sayer *et al.,* 2016). By examining fish scale remains it is possible to determine the colonisation date of the lochs by fish, and additionally make inferences about the size and age of fish in the population. However, there was no direct evidence of brown trout populations from scale remains in any of the four cores despite all four sites being known to currently contain brown trout. The lack of fish scale remains in sites known to contain trout is surprising, but could result from low fish densities. It is unlikely that the remains were undetected or degraded as other smaller and less robust macrofossil remains were found in the cores.

b. *Do other macrofossil indicators provide evidence of fish introduction at the lochs?*

Where evidence from fish scale remains is lacking, fish presence can also be established indirectly by examining species sensitive to fish predation, such as

Chaoborus sp. or *Daphnia* species. Previous palaeolimnological studies have demonstrated the suitability of using C*haoborus* sp. and/or *Daphnia* sp. disappearance as an indicator of fish presence (Jeppesen *et al.,* 2002; Sayer *et al.,* 2016; Uutala, 1990).

The remains of C*haoborus flavicornis* were detected in the lower part of one core (FEAR_BB), and disappeared at ca. 1980. Fish introductions to Flow Country lochs are believed to have occurred primarily around the latter part of the 19th century and early 20th century; principally in response to increased interest in fishing pursuits on sporting estates (Hancock per. comm.). If the disappearance of C*haoborus* sp. remains in Loch FEAR are indicative of a fish introduction it occurs much later (1980) than would typically be expected. Whilst this might still appear plausible for a remote loch in the Flow Country, Loch FEAR is positioned close to the Altna breac railway station and the old Lochdhu hunting lodge and hotel, both of which allow easy access to the site for anglers, and would have made it a priority site for earlier introductions. Other proxies in Loch FEAR show an unusual trend, that is not observed in the other study sites, there is a step increased in all groups in 1940 followed by a stepped decline in 1980 (Figure 6.44). An outlet weir is present at Loch FEAR; however, no information was obtainable concerning when the structure was installed or when it more recently failed. It is possible that the changes, observed in multiple taxa are due to changes in the water level of the loch during this time. This theory is somewhat supported by the ecology of *Chaoborus flavicans,* which have been shown to respond to changes in water level in addition to fish predation pressure. In a Finnish study Luoto and Nevalainen, (2009) found *Chaoborus flavicornis* to be more abundant in deeper lakes (2-7m) compared to shallower (1-2m) ones. As fish stocking in Loch FEAR in the 1980s appears unlikely it is possible that the disappearance of *Chaoborus* sp. from Loch nam Fear is associated with a reduction in water level (following the weir failure) rather than a fish introduction.

None of the other lochs contained *Chaoborus* sp. remains in the core with the exception of one mandible in AMHU at 5.5-6cm depth, (ca. 1905); the indirect evidence of fish introductions from *Chaoborus* sp. remains at AMHU is not conclusive.

Previous research has also used changes in zooplankton populations to indicate fish introductions; typically by reductions in large planktonic taxa (Davidson *et al.,* 2010; Jeppesen *et al.,* 2002, 1996). Morphological changes (such as reduced epphipia size or mucros length) have also been associated with fish introductions and changes in fish population structure. None of the sites in this study show declines in planktonic *Daphnia* sp. epphipia which would be indicative of fish introductions. The eppihipia size and mucros length of Cladocera were not assessed in this study and it is therefore possible that subtle changes in brown trout population structure may have been overlooked.

c. *Is there evidence of a change to macroinvertebrate communities that could be associated with brown trout introductions?*

It is hypothesised that changes to brown trout populations in Flow Country lochs could be effecting macroinvertebrate populations in a manner that is detrimental for competing species, such as common scoter. There is no strong direct or indirect evidence that fish introductions have taken place in the four sites, although it is acknowledged that subtle changes in population structure may have been undetected. It is therefore important to examine whether changes in invertebrate abundance or composition have occurred that could be associated with either introductions or changes in population structure. The abundance of macroinvertebrate remains at the four study sites has increased since ca. 1850, with noticeable increases in abundance occurring around the 1980s period (Figure 6.44). The composition of the invertebrate communities at the sites has also been shown to have been relatively stable until the 1980s-1990s. Changes in abundance and community composition take place later than changes in fish communities are thought to have occurred. The changes in invertebrate communities observed since the 1980s (when common scoter decline began) indicates an increase in abundance, particularly groups such as Coleoptera, Trichoptera and Ephemeroptera, all of which are consumed by both brown trout and common scoter (Bengtson, 1971; Cramp and Simmons, 1977; M Hancock *et al.,* 2015). Evidence from macrophyte and diatom communities also indicates an increase in nutrients during this period, suggesting changes in nutrients rather than fish populations are driving the observed change in community composition since the 1980s.

ii) Are the effects of afforestation (in the 1980s) evident at the four lochs?

Drainage and planting of the forestry around the study lochs occurred between 1985 and 1989. Removal of trees is known to have taken place in 2003 (Loch LEIR) and 1999 (Loch TALA), whilst the forestry at Loch FEAR remains. The nearest forestry to AMHU is more than 0.5km away and was planted between 1986 and 1989. Planting coniferous forestry in the catchments of peatland lochs has been shown to increase sediment accumulation rates (Littlewood *et al.,* 2010) and nutrients inputs (due to fertiliser additions, (Cummins and Farrell, 2003a; Renou *et al.,* 2000)) and cause acidification (Nisbet and Evans, 2014). Changes to invertebrate and zooplankton communities have also been documented following forestry plantations (Drinan *et al.,* 2013b, 2013c) which could have implications for breeding scoter. Big Ben cores in this chapter were used to assess whether changes to the physical, chemical and/or biological characteristics have taken place as a consequence of forestry.

a. Does geochemical analysis of the cores indicate that there has been a change in sedimentation rates or sediment composition that could be a consequence of increased erosion associated with the 1980s?

Palaeolimnological data indicates that there has been an increase in sediment accumulation rate at three of the four study sites (AMHU, LEIR and TALA). However, the patterns are not consistent. Whilst Loch TALA does show increases consistent with the timescale of forestry Lochs LEIR and AHMU show increases in sediment accumulation rate and organic matter occurring over much of the twentieth century, and at FEAR there is an increase in sediment accumulation rate followed by a decrease post 1960 (Figure 6.44).

The changes in organic matter concentrations in the cores for the last 150 years do not indicate strong patterns, although gradual increases in organic matter content are shown in Lochs FEAR and LEIR post 1980 and post 2000 in AMHU. Overall the evidence is only weak that the forestry has effecting the physical characteristics of the lochs.

b. *Is there evidence of changes to water chemistry during/or since the 1980s?*

There is strong evidence that the chemistry of the lochs has changed since the time of forestry activities in the catchments of the lochs. An increase in nutrient tolerant diatom species (such as *Asterionella formosa*) has occurred and sensitive macrophyte (*Isoetes* sp.) and chironomid taxa (*Diamesiene*) have shown concurrent declines. Although there is some evidence of lochs becoming more productive over the course of the twentieth century, (as evidenced by overall increases in abundance of many taxa) (Figure 6.44), statistically significant shifts are identified during or in the years following forestry planting (Figure 6.45).

c. *Has the abundance and/or composition of invertebrate communities changed since the 1980s?*

Palaeolimnological analysis indicates a statistically significant change in the biological communities of lochs, particularly during and/or post the 1980s (Figure 6.45). The abundance of diatom, cladocera, macrophyte and invertebrate remains increases over the twentieth century, and these increases are accelerated post 1980s (Figure 6.44). In FEAR, LEIR and TALA the significant changes in all groups occur during the period of forestry plantation. At loch AMHU, where forestry plantation is more than 0.5km distance, a statistically significant shift occurs later (ca. 2000 onwards) and there is also evidence of a shift in diatom and invertebrate groups at ca. 1970. At loch FEAR there is evidence of a shift in all groups during the 1980s. At both LEIR and TALA, where the shift in invertebrate populations occurs later than for the other groups, forestry has been harvested at both of these sites

6.5 Discussion

This chapter aimed to explore two theories for common scoter decline in the Flow Country. Firstly, that afforestation and drainage of the Flow Country catchments in the 1980s may have altered the physico-chemistry of the lochs. It was postulated that afforestation of blanket bog surrounding the scoter breeding lochs could have adversely affected the physical loch structure and/or invertebrate food supply for common scoter. Alternatively, the second theory centred around the idea that the competitive balance between brown trout and scoters may have altered in recent decades, either as a result of decreased fishing pressure or because of fish stocking at previously fishless sites. Common scoters compete with brown trout for food and therefore changes in the abundance or population structure of brown trout could have resulted in reduced invertebrate abundance which could be detrimental for common scoter.

The palaeolimnological evidence from this chapter demonstrates that a gradual increase in nutrient availability has been occurring in the four study sites between ca. 1850 and 1980. A distinct increase in productivity is evident at all sites during the ca. 1980s. Between the 1980s and present, trends of increasing productivity are accelerated, with increases being larger and more rapid between 1980 and present than between ca. 1850 and 1980. The increases in productivity could be attributed to a number of anthropogenic activities that have been shown to influence peatland catchments including; drainage, grazing of livestock, forestry, rotational burning and atmospheric deposition (Rydin and Jeglum, 2013). The potential mechanisms and pathways of increasing nutrient availability in peatland lakes will firstly be discussed. This will be followed by a discussion of the implications of increasing productivity for breeding common scoter and an evaluation of the palaeolimnology approach to species decline research.

Mechanisms driving recent increases in productivity at four Flow Country lochs

i) Atmospheric deposition

Ombrotrophic bogs, like the Flow Country, receive the majority of their nutrients from atmospheric deposition, being largely disconnected from lateral movement of mineral rich waters (Rydin and Jeglum, 2013). Anthropogenic emissions of fertilising compounds such as nitrogen oxides (NOx) and ammonium (NH_4^+) have increased since industrialisation, as a result of increases in vehicle emissions, industry and domestic combustion (Jones *et al.,*2014). The deposition of these nutrients onto habitats that are adapted to very low N inputs can substantially effect N cycling within the system and result in changes to species composition and abundance (NEGTAP, 2001, Carroll *et al.,*1999). The exact pathways by which N deposition affects freshwaters is difficult to establish due to the interactions taking place throughout the N cycle in both the terrestrial and aquatic systems (NEGTAP, 2001). In addition to which, the effects of atmospheric N deposition can be further compounded by other more localised anthropogenic land management practices such as burning, grazing and drainage (Holden *et al.,* 2007). Palaeolimnological studies are able to demonstrate change at remote, low impacted sites that is hypothesised to have been in response to N deposition. The floristic change observed in communities such as diatoms has been shown to be rapid and to far exceed changes resulting from natural variability and/or climate change (Wolfe *et al.,* 2001 and 2006). Although the Flow Country is considered a low deposition region of the UK, in such low N-limited systems the effects of even modest increases in N availability has the potential to have more pronounced influences (Catalan *et al.,* 2013). The floristic changes in diatom communities observed in the current study are similar to those described in other lakes where N deposition is suspected, with increases in taxa such as *Asterionella formosa* in addition to overall increases in diatom biomass (Wolfe *et al.,*2006). It is possible therefore, that the gradual increases in nutrient availability at the study sites between ca. 1850 and 1980 are a result of atmospheric N deposition. The rapid changes observed post ca. 1980s, when emissions caps resulted in decreases in atmospheric nitrogen sources, suggest that other more localised factors, such as land use, could be influencing the lochs during these more recent times.

ii) Land-use

Drainage

The drainage of peatland habitats changes wetland bog systems into terrestrial environments that can be more easily used for anthropogenic services such as plantation forestry and grazing. The drainage of peatlands to increase their anthropogenic value has occurred for many hundreds of years, but has increased in both scale and extent in recent times as drainage machinery and technology has developed. The International Mire Conservation Group estimates total European losses of peatland to drainage of 130 000km^2, with several countries having lost up to 80% of their peatland. In the UK it is estimated that approximately a quarter of peatlands have been drained for use by agriculture (12%), forestry (13%) and peat extraction (<1%) (Rydin and Jeglum, 2013). Approximately a quarter of Flow Country sites surveyed in the mid-1980s had evidence of some drainage that was not associated with forestry activities (Lindsay *et al.,* 1988). Such drainage has been shown to increase run off and decrease the level of the water table, resulting in increased peat desiccation, shrinkage and air flow (Conway and Miller (1960) and Lindsay *et al.,*(1988)). Increased aerobic decomposition in peats, as a result of this increased air flow, increases the mobilisation and loss of minerals and nutrients (Holden *et al.,* 2004). These mobilised nutrients can be transported to nearby streams and lochs affecting their water quality (Holden *et al.,* 2004). Typically, large increases in ammonium (NH_4^+) have been observed (Lundin, 1994 and Miller *et al.,* 1996) in addition to increases in Ca, Mg, K and DOC (Sallantaus 1995, Miller *et al.,* 1996 and Astrom *et al.,* 2001). Studies examining nutrient release following peatland drainage have found that the export of nutrients is typically short-lived (Holden *et al.,* 2004). However, the timescales over which nutrient release from drainage ditches could be affecting nearby open waterbodies has not been the focus of long term study. The affects of extensions to the ditch networks together with the long-term influences of peat desiccation and degradation are therefore not well understood. Ditches are visible around several of the study sites from aerial imagery and could be a key pathway for nutrient transport into Flow Country lochs.

Grazing and burning

Grazing is one of the most common uses of peatlands in Europe and can be carried out at low densities without the need for drainage or fertiliser addition (Lindsay *et al.,* 1988). The potential impacts of grazing on the open waterbodies of peatlands is likely to be minimal. The majority of nutrients produced by livestock are obtained from the peatland itself and therefore little additional nutrients are likely to be added. However, grazing is often combined with rotational burning which is used to stimulate the growth of grasses and/or provide habitat suitable for species of game birds and deer. In Britain, burning of peatland is a widespread practice that has been shown to impact upon nutrient cycling, hydrology and surface vegetation (Holden *et al.,* 2007; Laubhan, 1995; Maltby *et al.,* 1990; Ward *et al.,* 2007). During the fire, nutrients and volatile materials (such as carbon, nitrogen, sulphur and cations of potassium, magnesium and calcium) are lost via the smoke and ash. Accumulation of ash will occur at the site of the fire itself, but has also been found to travel significant distances away carried by wind (Lindsay *et al.,* 1988). The absorption of nutrients from the ash at the site of the fire depends on the severity of fire itself and the extent to which the surface *Sphagnum* has been degraded. Severe degradation can result in a net loss of nutrients as severely damaged *Sphagnum* is unable to reabsorb nutrients from deposited ashes. The fire can also cause a deposition of hydrophobic waxes, which creates a water repellent film on the peat surface. This results in a reduction of the downward leaching of nutrients into the lower layers of the peat and can lead to increased surface runoff (Lindsay *et al.,* 1988; Ramchunder *et al.,* 2009). Increases in nutrient availability combined with increased surface runoff and a lowering of the water table can result in localised increases in nutrients. The paleolimnological data from this chapter provide some evidence to suggest that fire may have resulted in periodic increases in erosion and nutrient release. There are several occasions when peaks in charcoal counts occur at the same time as increases in both sediment accumulation rate and invertebrate and diatom abundance. However, the pattern is not consistent suggesting other factors may also be contributing to nutrient increases.

Plantation Forestry

Whilst gradual increases in productivity between ca. 1850 and 1970 appear most likely to be a result of atmospheric deposition, the stepped increased in nutrient tolerant taxa and overall abundance of both algae and invertebrates in the 1980s strongly suggest that forestry is affecting the study sites. Plantation forestry in the Flow Country primarily consists of non-native conifers; Sitka spruce (*Picea sitchensis*) and Lodgepole pine (*Pinus contorta*). Ploughing, drainage and fertiliser application are typically required for plantations to be successful on deep peat and have all been shown to affect the physical, hydrological and chemical characteristics of nearby waterbodies (Kentämies 1981, Miller *et al.,*1996, Prevost *et al.,*1999, Cummins and Farrell 2003, Ramchunder *et al.,*2009, McElarney *et al.,*2010 and Drinan *et al.,*2013a,b). Ploughing to create a series of furrows and ridges on which to plant new trees is commonly carried out to facilitate tree growth in water saturated peatland soils. The process has been shown to increase surface water runoff during the initial stages (Conway and Miller, 1960 and Burke, 1967). This can be particularly problematic for nearby watercourses if combined with fertiliser application, as excess nutrients are more readily transported into the surrounding catchment. Peat degradation resulting from ploughing has also been shown to result in further nutrient release as aerobic decomposition increases nutrient availability (Holden *et al.,* 2004 and Ramchunder *et al.,* 2009). At the time of planting, in addition to ploughing, a drainage network is also commonly installed to further reduce water retention and enable a more successful crop. Drainage can facilitate the transport of water over greater distances than ploughing alone, transporting nutrients more extensively across the catchment. Fertilisers are commonly applied at the time of planting to relieve deficiency, but can also be added later to facilitate further growth. Frequently used fertilisers are potassium, phosphorus and nitrogen based compounds (Renou and Farrell, 2005). Phosphorus is particularly mobile in peatland soils and substantial amounts of phosphorus can be lost to proximal waterways as run-off following application (Kenttämies, 1981; Renou *et al.,* 2000). Turkia *et al.,* (1998) used palaeolimnological techniques to examine changes in six small Finnish lakes, affected by forestry and were able to identify changes in diatom community composition associated with both ditching and fertilisation events, particularly signs of eutrophication. The extent of the nutrient enrichment was found to vary between sites, as was the case in the Flow Country sites examined in this chapter, and was probably due to differences in geology and hydrology.

Once established the trees in coniferous plantations have also been shown to exacerbate nutrient uptake by peatland soils, by efficiently scavenging atmospheric nitrogen pollutants and sea salts, increasing base cation uptake and creating an acidic surface layer on the soils (Nisbet and Evans, 2014). It is possible that the continued increases in productivity observed in the study sites since the time of forestry planting are the result of forestry scavenging and depositing atmospheric nutrients in the areas around the study sites.

Lochs Leir and Talaheel both had areas of deforested plantation close by, although it was unclear whether the deforested areas close to Talaheel were indeed within the catchment of the loch itself. The process of forest harvesting can also result in the release of nutrients into nearby water courses. Increases in levels of nutrients and alteration to pH, conductivity, dissolved oxygen, temperature and suspended sediments have all been demonstrated for waterways adjacent to felling (Finnegan *et al.,* 2014). O'Driscoll *et al.,* (2013) reported substantial changes to invertebrate communities' post felling, with increases in chironomid abundance and simultaneous decreases in macroinvertebrate diversity and species richness; however, diatom communities were not significantly affected by clear felling events. Similarly Räsänen *et al.,* (2007) used a palaeolimnological approach to assess the effects of forestry harvesting in small boreal lakes in Sweden and observed only small changes in diatom communities, mostly related to changes in species abundance rather than species composition. However, studies of Irish peatlands have demonstrated that forestry can have a significant influence on the biological communities of proximal waterbodies including cladocera (Drinan *et al.,* 2013b) and fish (Graham *et al.,* 2014). The results of the current study indicate that sites with minimal or possibly no catchment forestry (e.g. AMHU and TALA) still show signs of increased nutrient availability, post 1980. Whilst the gradual increases prior to forestry activities could be due to atmospheric deposition, the causes of increases post 1980 are more difficult to establish. It could be due to artificial drainage networks linking these sites to nearby forestry that are facilitating the transport of water and nutrients from these areas of the peat. Palaeolimnological analysis of a site further removed from forestry and any possible drainage ditches could be used to examine the extent of forestry effects.

iii) Food web alterations

Food web changes driven by top-down processes (such as fish) also have the potential to influence productivity and community structure in the lochs. None of the palaeolimnological indicators examined in this chapter were able to substantiate either fish introductions (to sites that were previously fishless) or changes to fish population structure. Palaeolimnological data from all four study lochs clearly indicates recent increases in abundance of invertebrate remains, including those typically sensitive to fish predation, such as *Daphnia* sp. If increases in invertebrate abundance and community composition are being driven by top-down processes then this would suggest either lower overall fish abundance (and therefore reduced predation resulting in more invertebrates) or changes to the balance between larger (trout) and smaller (stickleback) fish. There is no evidence to indicate whether the fish populations of the lochs have declined in recent times, indeed local anecdotal sources suggest a change in fish population structure are more likely. These changes are thought to have occurred as a result of reduced recreational fishing pressure on the lochs. However, if the lochs now contain a larger number of small fish (as is suggested) then the predation pressure on invertebrates would be likely to increase causing a reduction in invertebrate abundance, which is not what is indicated by the palaeolimnological data in this study. The increase in invertebrate abundance would suggest a release from predation pressure, if this is being driven by top down processes then an increase in larger piscivorous fish would be more probable. Overall it appears unlikely that top-down process are driving increases in productivity observed in the lochs, but more detailed surveys of fish population structure could be used to confirm this.

Summary

There are a number of potential mechanisms that could be causing the gradual increases in nutrients observed in the study sites between ca. 1850 and 1980, including land use practices and increased atmospheric deposition. With little evidence to indicate strong changes occurring in relation to land practice and management during this time, it is perhaps most likely that the changes observed result from atmospheric sources of nutrient deposition. Whilst the focus of this study was to examine environmental change in relation to recent declines in common scoter populations, examining further samples from earlier in the cores could establish how the 1850-1980 trend relates to pre-1850 trends and whether atmospheric deposition is the most likely cause of inferred increase in productivity.

Stepped productivity increases observed in the 1980s and the accelerated trend between 1980 and present appear most likely to be a result of forestry activities situated either directly within the catchments of the lochs or connected to the catchments of the lochs by drainage networks.

Implications of recent environmental change for common scoter

The palaeolimnological evidence from this chapter indicates the algal, invertebrate and macrophyte communities of the lochs have changed substantially over the last 150 years, particularly since the 1980s. There have been increased in abundance in addition to shifts in community structure that indicate an increase in nutrient availability.

Common scoter populations in the Flow Country peaked in the 1980s and have declined by almost 50% since 1990. Recent increases in invertebrate abundance, as indicated by the palaeolimnological data, suggests that reductions in invertebrate food resources are not the primary factor limiting scoter breeding at these sites. Previous research found that common scoter occurred more frequently at Flow Country sites with mesotrophic (rather than strongly oligotrophic) conditions (Fox and Bell, 1994). However, results from this thesis indicate that by the time this study was carried out (in the mid 1990s) the lochs of the Flow Country may already have experienced substantial nutrient enrichment. Common scoter have been shown to be highly site faithful in other parts of their range (I.K. Petersen and G. M. Hilton per. comm.) which makes it difficult to determine whether the association with mesotrophic conditions observed in the 1990s was a result of site preference or site fidelity.

In addition to increases in overall abundance, palaeolimnological data has also provided evidence of substantial shift in invertebrate community composition during the period since common scoter decline. The feeding strategies of common scoter are not well understood. However, the limited evidence available suggests they are opportunistic feeders, consuming abundant and easily accessible prey items (Fox, 2003). It would seem unlikely therefore that shifts in community composition would be detrimental to adult breeding scoter. However, an additional implication of the observed community shift could be a move towards a community made up of smaller, less profitable taxa. The diversity and size classes of invertebrate species have been shown to affect lake use by other diving duck species (Eadie and Keast, 1982) and could be a particular problem for young birds needing to rapidly build up reserves.

The palaeolimnological evidence from four Flow Country lochs has provided clear evidence of recent environmental change and it appears highly likely that changes are associated with forestry activities. It remains difficult to confidently establish the mechanisms by which increased productivity and invertebrate abundance could result in declines of common scoter, particularly as they are thought to be generalist feeders. The results of this chapter could indicate either that another factor, besides food availability, is detrimentally influencing scoter breeding in the Flow Country. Alternatively, the shift in invertebrate community composition is resulting in a less profitable food resource, which could be a particular problem for young birds. In either scenario further work to establish mechanisms by which scoter feed would be valuable in addition to a better understanding of fledging success.

Evaluating the use of a palaeolimnological approach to species decline research

This chapter has demonstrated the applicability of a palaeolimnological approach to separate the spatially correlated variables associated with competing theories for common scoter decline. The benefits of a multi-indicator approach to build a clear, long term picture of recent environmental change at different trophic levels have also been demonstrated.

The palaeolimnological analysis in this chapter has demonstrated the benefits of examining biological indicators at different trophic levels to facilitate understanding of environmental change. However, to allow for more time to be spent on a larger number of indicators, the taxonomy of some groups (chironomids and cladocera) was not fully resolved. The current study demonstrates that whilst extra information could have been gained from higher taxonomic resolution of these groups, it was not vital, as key patterns could be established to answer the conservation questions of concern. This has implications for other conservation based palaeolimnological studies, in terms of prioritisation of resources.

One limitation of using palaeolimnology in lochs which have a slow sediment accumulation rates, such as those in the Flow Country, is the inability to resolve annual (or near annual) scale change. Whilst a near annual resolution has been possible in other studies (Brooks *et al.,* 2012) and could have been useful in this case, it was not vital and the determination of the key drivers of decline were not substantially hindered by being at a near decadal timescale.

Ecological studies of species decline typically rely on contemporary data sources that provide only a snap shot of environmental conditions, typically over very limited time scales. A limitation of this approach is that it can be difficult to disentangle multiple spatially correlated variables, even if they are temporally separable. In this chapter palaeolimnological techniques have been shown to facilitate the diagnosis of species decline by providing detailed and standardised data over timescales substantially longer than those typical in traditional ecological approaches. However, a limitation of the palaeolimnological approach is that the analysis of core material is a time intensive process which limits detailed, fine resolution analyses to a smaller number of sites than could be covered by a traditional ecological approach. When the number of sites is small it can be difficult (or impossible) to answer questions of species decline using hypotheses testing approaches that are more familiar to contemporary ecologists. Use of palaeolimnology by the conservation community has been limited and a lack of understanding between respective fields has been suggested as one reason for this (Davies and Bunting, 2010). The findings from this study exemplify the benefits and limitations of a palaeolimnological approach.

6.6 Key findings and implications

- Four lochs in the Flow Country were cored using a wide bore, Big Ben corer with the aim of examining questions around the changes in fish populations and as a result of forestry that could be detrimental for breeding common scoter

  ⟶ It is possible to use this technique in these shallow lochs
- Lithostratigraphic analysis indicated the cores had a conformable stratigraphy, and sediment primarily silt with with sandy layers

  ⟶ Sandy layers indicate dynamic change however there was no clear pattern between sites spatially or temporally
- Three of the four cores were dated using ^{210}Pb, and one by cross correlation of XRF profiles with a ^{210}Pb dated Glew core from the same site. ^{137}Cs and ^{241}Am peaks in the three radiometrically dated cores were broad or absent which could have indicated physical mixing. However cross correlation with the Glew cores confirmed the dates established by the CRS model in two oout of three sites. The dating of TALA_BB could not be substantiated with confidence.

  ⟶ Cores from shallow wind stressed sites can be dated, some chemical mixing of ^{137}Cs and ^{241}Am may occur but no physical mixing was evident in most cases.
- Multi-proxy analysis of the four cores indicated an increase in loch productivity with many groups from multiple trophic levels increasing over the last 150 years. A distinct increase was discernible in the 1980s; particularly in nutrient tolerant taxa, whilst nutrient sensitive taxa decreased. Palaeolimnological data provided strong evidence that the lochs of the Flow Country have experienced substantial change over the last 150 years, and particularly since the 1980s. Whilst there was no evidence of changes in fish populations having a detrimental effect on invertebrate food availability, there were increases in abundance and shifts in community composition associated with the 1980s and commercial forestry activities.

  ⟶ Palaeolimnology can be used to disentangle spatial correlated theories of species decline, generate and develop hypotheses and provide evidence for conservation management

CHAPTER 7: SUMMARY, CONCLUSIONS AND FUTURE DIRECTION

7.1 Overview

This chapter reviews the objectives and findings of this thesis; it brings together the conclusions from each chapter and discusses the management implications for Flow Country lochs and the conservation of common scoter. The future direction of research based on the findings from this thesis are identified.

7.2 Introduction

The common scoter is a UK red-listed breeding species and a priority for conservation, having experienced declines of more than 50% over the last 30 years. The Flow Country in Northern Scotland is one of several areas in Britain where the species breeds, and is an important stronghold, where declines have proceeded more slowly. The Flow Country is an internationally important wetland, consisting of over 440,000 hectares of blanket bog, interspersed with pools and oligotrophic lochs. Annual common scoter monitoring, covering approximately 100 sites in the Flow Country, has documented a substantial decline in the last 30 years. Research in Scotland on common scoter decline, has to date used traditional ecological approaches to characterise and compare lochs that are currently, or have historically been used by common scoter. Previous research has established that there is a statistically significant association between common scoter presence and loch characteristics such as; high pH and conductivity (Fox *et al.,* 1989), shallow shorelines and soft sediments and an abundance of large bodied invertebrates (Hancock *et al.,* 2015). However, studies to date have not able to provide an in-depth assessment of the within-loch relationships at multiple trophic levels, particularly in the context of detailed physio-chemical data. Nor have substantial attempts been made to evaluate landscape scale characteristics and common scoter distribution using powerful tools such as GIS and/or SDM. Most importantly these data, based on a contemporary snap shot of conditions, are unable to provide any information about recent environment change at common scoter breeding sites. Without a temporal context, in which to view contemporary conditions, it is impossible to determine the extent to which changes in the lochs could be influencing declines. Long term data can identify whether particular lochs have always had more (or less) favourable conditions than others, or whether differences in the extent (or type) of change at the loch is related to its current value to common scoter. Long term data can also provide evidence as to whether observed environmental changes are the result of anthropogenic pressures and/or natural variability. In addition to understanding why a species has declined, long term data can also be important in a practical management context. It can be used to identify sites that are the least impacted, and sites that should be a priority for management and/or restoration. Unfortunately, long term monitoring data, covering a range of variables is frequently lacking, inconsistent or non-existent. This was the case for lochs in the Flow Country. No long-term data was available to provide context to recent common scoter declines, and consequently it was difficult to disentangle competing theories, or make decisions as to the most appropriate and cost-effective management interventions. This thesis takes a unique approach to understanding the decline of a priority UK waterbird species, the common scoter. Detailed contemporary ecological survey data is combined with geospatial modelling and palaeolimnological reconstructions to provide a detailed understanding of the drivers of decline.

An overview of how each aim of this research was met is detailed below and an overview of the main conclusions is given in section 7.3 of this chapter. Sections 7.4 and 7.5 identify the management implications of these findings and directions for future research.

Aim 1: Determine levels of heterogeneity in Flow Country lochs

Whilst common scoter records for the Flow Country were more extensive and standardised than for any other breeding location in Scotland, data relating to the physical, chemical and biological communities of the lochs was shown to be substantially lacking. Chapter 3 used newly collected survey data to characterise 18 Flow Country lochs. These analyses demonstrated that the algae, chironomid and macrophyte species present were generally typical of those found in low nutrient, acidic lochs. Analysis did, however, indicate that there was also much variation between the biological communities of the study lochs. Some lochs could be grouped based on algae, invertebrate and water chemistry characteristics, and three loch types could be identified based on macrophyte communities (Palmer *et al.,* 1992).

The environmental variables explaining the differences in the composition of diatom, invertebrate and macrophyte communities were explored using constrained multivariate analysis. Key influences included water chemistry (DOC, Mg, and Ca), predation pressure (brown trout weight) and habitat structure (macrophyte cover).

Aim 2: Develop and refine hypotheses for common scoter decline in the Flow Country using within-loch data

Historic common scoter survey data was used to determine a scoter loch value for each of the 18 study sites. This was used as a response variable in a general linear model. Due to the large number of potentially influential within-loch variables, three sub-models (physical, chemical and biological) were initially run to identify the variables to be taken through to a final model. Variables taken through this initial model refinement process were sediment type, water depth, DOC and the abundance of macrophytes, invertebrates and fish. The statistically significant variables in the final model were DOC, water depth and sediment type. Common scoter loch use was higher at lochs with low DOC concentrations. The relationship between scoter loch use and sediment type varied depending on water depth, with soft sediment being more important to scoter at deeper sites. Although macrophyte cover, chironomid and fish abundance were non-significant in the final model, they were all considered as somewhat ecologically relevant due to making it through to the initial model refinement process. Overall Chapter 3 addressed aim 2 by determining that common scoter loch use is influenced by physical (sediment type and water depth), chemical (DOC) and, to a lesser extent, biological (fish and chironomid abundance) characteristics of Flow Country lochs. By combining these data with current literature and knowledge of pertinent Flow Country issues, the following theories concerning common scoter decline were developed:

(1) Afforestation and drainage of the Flow Country catchments in the 1980s may have altered the physico-chemistry of lochs through increased sedimentation and/or DOC import which could adversely affect physical loch structure and/or invertebrate food supply for the common scoter.

(2) Common scoters compete with brown trout for food, and the competitive balance between brown trout and scoters may have altered in recent decades, either as a

result of decreased fishing pressure or fish stocking events. Changes in the abundance or population structure of brown trout could have resulted reduced invertebrate abundance which could be detrimental for common scoter.

Aim 3: Explore the influences of landscape scale drivers on common scoter distribution in the Flow Country

Maxent, a species distribution modelling approach, was used to examine the contribution of landscape variables in explaining common scoter distribution in the Flow Country. Influential landscape variables identified in the Maxent analysis included proportion of forestry close to lochs, soil moisture and bedrock geology. The relationship between likelihood of common scoter presence at a loch and the proportion of forestry was unimodal, with scoter presence most likely at sites with 50-70% of bog within a 500m buffer of the loch. Similarly, common scoter presence was more likely where soil moisture was neither excessively wet nor dry. The likelihood of common scoter presence was higher at sites with igneous bedrock types underlying the lochs. The relationships between landscape variables (forestry, soil moisture and bedrock geology) and important within-loch features, identified in Chapter 3 (DOC, sediment type, shallowness and the abundance of fish, invertebrates and macrophytes), were also explored. No statistically significant relationship could be identified between key loch characteristics and landscape features using GLMs.

The implications of these findings were discussed in relation to whether the association between landscape variables and common scoter presence was correlative or causal. The core of common scoter breeding area in the Flow Country is located in the centre of the area selected for forestry activities. The unimodal relationship between scoter presence and proportion of forestry, together with high site fidelity and continued scoter declines does not support the theory that common scoter are benefiting from, or avoiding, changes occurring as a consequence of the forestry. Overall a correlative relationship was more probable, with scoter continuing to attempt breeding in the same core Flow Country area, despite the presence of forestry plantations.

Aim 4: Examine the effect of annual climate variation on both common scoter and key within loch features

In addition to hypotheses concerning forestry and fish, there is also concern in the conservation community that, as a sub-arctic breeder on the southerly edge of its range, common scoter are being influenced by climate change. Annual climate variations can be a useful indicator of a species resilience to climatic change (Campbell *et al.,* 2013). This thesis therefore explored whether the effects of annual climate variations at either the wintering or breeding grounds have influenced the number of scoter breeding in the Flow Country. Harsh winters could reduce the body condition and breeding propensity of arriving birds, and have implications for total numbers returning to breed in following years. Total numbers of common scoter in the Flow Country could also be affected by poor summer climate. The nesting success of females and development and fledging of ducklings could be affected by reduced body condition and/or phenological mis-matches. General linear models were used to examine associations between total common scoter numbers and climate at both regional (wintering grounds) and local (breeding grounds) scales. No significant relationship between change in common scoter numbers and annual variations in climate could be identified. The findings from this aim suggest that local landscape and within-loch influences could be more pertinent to common scoter decline than local or regional annual climate variation.

Aim 5: To take short sediment cores from a number of Flow Country lochs and use lithostratigraphic and geochemical analyses to determine the suitability of these sites for palaeolimnological research

The application of palaeolimnological techniques depends on sediments being deposited in a time-depth sequence and remaining undisturbed by physical mixing. Concerns have been raised over the implications of physical sediment mixing particularly for shallow, potentially wind stressed lochs, such as those in the Flow Country. Sediment cores were taken from 18 Flow Country lochs and lithostratigraphic and geochemical analyses carried out to determine core stratigraphy. There was no evidence of physical sediment mixing in the cores, although there was evidence in two of the 18 cores that some of the surface sediments could have been lost. Cores taken in shallow, wind stressed lochs can have a conformable stratigraphy that is not substantially affected by physical mixing; the findings from Chapter 5 demonstrate that palaeolimnological approaches are appropriate in these systems.

Aim 6: Use a palaeolimnological top-bottom approach to determine the extent and type of environmental change in Flow Country lochs, particularly in relation to levels of current loch use by common scoter

A multiproxy approach was used to characterise diatom and chironomid communities in the tops and bottoms of 18 cores. The lochs were shown to have experienced substantial shifts in their diatom and chironomid communities over the last 150-200 years, and additionally a noticeable increase of nutrient and acid tolerant taxa was observed over this period. The implications of recent environmental change were considered in relation to current common scoter loch use. Some grouping of lochs was evident in relation to the extent and direction of recent community change and current common scoter loch use. Some sites with low scoter loch value were shown to have communities of chironomids and diatoms distinct from sites with high scoter loch value both now and historically, which could indicate that differences between sites have persisted over a substantial period. However, patterns were inconsistent and difficult to interpret at coarse temporal resolutions, particularly when the time intervals represented by the bottom slices could vary between cores.

Overall a large amount of change has occurred in both diatom and chironomid communities in 18 Flow Country lochs over the 150-200 years. Whilst some patterns in relation to scoter loch use were evident, top-bottom analysis was unable to establish the precise timings or timescales for observed increases in nutrient tolerant taxa (or identify the most likely drivers), nor was it possible to examine recent environmental change, over timescales contemporaneous with common scoter decline.

Aim 7: Undertake wide bore, multi-proxy palaeolimnological analyses at four Flow Country lochs to examine recent environmental change at a fine temporal resolution, and explore the implications for common scoter

Four Flow Country lochs were cored using a wide bore sediment corer, developed to enable large volumes of sediment to be collected for multiproxy analysis. Diatom, chironomid, and macrofossil (including plant and invertebrate) communities were examined for a period covering the last 150-200 years. Results indicated that the overall abundance of diatoms, chironomids and invertebrates had increased over this period. Distinct, stepped increases were visible at a point determined to be ca. 1980 in several cores and taxa, and at the same time there were decreases in nutrient sensitive taxa such as *Isoetes* sp*., Diamesinae* sp. Atmospheric nutrient deposition was considered as the most likely cause of gradual increases observed between ca. 1850 and 1980, although further work of samples down the core would be needed to confirm this.

Palaeolimnological data covering the more recent past (1980-present) was considered in the context of the two theories for common scoter decline. Evidence did not support the theory that invertebrate abundance had been reduced because of increased consumption by fish. There was evidence to support a marked change in physical, chemical and biological characteristics of the lochs concurrent with forestry planting.

7.3 Conclusions

- Study lochs were generally typical of low nutrient, acidic waterbodies but variation existed between them in terms of both physico-chemistry and their biological communities.
- The within-loch characteristics associated with common scoter presence were DOC (positive), sediment type and water depth (interaction, with soft sediments more important at deeper lochs), trout abundance (negative), macrophyte cover (positive) and chironomid abundance (positive).
- Landscape features influencing common scoter distribution in the Flow Country were proportion of forestry close to a loch, the soil moisture and bedrock geology. The relationship between probability of common scoter presence and

both forestry and soil moisture was unimodal. Probability of common scoter presence was highest at lochs with an igneous bedrock geology.

- No relationship could be identified between changes in the number of common scoter and annual variations in climate
- Potentially challenging palaeolimnological environments, such as the shallow lochs of the Flow Country could be cored, and the cores had a conformable stratigraphy not affected by sediment mixing.
- Despite remoteness and apparent lack of anthropogenic impact, top-bottom palaeolimnological evidence indicated that the lochs of the Flow Country are dynamic environmentally and have undergone substantial change over the last 150-200 years. Additionally, there was evidence that both nutrient and acid tolerant taxa had increased.
- Fine scale palaeolimnological analyses at four lochs was able to provide evidence of recent environmental change at a fine temporal resolution. Overall diatom abundance has increased over the last 150 years, and additionally a community shift has occurred, with nutrient tolerant taxa increasing, particularly around a period associated with the 1980s. Community composition of aquatic macrophytes has altered over the last 150 years; decreases in oligotrophic species such as *Isoetes* sp. have occurred, and associated increases in Moss sp. and *Juncus* sp. were observed. Chironomid abundance increased over the last 150 years at all four sites. Despite the taxonomic resolution of the chironomids being low, a loss of nutrient sensitive *Diamesinae* species was observed. The invertebrate abundance at all four study lochs also increased, with the abundance of invertebrate remains in recent sediments being higher than as any point down core.
- Recent environmental change at four Flow Country lochs was considered in relation to the following two theories for common scoter decline:
    i. Afforestation and drainage of the Flow Country catchments in the 1980s may have altered the physico-chemistry of lochs through increased sedimentation and/or DOC import which could adversely affect physical loch structure and/or invertebrate food supply for the common scoter.

ii. Common scoters compete with brown trout for food, and the competitive balance between brown trout and scoters may have altered in recent decades, either as a result of decreased fishing pressure or fish stocking events. Changes in the abundance or population structure of brown trout could have resulted reduced invertebrate abundance which could be detrimental for common scoter.

Palaeolimnological evidence strongly supports the theory that forestry has affected the lochs of the Flow Country. There is no evidence of changes in fish populations or that the abundance of invertebrate food resources has reduced due to increased consumption by fish in recent times. The lochs appear to be becoming less oligotrophic, particularly since the 1980s. The associated shifts in community composition could make the lochs less profitable or suitable for common scoter who typically choose low nutrient, oligotrophic sites.

7.4 Management implications

The implications of this research for future research and management could be considered on two levels. Firstly, this research will encourage further collaboration between palaeolimnologists and conservation practitioners. Cross-disciplinary working has already been advocated (Davies and Bunting, 2010; Froyd and Willis, 2008) and this thesis provides further evidence of the insights that can be gained by adopting a palaeolimnological approach to address issues of conservation management. Secondly, this research has more specific management implications for Flow Country lochs and breeding common scoter. This thesis provides evidence of recent environment change in Flow Country lochs, and in particular indicates that increases in nutrient availability have occurred since the 1980s. Palaeolimnological data demonstrate that, despite their remote location and largely unimpacted appearance, the lochs of the Flow Country are complex and dynamic environments, which are experiencing increasingly rapid change. A palaeolimnological assessment of a larger number of lochs is advocated, with the aim of assessing the extent of change, and using these findings to prioritise sites for protection and restoration. The findings from this research also highlight the impacts that forestry plantations can have for freshwater lochs in blanket bogs. The number of new plantations on areas with deep peat has declined in recent times (Patterson and Anderson, 2000), but this thesis illustrates the long-term effects historic planting can have, and highlights the need for harvesting practices (such as ditch blocking) that limit the export of nutrients and sediment to freshwater lochs.

In terms of the conservation management for common scoter, this thesis provides evidence that invertebrate abundance in Flow Country lochs has not decreased in recent times, however shifts in community composition have occurred. Common scoter breed on oligotrophic lakes throughout their range suggesting they are particularly adept at exploiting resources in freshwaters where overall resource abundance is low. A preference and/or particular adaptation for these types of site, combined with strong site fidelity, could be problematic for scoter in places where nutrient levels increase and the community shifts to include taxa that are less easy or profitable for scoter to exploit. The implication of this research for management in the Flow Country centres around ensuring further nutrient enrichment is limited as much as possible, particularly at lochs which are key breeding sites for common scoter.

7.5 Research limitations and future direction

This thesis demonstrates the value of a collaborative, cross-disciplinary approach between palaeolimnologists and conservation practitioners to address issues of wetland management and species conservation, however there were a number of limitations to this study which could be addressed by future research.

The primary limitation of this study was that the data used to delineate the catchments of the lochs were somewhat questionable and resulted in ambiguity about the abundance of different landcover types within the catchments. Using generic GIS modelling approaches that use 50m DEM to delineate catchments is clearly more difficult in very low gradient environments such as the Flow Country. This could be addressed by using a finer scale DEMs and/or complementing GIS models with on the ground assessment of the hydrological processes. The arguments presented in this thesis could be further strengthened and somewhat clarified by palaeolimnological analyses from additional sites. The problems encountered in accurately establishing the catchment area of the lochs and the extent and distribution of drainage ditches could be addressed with more detailed mapping and hydrological assessment. This would be key to establishing how much connectivity there is between lochs and areas of forestry and address the problem encountered with establishing a palaeolimnologically suitable unforested site.

The gradual increases in productivity observed at the study sites between ca. 1850 and 1970 were tentatively attributed to increases in atmospheric deposition during this period. However, this theory could be confirmed by examining further samples to establish how this trend compares to pre-industrial conditions.

The future direction of research in this area should make palaeolimnology a more readily available and accessible tool for conservation practitioners. Palaeolimnology is a rapidly advancing field with new methods being developed to expand the number of ecological indicators available, and allow even more detailed interpretation of sediment core archives. For example, analysis of stable carbon and nitrogen isotopes (13C and 15N) in invertebrate and plant remains have been shown to give insights into food web structure (Heiri *et al.,* 2012). Similarly, further work could explore the possibility of identifying ancient DNA (aDNA) in bulk sediment samples, to establish whether introduction of fish species (e.g. brown trout) can be determined in lochs that are thought to have been historically stocked.

Chapter 3 gathered a large amount of new data for a relatively large number of sites, however, it would have been useful to have a more detailed assessment of fish populations within the sites. Quantitative population assessments and fish stocking data would have been particularly useful as they could have provided further insights into the factors structuring the communities of the lochs. In the Flow Country, practical management intervention work has already begun, that includes a quantative assessment of fish populations within the lochs. The RSPB is working with the local angling community to increase fishing pressure at several lochs and to compare the abundance of large bodied invertebrates available between these lochs and sites at which fishing pressure has not changed. The use of fish exclosures to increase invertebrate abundance is also bein trialed. In the future, the longer-term effects of this intervention could be examined using palaeolimnological techniques. Similarly, palaeolimnology could be used to establish the effects of loch restoration and determine impacts of long term environmental change.

This thesis has applied the palaeolimnological approach in a novel way, to address an issue that would typically be the remit of contemporary ecology and strict hypothesis testing. Combining palaeolimnological and ecological approaches can be challenging. Whilst palaeolimnological data can provide a substantial amount of detailed data concerning change over time, it can be difficult to generate the large sample sizes typical of ecology studies, and therefore traditional approaches to hypotheses testing can be difficult. This thesis was able to apply an amalgamation of both palaeolimnological and ecological approaches, which allowed detailed data concerning recent environmental change to be used to answer questions of applied conservation management providing a strong foundation for future cross disciplinary research.

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