The characteristics and effects of management fire on blanket-bog vegetation in north-west Scotland

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'When we try and pick out anything by itself, we find it hitched to everything else in the universe'.

John Muir (1911). My First Summer in the Sierra.

Fire is a good servant - but a bad master.

Finnish proverb

'I love deadlines; especially the whooshing noise they make as they go by.'

Douglas Adams

Declaration

I hereby declare that this thesis has been composed by myself.

The work this thesis describes is my own work, except where stated otherwise, and has not been submitted in application for any other degree.

Alistair Hamilton
May 2000

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Abstract

The wet and mild climate in north-west Scotland has resulted in a landscape dominated by wet heath and blanket-bog vegetation. Blanket bog is of high conservation value, but of poor agricultural quality. Along with wet heath, it is used as extensive grazing for sheep and deer and, over these large unfenced areas, fire is one of the few viable management options available to estate managers and crofters. Fire in these areas is used to promote the rapid spring regrowth of grass and sedge species (the 'early bite'), in contrast to the better-known grouse moor (dry heathland) fires where regeneration of *Calluna vulgaris* is the aim. The characteristics and effects of management fires in blanket-bog vegetation are virtually unknown, and this lack of knowledge is reflected in the almost universal recommendation of conservationists that blanket-bog vegetation should not be burnt at all, or that burning should be minimised. Information about the management fires themselves, and their effect on the blanket-bog habitat, is therefore required in order to refine burning guidelines in accordance with the management objectives.

This thesis firstly describes the background to the use of fire in north-west Scotland, putting fire in the context of a changing landscape and culture. Using fires from the spring of 1996, 1997 and 1998, the fuel complex is described, and equations to predict fuel load from pre-fire survey variables are presented. The results emphasise the very high spatial variability in fuel load, and this is in turn reflected in the variability in fire temperature regimes and in estimates of fire intensity. The usefulness of different fire characteristics is discussed with respect to possible objectives for fire studies, and the importance of appreciating the different spatial and temporal scales at which various processes and fire effects operate, and at which fire characteristics should be measured, is stressed.

The effects of fire on the *Sphagnum* layer are described with respect to fuel availability, grazing, and position, and the recovery of the *Sphagnum* followed for up to three years after burning. The regrowth rates of the two most important vascular species, *Calluna vulgaris* and *Molinia caerulea*, are compared under grazing and no-grazing treatments. The considerations for and against burning blanket bog are reviewed, and recommendations for management of prescribed burning given. The urgent need for further research into fire characteristics and effects in the UK is stressed, with recommendations made for the areas most in need of further study.

Plant nomenclature

Vascular plant species names follow Stace (1999), and bryophyte species names follow Smith (1980).

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Chapter 1 BLANKET BOG HISTORY AND MANAGEMENT, AND FIRE ECOLOGY

1.1 Introduction to the blanket bog habitat

The overall aims of this thesis are the description and quantification of management fire characteristics and the initial recovery of the main vascular species and the *Sphagnum* layer in blanket-bog vegetation in the north-west of Scotland. The intention is that the results and conclusions should be used to inform current and future management practices. Land management and the ecology of the overall habitat do not exist in isolation, in that both are interlinked and each has an associated history of evolution over time. It is therefore relevant to begin a review of blanket-bog management and fire ecology with a brief history of the habitat and its management.

1.1.1 Extent, distribution and origins

There are several different types of peat-forming ecosystem, and this study concerns what are termed blanket bog or blanket mire habitats. The terms 'mire' and 'bog' are both used to refer to peat forming ecosystems. Tallis, Meade & Hulme (1998) argue for the use of the description 'blanket mire' but the more traditional and widely used term 'blanket bog' has also been recommended (Wheeler & Proctor, 2000), and is used hereafter. The dominant type of bog in Britain, and particularly in Scotland, is ombrotrophic bog, where the supply of water and nutrients are derived solely from precipitation. Of the two types of ombrotrophic bog, blanket and raised, the former is by far the most extensive.

Peatlands cover some 500 million ha (3%) of the Earth's surface (Bellamy, 1995), with blanket bog estimated to cover 10 million ha (Lindsay *et al.*, 1988). The extent of blanket bog in Scotland depends on the definition adopted – for example Moore & Stephenson (1998) refer to 1 500 000 ha of 'blanket peat', whereas the area of peat >1 m in depth is estimated at 1 056 000 ha or 13% of the total land area (Coupar, Immirzi & Reid, 1997). This latter estimate is 71% of the total UK blanket bog resource, 47% of the UK and Ireland total, and over 10% of the world resource. Blanket bog occurs where there is high precipitation, spread over the year, and low evapotranspiration. Other requirements, listed in the review by Lindsay *et al.* (1988) include low mean temperatures, a small temperature range, low angle of slope, and (of lesser importance) a substrate with low pH and base content. The distribution of blanket bog therefore shows a strong northern and western bias (Figure 1.1) as a result of the colder and wetter climate in the north and the increasing oceanicity in the west (Ratcliffe & Thompson, 1988). The importance of the latter gradient in determining plant community distribution has been emphasised by Brown, Birks & Thompson (1993) and by Nolan & Robertson (1987).

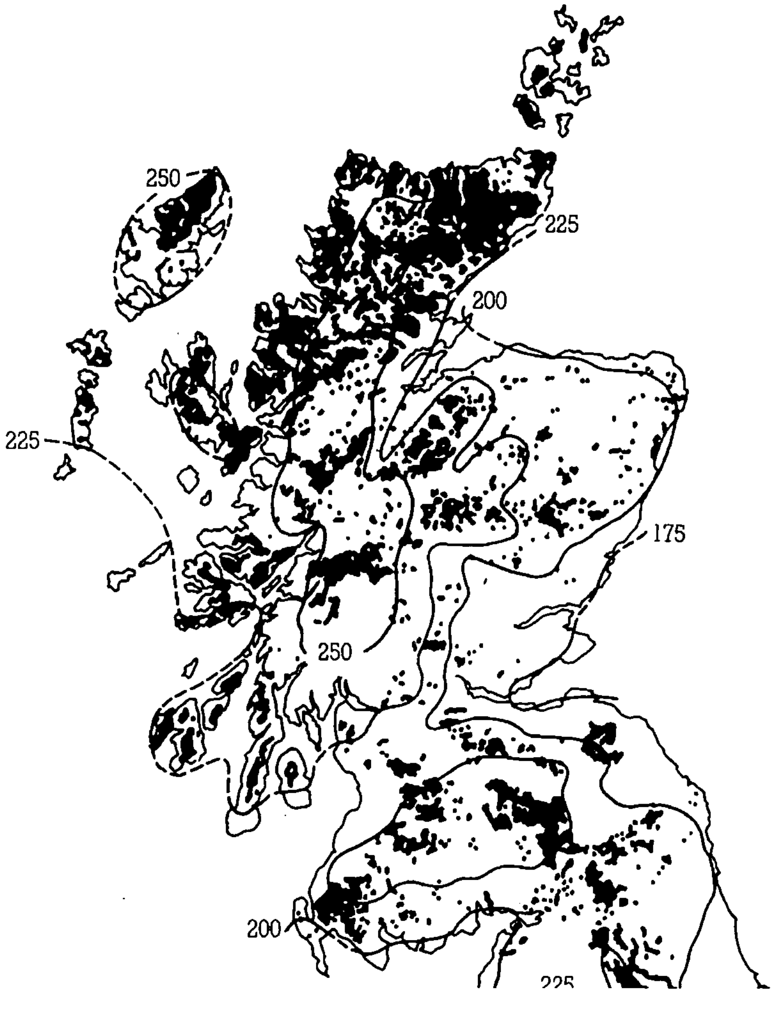

Figure 1.1. Peat deposits and isopleths for the annual average number of rain days (1901 – 1930) across Scotland. A rain day is defined as a 24-hour period during which at least 2.5 mm of precipitation is recorded. From Lindsay *et al.* (1988).

Bogs are formed via two main pathways, paludification and terrestrialisation (Lindsay, 1995; Birks, 1988). Both of these involve waterlogging, the consequent lack of plant decay, and the subsequent accumulation of peat (partially decayed plant matter). Paludification is peat formation directly onto a soil or rock substrate, and is the main process by which blanket bog forms. A true bog is only formed once the peat is thick enough to prevent plant roots reaching the mineral soil or rock and underlying groundwater table. Peat formation can occur on slopes of up to 20°, and in extreme peat-forming conditions on slopes of 30° (Lindsay *et al.*, 1988). As well as being waterlogged much of the time, other properties of bogs include a low pH (3.5 – 4.5), low productivity, low decomposition rates, and a low floristic diversity (Lindsay, 1995) as few vascular plant species can tolerate such conditions. Species of the genus *Sphagnum* are usually widespread on blanket bogs, and are often the major constituent of peat. They can form an extensive carpet over the bog, and as a result are the substrate through which other plants grow. They hold water very effectively (up to 14 times their own weight), and are efficient at mopping up nutrients that are deposited on the bog surface. The overall poor agricultural properties of blanket bog have resulted in it once being described as a 'wet desert' (Lindsay *et al.*, 1988).

1.1.2 Conservation importance

Although covering large areas of Scotland, blanket-bog is a habitat in decline. The proportion of Scotland covered by blanket bog is estimated to have dropped from 29 % in the 1940's to 23 % in the 1980's (Mackey, Shewry & Tudor, 1998). This is a 21 % reduction in area, with losses mainly due to afforestation and conversion to rough grassland and dry heathland (via drainage).

The various reasons for conserving peatland systems in Ireland are listed under scientific, economic, cultural and moral headings by Watts (1990), and these headings apply equally to Scotland. Blanket bogs are often thought of as species poor, however there is a growing recognition of their conservation importance both nationally and internationally. Lindsay *et al.* (1988) note that the British blanket bog and wet heathland habitats are unique because of the extreme Atlantic influence on the flora and fauna. Indeed, Scotland is noted to contain 'type' examples of blanket bog, and this is reflected in the international opinion in favour of listing the Flow Country (a large area of blanket bog) in Caithness under the World Heritage Convention (Lindsay *et al.*, 1988). The blanket bogs of Caithness and Sutherland as a whole are also recognised within the UK for their importance, with Keatinge, Coupar & Reid (1995) suggesting that half the remaining unafforested area of the Flow Country (175 000 ha) be granted SSSI status. 40 000 ha of this area is already notified as such. Of the 38 mire and 28 heath communities identified by Rodwell (1991), six are confined to the UK and seven are rare elsewhere (Thompson *et al.*, 1995). Among the 'core' objectives for conservation in the UK, Thompson *et al.* (1995) include the restoration of dwarf-shrubs and bryophytes (especially *Sphagnum* species) to blanket bog, with a reduction in burning recommended to further this aim.

The value of blanket bog habitat other than for the plant species and communities they contain has received much attention, but as noted by Shaw *et al.* (1996) it is often difficult if not impossible to distinguish the information relevant only to blanket bog. Sources of information tend to cover all heathland and moorland habitats. The importance of blanket bog and associated habitats (wet heath, dubh lochans, lochs, streams, sea lochs) for birds has been discussed by many authors (Shaw *et al.*, 1996; Usher & Thompson, 1993; Thompson *et al.*, 1995; Stroud *et al.*, 1987). The Flow Country alone contains significant fractions of the total EC breeding populations of 11 species (Stroud *et al.*, 1987), and is attributed with a 'wider ecological spectrum of breeding birds' than any other moorland area in the UK. The invertebrate fauna has also been a focus of attention (Shaw *et al.*, 1996; Usher *et al.*, 1993; Coulson, 1988), although most of the information available relates to northern English sites and in particular to Moor House National Nature Reserve (NNR) in Cumbria. However, Coulson *et al.* (1995) found that the invertebrate fauna of the Flow Country is distinct from northern English sites, in particular with respect to species assemblages. One of the main overall conclusions appears to be that invertebrate diversity is favoured by spatial and temporal variation in the habitat, which in turn is maintained by the appropriate burning, grazing and cutting regimes (Usher *et al.*, 1993; Usher, 1995). Shaw *et al.* (1996) note that the mammal fauna on blanket bogs is neither particularly rich nor rare, with the species present also being found in other habitats.

On a global scale, the peatlands of the world contain a large store of carbon, and the fate of this carbon has implications for climate change. Within the UK, an estimated 115 million tonnes of carbon are found in the vegetation, in contrast to 22 000 million tonnes stored in the soil (Harrison *et al.*, 1995). The vast majority of the soil carbon is found in peat and peaty soils, and these in turn are mainly found in the north and west of the UK. Management of wet heath and blanket bog in north-west Scotland may therefore have major implications for the carbon budget of the UK as a whole.

1.1.3 Cultural and economic importance

The cultural heritage value of bogs is also an issue in considering their future management, and is stressed by Watts (1990) and Hamilton, Legg & Li (1997). Blanket bogs tend to be found in areas with small and isolated local communities, supporting a way of life that is now valued. The seasonal influx of tourists demonstrates this, as they travel to places such as the north-west of Scotland for more than simply the scenery. Tourist perceptions are thus important, as tourists are responsible for bringing in a sizable proportion of the income in otherwise economically struggling parts of the country. As noted by Hamilton *et al.* (1997), the land in the north-west of Scotland is of poor agricultural quality with most of the income derived from sporting interests and heavily subsidised extensive sheep farming on estates, or from sheep farming alone in crofting areas. Sporting interests are dependent mainly on red deer (*Cervus elaphus*) and fishing, with generally low densities of red grouse (*Lagopus lagopus*) making grouse shooting in many cases uneconomical. Despite the poor agricultural quality of the land, it supports a sizeable proportion of the local people either directly or indirectly.

The anaerobic conditions found within the peat body are an ideal environment for the preservation of various materials, referred to as the peat archive (Lindsay, 1995). These include archaeological artefacts, indicators of climate, macrofossils (plant and animal remains), and pollen and charcoal. These can provide valuable information about the development of the habitat over time, which is of value in understanding the current state of the system. The importance in understanding the origins and evolution of an ecosystem, in order to inform its current and future management, has been emphasised by many authors (Pyne, Andrews & Laven, 1996; Ostlund, Zackrisson & Axelsson, 1997). The latter authors note that the 'present status and future development of ecosystems are dependent not only on general ecological processes but also on their past status, and in particular, conditions of origin'. An understanding of blanket bog development in north-west Scotland, and the role of man and fire, is therefore relevant to understanding its current status and management.

1.2 Vegetation history and the role of fire in vegetation development

1.2.1 Post-glacial development

After the ice retreated at the end of the last ice age, tundra-type vegetation covered thin skeletal soils. Extensive blanket bog formation did not start immediately, and Birks (1988) notes that 'there is no general date or single cause for upland blanket-mire origin'. The overall development of vegetation in these areas was more complicated, with pollen records indicating that bog only developed in many areas after other vegetation types, such as woodland. However Tipping (1994) notes the difficulties in attaching dates to woodland expansion or contraction, and also questions exactly what is meant by woodland 'cover'. This subject has also been addressed by Fossit (1994) who emphasise the difficulty in identifying and interpreting the pollen record. Nonetheless, tentative dates have been attached to major vegetation changes. Between 10 000 and 8 000 BP (before present) the Scottish climate was perhaps at an optimum for tree establishment, with higher than present insolation due to Milankovitch cycles (Birks, 1988). Slightly later than other areas due to the Loch Lomond Stadial (a re-advance of the ice), north-west Scotland was successively colonised by many different tree species. The main species and colonisation dates, estimated by Birks (1989), are: birch (*Betula* spp) ~ 9 750 BP; hazel (*Corylus avellana*) ~ 9 500 BP; elm (*Ulmus glabra*) ~ 8 500 – 8 000 BP; alder (*Alnus glutinosa*) ~ 6 500 – 6 000 BP; and oak (*Quercus petraea*) ~ after 6 000 BP. These dates show when a 'critical low density' was reached for each species (i.e. the density above which enough pollen is produced and preserved for detection by pollen analysis) and indicate relative and approximate dates of arrival.

In the case of Scots pine (*Pinus sylvestris*), Birks (1989) gives the arrival date in north-west Scotland as 7 900 BP, however Bennett (1995) argues for Scots pine being widespread as far north as Assynt by 8 800 BP. Birks (1988) puts Coigach/Assynt within a birch-hazel dominated zone between 7 000 and 5 000 BP, although notes that '*Pinus sylvestris* was an important but not dominant component in the Assynt, Inverpolly and Ullapool areas'. In contrast, Bennett (1995) argues that between 8 800 and 4 400 BP Scots pine became more dominant. One interpretation is that a mosaic of pine and birch/hazel woodlands existed, with mire in flatter areas and heathland existing in woodland gaps and above the tree line. Bennett (1995) puts the arrival date of the first farmers at around 6 000 BP and, probably using fire as an aid, they would have cleared trees to plant crops and provide grazing areas for their animals. Prior to this date, the effect of man in the area would have been local, with hunter-gatherers mostly scattered around the coasts. Between 5 000 and 3 200 BP what Bennett (1995) describes as a 'patchy and irregular' decline of Scots pine occurred in the north-west. Others (e.g. Birks (1994), note a much sharper and shorter decline, as shown by the abundant Scots pine stumps found under peat in the area, all dated within a few centuries of each other at around 4 000 – 4 400 BP. At this time all tree species appeared to be decreasing in range and/or abundance, resulting in a retreat of the range of Scots pine to south of the Ullapool area by around 3 800 BP (Gear & Huntley, 1991). Bennett (1995) proposes several possible mechanisms for this:

1. regional climate change, to one more storm-prone and oceanic;
2. volcanic eruption in Iceland resulting in acid deposition (see also Birks, 1994);
3. anthropogenic pressures (forest clearance, grazing animals);
4. pathogenic attacks;
5. change in fire regime.

Birks (1988) notes several lines of evidence for the first proposal, and there is an apparent coincidence of the Scots pine decline and some volcanic deposits, supporting the second proposal (Birks, 1994). However, Bennett (1995) queries why only Scots pine should be affected by acidic deposition, and also notes that the decline in Scots pine seems too abrupt for anthropogenic pressures to be the cause (the third proposal). He also highlights the lack of evidence for the fourth option, and the available charcoal record does not appear to support the last. A possible synthesis may be that the spread of Scots pine to the north and west was onto marginal sites for the species, aided at the time by favourable climatic conditions. A change to a wetter climate around 4 000 BP (Birks, 1988) and increasing anthropogenic pressures resulted in the species being unable to regenerate in these marginal areas. This date is also cited as the start of much bog formation (Birks, 1988), and this would explain the preservation of many pine stumps of a similar age. The first extensive, as opposed to local, forest clearance in the north-west (again probably aided by fire) is thought to be around 3 700 – 3 900 BP, with further clearances in north Sutherland at 2 600 – 2 100 BP (Birks, 1988). O'Sullivan (cited Smout, 1997) proposes that blanket mire had largely replaced forest prior to large-scale impact by humans – humans may simply have reinforced what was already happening due to the climate. In contrast, Lindsay *et al.* (1988) note the suggestion that anthropogenic burning was a major factor in removing the trees from the Flow Country. Whatever the cause, it appears that widespread peat formation was starting or was already underway in many areas by 4 000 BP, suggesting that bog and wet heath were widespread by this time.

Bunting & Tipping (1997) studied a 6.8 m peat core taken behind a stormbeach ridge at Badentarbat, close to the study sites for this thesis. It was examined for pollen and charcoal remains, and adjacent field systems (on wet heath) were also examined. The results (Table 1.1) show what appears to be a period of cultivation at the same time as the decline in Scots pine (with fire probably used to clear vegetation). The site may then have been abandoned for some time possibly due to waterlogging, and there is then evidence for several phases of renewed human activity.

Table 1.1. Interpretation of results from core and field system examination at Badentarbat. Summarised from Bunting & Tipping (1997).

Interpretation of core	Field system interpretation
4 000 BP. Pine decline, increase in charcoal (forest clearance?). Wetter species increasing (woodland and heath/bog)	*4 500 – 4 000 BP.* Tilled mineral soil
3 200 BP. Further increase in charcoal, increase in domestic grazing	
2 000 BP. Decrease in charcoal, reversion to bog communities (site abandoned by humans?)	*2 500 – 2 000 BP.* Peat growth on field system site begins. Decline in human activity
1 600 BP. Still little charcoal, but increase in cereals & herbs (due to domestic grazing and/or crops)	
850 BP. Increase in charcoal	*1 100, 850 and 500 BP.* Renewed human activity, with crops from 850 BP

Although the record shows wide fluctuations in the amount of charcoal deposited, there is constant evidence of fire in north-west Scotland. The precise role of fire in the formation and maintenance of mire communities may be unclear, but it is unmistakable that fire has played some role throughout their history. Moores and Stevenson (1998) refer to the charcoal record on Lewis as indicating 'burning in these areas for millenia'. The history of the vegetation and land use as a whole is not simple and the available evidence not easy to interpret, however the story is of post- glacial development and succession of vegetation influenced by a changing climate and variable human impact. The concept of a 'climax' vegetation ever having existed is debatable. For example, even a few thousand years of birch/hazel forest would have resulted in soil change, and if the human and/or climate-forced change to wet heath and bog had not occurred, a change toward another vegetation type undoubtedly would have.

1.2.2 Vegetation and land use after 1600

One view (Birks, 1988) is that almost complete woodland clearance in north-west Sutherland only occurred in the last two to three centuries. However Smout (1997) presents evidence from the first maps and surveys of the Highlands in the mid-1600's that indicates that much of the land was already bereft of woodland cover by this time, and presumably was much as we see it today. Fenton (1997) proposes that '....much of the Highlands have been virtually treeless for, say, 4000 years.' Walter & Kirby (cited Smout, 1997) propose that only 4 % of the land surface of Scotland in the Middle Ages was covered in woodland. At this time the goat was an important domestic browser/grazer, and Smout (1997) notes that in 1698, 100 000 goat skins were exported from Scotland to London. The other main domestic animals would have been cattle, horses and small sheep. A survey of ten farms in Assynt in 1799 showed a cattle to sheep ratio ranging from 4:5 to 1:5, with a mean of 1:3 (Smout, 1997), demonstrating the rise in importance of cattle from the late seventeenth to early eighteenth century (Dodgshon, 1994). This was reflected in the large numbers of cattle exported to England, an average 20 – 30 000 per year by the end of the 1600's (Whyte, 1979). Although Smout notes that Cheviot sheep became important in Highland land-use around 1760, they may have taken longer to become established in the north-west Highlands. During this time, the bog and wet heath areas would have been used as a source of peat for domestic fuel, turf for fertilising inbye land (Dodgshon, 1994), and for extensive grazing, with burning used to promote vegetation regeneration. It is not known whether fire at this time was used in a haphazard fashion, or whether there was some degree of sophistication in its use. Darling (1955) argues that the decline in cattle numbers and rise in sheep numbers at this time was accompanied by an increase in burning, leading to what is described as a regime of 'unbalanced grazing and fire.'

Although changes in the Highland economy and population were ongoing, the increase in importance of sheep accompanied a decline in the numbers of people on the land. After the unsuccessful 1745 uprising, many Highland clans lost their land to the Crown. The new owners (and many of the clan chiefs remaining) were not willing to uphold the old system of receiving rent 'in kind' from tenants, and increasingly looked to the introduction of sheep in large numbers for an income (Dodgshon, 1998). To make way for the sheep many people were cleared from the land, especially from the fertile inland straths. They were either forced to emigrate, or move to the industrial areas for employment, or they tried to make a living on the coast. The latter option resulted in the crofting system which exists today. Alongside this new emphasis on sheep, fire would still have been used as a management tool, and it is because of combined burning and heavy grazing that *Calluna vulgaris* (hereafter referred to as *Calluna*) is thought to have started to decline, in the mid eighteenth century according to Birks (1988). The decline in *Calluna*, which continues today, is currently of concern to nature conservation (Thompson *et al.*, 1995). On both the estates and common grazings the land use since the mid-18th century has probably changed very little, with sheep still the main source of agricultural income and management practices very similar. However the system is entirely dependent upon the Government subsidy for hill farming, even more so after the crash in sheep and lamb prices in 1998.

The current economic climate combined with proposed changes to the subsidy system (for example, reducing the sheep subsidy) could mean changing land use objectives for these areas, and consequent changes in the burning and grazing regimes. However, understanding the effects of changes in land management requires an understanding of the current management.

1.3 Current management of blanket bog vegetation, and the role of fire

1.3.1 Management objectives

The main land use for blanket bog, on both privately owned estates and croft land, is extensive grazing for sheep. Such areas are commonly referred to as 'outbye', 'common grazings', or 'hill grazings'. Due to the extensive nature of the grazing, blanket bog areas are not usually managed as separate units, but as part of larger areas incorporating other habitat types. Many of these areas are also used for deer stalking, and to a much lesser extent for red grouse shooting. Nature conservation as a land use is becoming increasingly important, with Bignal & McCracken (1996) noting that the conservation importance of extensive farming systems has long been under appreciated. Where once conservation was regarded as being almost in opposition to more traditional land uses, it is now more widely accepted that traditional land uses can be continued in a manner that is sympathetic to conservation aims. Indeed, conservation may be the only means of preserving these traditional land uses.

Forestry was, at one point, considered a major land use for peatlands. In 1978, over half of the afforested area in the north of Scotland owned by the Forestry Commission was on peat of some sort (Taylor, 1981). Drainage, fertilisation, and planting on turves were all used to aid tree establishment. Since then however this trend has changed, with the emphasis now on restoring blanket and raised bogs that were afforested. For example, different restoration techniques have been tried at Forsinard RSPB reserve in the Flow Country (Wilkie & Russell, 1997). This reversal in policy was due to an increasing awareness of the conservation value of blanket bog coupled with much of the forestry in these areas being uneconomic.

1.3.2 Management options

Drainage

Stewart & Lance (1991) studied the effectiveness of drains (or 'grips') in the North Pennines and found their effect on the water table to be very localised, and that there was no clear response of heather (drainage being meant to improve the heather cover). These authors supported the withdrawal of government subsidies for drains (in 1986), and there is now much interest in different techniques in blocking drains for restoration purposes. Barkman (1992) notes that 'strong' drainage of Dutch bogs can lead to eventual tree invasion, but this is presumably due to well maintained and/or extensive drains and controlled grazing, rather than a one-off attempt at drainage accompanied by uncontrolled grazing.

Grazing

More commonly thought of as a land use, grazing can also be used as a proactive management tool to achieve specific objectives (Andrews & Rebane, 1994). For example, the re-introduction of deer grazing to part of Forsinard RSPB reserve in Caithness is being carried out to alter the structure of the vegetation, and cattle are being used for similar purposes on parts of the RSPB Birsay Moors reserve on Orkney.

Burning

Burning is widely used as it is thought to achieve the aims of producing new growth for the sheep and deer (especially in the spring following a burn), and making that new growth more accessible. Fire is easy and inexpensive to apply, and it is the most widespread land practice in the Flow Country (Lindsay *et al.*, 1988).

1.3.3 Fire as a management tool

Burning in Scotland is subject to legislation which forms the basis of the Muirburn Code (Phillips, Watson & MacDonald, 1993), which sets out the legal requirements for burning as well as suggestions for using fire in different habitats. The main requirement is that burning is done (on land below 450 m) within the period 1st October to the 15th April, although it can be carried out with the landowners permission until the end of April. Fire is mainly used in the north-west to stimulate new growth for grazing animals, which is the 'early bite' referred to by Darling (1964). In central and eastern Scotland, burning is carried out on dry heathland principally for grouse, and small burns are required due to grouse behaviour. In contrast, the main aim in the north-west is to provide grazing for sheep and deer, in the form of the grass and sedge species which grow very quickly following a fire. As a consequence, there is no perceived need for burns of small area, and burns tend to be large and (Hamilton *et al.* 1997). This is further exacerbated by the lack of manpower available in these areas, and the few suitable burning days in a typical year (Currall, 1981) making burning difficult to plan for - which results in few (if any) people attending what are, for the UK, large fires.

The Muirburn Code does make some recommendations for burning blanket bog vegetation or on peat, but these are based on limited information. Far from following any burning code, some land managers use fire with what, at first; appears to be an indiscriminate approach. Darling (1955) refers to 'the irresponsible conditions under which burning is all too general in the West Highlands', and more recently Hobbs & Gimingham (1987) noted that there is no systematic burning in the north-west. Many authors have made recommendations regarding burning in blanket bog habitat, summarised in Table 1.2. As can be seen, not only is there no consensus about burning guidelines, but there is even debate over whether fire should be used at all on blanket bog.

Mention should be made of what Goodfellow (1998) refers to on Dartmoor as a 'culture of fire'. This also applies to the north-west, where fire is perceived as very much a natural part of land management. Although the main reason for burning is for sheep grazing, even if the sheep subsidies resulted in a drastic reduction in livestock it is likely that fire would still be used a great deal. Local people talk of areas 'needing a good burn' not so much from a grazing value viewpoint, but rather from informal consideration of heather age or amount of litter. It is this attitude coming against the 'no burn' attitude of conservation bodies that has caused many problems. To create the conditions necessary for change on both sides, it is necessary to work within this 'culture of fire' and promote the most appropriate use of fire, dependant upon the required objectives.

Table 1.2. Recommendations for management burning of blanket bog, adapted from Shaw *et al.* (1996).

Burning recommendations	Source
Bogs should not be burnt.	MAFF (1992) and MAFF (1992)
Bogs should not be burnt, or at least rotation not < 15-20 years.	Phillips *et al.* (1993)
(i) Burning on bog minimised; (ii) use variable burning cycles; (iii) conserve wet flushes; (iv) burn upland heath margins less intensively.	Usher & Thompson (1993)
Limited rotational burning and burning of firebreaks may be necessary close to public access points and footpaths.	Phillips, Yalden & Tallis (1981)
Burning of bog to be avoided, and fire should not be used in M17 or M18, in any other *Sphagnum*-rich community, and particularly not in any bog system with pools and ridges.	Rowell (1988)
Marked reduction in burning on bogs (allow development of mosaics).	Thompson *et al.* (1995)
Avoid burning bog or mires.	CCW (1992)
Bog areas should not be burnt at all.	NCC (1989)
"If management objectives for a site are to conserve or enhance an active peatland ecosystem, burning should not be used to control the vegetation."	RSPB (1995)
Bog vegetation should be burnt on a long cycle (with careful control) or not at all – recommended ban on burning bogs.	Coulson *et al.* (1992)
(i) Burning restricted to 1st December to 8th March; (ii) heather must cover >70% of the ground, and be >25cm tall; (iii) minimum burning rotation of 12 years (or 20 years?), with limitations on amount that can be burnt in any 3 year period; (iv) no burnt patches >2ha in extent; (v) every reasonable effort made to avoid damage to the underlying moss layer, particularly *Sphagnum*.	SNH (unpublished site filenotes from A. MacDonald & A. Coupar)

1.3.4 Effects on the physical environment

Lindsay *et al* (1988) summarise the effects of fire on the peatland environment. As with all fires, nutrients (in particular N and S) can be lost through smoke and volatilisation, with higher temperatures resulting in increased nutrient losses (Evans & Allen, 1971). The nutrients deposited as ash may either be used by vascular plants in regrowth, captured by the *Sphagnum* layer, or leached and lost from the system. Stevenson *et al.* (1996) found that fire frequency had an effect on mineral and nutrient content of dry heathland soils, but there is no equivalent information for wet heath or bog habitats. Fire in these habitats can result in a layer of waxes and bitumens being deposited on the peat, which may hinder plant/community recovery, or conversely may even protect the peat from erosion. When more severe fires occur, there may be complete vegetation loss and even some of the peat consumed. In these situations plant establishment on bare peat is very difficult (Gore, 1981), as the peat may continually erode due to wind, water, and effects of frost. On bare peat, the microclimate can also be very hot in sunlight, in part due to the low albedo of the peat surface. Severe fires can also be the initiator for severe erosion events, perhaps resulting in complete habitat loss (Mackay & Tallis, 1996; Tallis, 1987).

1.3.5 Effects on the vegetation, and subsequent recovery

Fire can kill a plant either through complete, or incomplete, combustion of the plant itself, or through exposure to radiative heat. Plant death or damage due to the first cause is obvious, but cell or tissue death due to heat alone, for a given temperature, is dependant upon the state of the cells at the time of the fire. Important factors are their degree of hydration, whether they are resting or metabolically active, and the duration of the temperature experienced (Whelan, 1995).

The ability of different species to persist after a fire can be split into two broad categories, referred to here as vegetative survival and reproductive survival. Most blanket bog management fires typically result in restricted damage to the moss and peat layers, and therefore also to the underground stems and rhizomes of vascular plants. As a result most individual plants involved in such a fire survive by vegetative means, however the surviving organs/tissues must still endure the flux of heat energy. Given that the thermal death point for typical mesophytic plant cells is between 50 and 55 °C (Hare, 1961; Larcher, 1995), the survival of plants above this temperature is due to the protection of important tissues. One way to achieve this is through ‘vegetative protection’ where meristematic tissue is protected, for example, in a tussock (e.g. *Molinia caerulea,* hereafter referred to as *Molinia*). Alternatively, in the case of shrub species a small degree of protection may be afforded by the stem bark. Most importantly in this habitat, protection can be offered by either the peat or the moss layer. This avenue of survival is utilised to some extent by all vascular species on a blanket bog, and the presence and continual upward growth of moss species (especially *Sphagnum*) may thus be important.

Reproductive survival involves the death of individual plants caught in a fire, with new individuals growing either from seed surviving the fire or arriving after the fire has passed. As noted above, the characteristics of management fires mean that many plants survive vegetatively, but reproductive survival will become increasingly important in certain situations, such as:

- after a severe burn, where the upper peat or moss layers, which contain the meristematic plant tissues, are consumed or the tissues damaged;
- where there are large areas of bare peat present already (perhaps due to previous fires or grazing);
- where the plants present do not possess the meristematic tissues necessary for vegetative regrowth. For example, old *Calluna* is less able to re-sprout, or a plant species present may have meristematic tissues that are not protected from fire.

There is little information about the effects of fire on *Sphagnum,* but there is observational evidence for fire having little impact on the moss. Daniels (1991) states that 'management burning is not normally harmful to *Sphagnum'* and Barkman (1992) that ‘fire is one of the least drastic disturbances in living bogs’. Both authors note that fire tends to pass through the vegetation layer on top of the *Sphagnum.* In contrast, there is anecdotal evidence, noted by Ward, MacDonald & Matthew (1995), that *Sphagnum imbricatum* recovers poorly after fire, and Mowforth & Sydes (1989) state that some *Sphagnum* species may be eliminated by fire, but cite no evidence to support this. Ratcliffe (1964) notes that certain *Sphagnum* species ‘seem’ particularly susceptible to fire (although again with no evidence), and highlights in particular the importance of the frequency of fire occurrence. The view that fire is harmful to blanket bog is the ‘default’ view, reflected in the guidelines in Table 1.2, that burning is generally regarded as being bad for the *Sphagnum* layer.

1.4 Fire definition and characteristics

1.4.1 Fire, combustion, and heat transfer

For a fire to occur fuel must be present, and in the case of vegetation fires that means plant material, dead or alive. Fire is the manifestation of the release of energy previously locked up in the plant cells as chemical bonds, this energy having originally been captured from sunlight by photosynthesis.

All fuels go through recognisable stages during a fire - preignition, ignition, and combustion. Energy must first be added to a fuel, raising its temperature. This endothermic process (called preignition or preheating) first results in some low-temperature volatiles (if present) being removed. Surface water is then evaporated (up to 100 °C), then adsorbed water is removed, and finally pyrolysis (decomposition by heat) of cell constituents occurs. One of the major plant components, cellulose, will start to volatilise at 250 °C, with rapid breakdown occurring at 325 °C (Pyne *et al.*, 1996). The products of volatilisation are flammable gases. Ignition occurs at the cross-over point between the endothermic reaction (preignition) and an exothermic reaction. The temperature required for ignition can vary, but for the attachment of a flame it is between 325 - 480 °C (Pyne *et al.*, 1996). The resulting process, called combustion, can then proceed in two different ways. The first and most recognisable is flaming combustion, where the gases released by pyrolysis mix with the oxygen in the atmosphere and burn to produce a flame. The faster these gases are produced, the further they have to travel from the fuel in order to mix with oxygen (the oxygen closest to the fuel being depleted), hence the variability in flame size. Smouldering (or glowing) combustion occurs where conditions do not allow flaming combustion to proceed, such as in densely packed fuel or where there are not sufficient volatiles given off (Pyne *et al.*, 1996). Smouldering results in incomplete combustion of the fuel components, and leaves many residues such as ash, charr and smoke.

The energy required to dry fuels and raise them to ignition temperature can be transmitted to the fuels by three possible mechanisms (Pyne *et al.*, 1996). Energy transfer by conduction requires materials to be in contact, so the distribution and size of fuel particles will determine the efficiency of this process. Convection transfers energy by the movement of heated air so materials above or downwind of a fire will receive heat in this manner, with wind direction and speed influencing this effect (Pyne *et al.*, 1996). Finally, energy transfer by radiation is probably the most important pathway, as the materials concerned do not need to be in physical contact with each other. This is the heat energy felt on approaching a fire.

1.4.2 Types of fire and quantifying fire behaviour

Types of fire

There are three types of vegetation fire commonly distinguished - ground fires, surface fires, and crown fires. The latter only occurs in wooded habitats when the fire moves through the crown of the trees, and very high fire intensities are reached. Ground fires occur when the fire burns (or more commonly smoulders) in the soil organic matter. Although ground fires on blanket bog (peat fires) have been studied in terms of fire characteristics (Frandsen, 1997; Hungerford, Frandsen & Ryan, 1995; Wein, 1983; Frandsen, 1991; Frandsen, 1997) and fire control/prevention (Chistjakov, Kuprijanov & Gorshkov, 1983), such fires are rarely a consequence of management burning in Scotland, due to the prevailing conditions during the statutory management burning period. The present study is therefore solely concerned with surface fires, which move through the surface vegetation and the fuel this provides. These fires can be further classified into headfires and backfires. The former moves with the wind, and is the commonest type of fire (Hobbs & Gimingham, 1987). A backfire burns against the wind, and moves much more slowly than a headfire burning at the same time.

Rates of spread

The rate of spread (ROS, usually measured in m min^{-1}) of a fire is the speed of movement of a particular fire-front. It is measured for the point or fire-front of interest perpendicular to the fire-front, and can vary a great deal with changing conditions (Pyne *et al.*, 1996). Cheney, Gould & Catchpole (1993) found that windspeed had a much greater effect on ROS than either fuel load, fuel moisture or fuel arrangement. ROS for management fires in the UK have shown wide variation: Thomas (1971) noted a bracken fire moving at 0.78 m min^{-1} and a heather/grass fire at 12.6 m min^{-1}; Hobbs & Gimingham (1984) recorded a range of values for dry heather moorland of between 0.12 to 2 m min^{-1}; Kayll (1966) in similar habitat recorded a range between 3 to 6 m min^{-1}; and Currall (1981) recorded a speed of 5 m min^{-1} for a wet heath fire.

Fire temperatures

Although maximum flame temperatures of 1 900 to 2 200 °C are theoretically possible from vegetation fuels, temperatures greater than 1 650 °C are regarded as 'exceptional' (Pyne *et al.*, 1996). The commonest flame temperature range is much lower, at 700 to 980 °C with maximum temperatures of 800 to 1 200 °C. Temperatures reached during smouldering combustion are lower than for flaming combustion (peaking at 600 °C, but typically above 300 °C), but can last much longer (Pyne *et al.*, 1996). Smouldering combustion is a feature of fires that has been little studied in comparison to the more obvious flaming fire-front. The recording of temperature in UK management fires has focused on maximum temperatures, and the following maximum temperatures for the canopy of dry heath fires have been recorded: 220 – 840 °C (Whittaker, 1961); 340 – 790 °C (Hobbs & Gimingham, 1984); 940 °C (Kenworthy, 1963); 155 – 581 °C (Allchin, 1997). Temperature is discussed further in Chapter 3.

Fire intensity

Although fire temperature is one of the most characteristic variables of a fire, it only quantifies one aspect of a fire. As noted by Whelan (1995), it gives no indication of the overall energy released. To overcome this, the concept of fire intensity has been developed, which involves the quantification of the time-temperature relationship, or heat flux. There are several different ways of measuring fire intensity, and methodologies relevant to the present study are described in detail in Chapter 4. One method is to measure the total energy output for a given area over the duration of the fire (units of kJ m^{-2}). Another, perhaps the most commonly used worldwide, is 'fireline intensity', first defined by Byram (1959), which is the energy release per unit time per unit length of fire-front (units of kW m^{-1} or kJ s^{-1} m^{-1}).

Table 1.3. Typical ranges of fire intensities for boreal forests, from Van Wagner (1983).

Fire description	Intensity (kW m^{-1})
Smouldering fire deep in organic layer	<10
Surface backfire	100 - 800
Surface headfire	200 - 15 000
Crown fire with a single front	8 000 - 30 000
High-intensity spotting fire	Up to 150 000

Table 1.3 gives a rough guide to intensity values for boreal forests, but a warning is sounded by McCaw, Smith & Neal (1997) who note that fire intensity values should be used with caution when comparing fires in fuel types that are 'structurally very different', due to different fire

behaviour in response to fuel arrangement. Nonetheless, intensity values can convey much information about a fire. Its measurement in the UK has been very restricted, but some data are available. A range of 43 - 1112 kW m^{-1} was recorded for controlled dry heathland fires (Hobbs *et al.*, 198a) with 2430 kW m^{-1} being estimated for an uncontrolled dry heathland fire (Kayll, 1966). Also in dry heathland, Allchin (1997) recorded total heat flux per unit area, with mean values ranging from 17 857 to 43 681 kJ m^{-2}.

Other fire characteristics

Various other fire characteristics can be measured. Flame length is measured from the point of origin to the tip of the flame, and is a function of fireline intensity. Flame depth measures distance from the front of the fire to the rear of the flaming zone. A commonly used measurement in forest systems is tree scorch height, which can be used as a proxy measure for intensity of surface fires (Pyne *et al.*, 1996).

1.5 Variables that affect fire behaviour

1.5.1 Weather

Season

Many areas have well-defined fire seasons, and the fire behaviour and effects at these times may be reasonably predictable, given no extreme or unusual conditions (Whelan, 1995). Fires outwith the normal season can exhibit different behaviour and effects due to the different environmental and biological conditions. For example, summer fires on heathland and moorland, due in the main to drier conditions, can have much more severe effects on the environment than normal management fires (Legg, Maltby & Proctor, 1992; Maltby, Legg & Proctor, 1990). Fires out of season can also affect the recovery of plants, for example Kauffman (1990) demonstrated the different responses of sprouting shrubs in North America after different seasons of burn. Fuel characteristics can also vary with season, for example in redberry juniper (*Juniperus pinchotil* Sudw.) in the USA, where seasonal variation in fuel characteristics were highly correlated with length of pre-heating ignition time (Bunting, Wright & Wallace, 1983).

Windspeed

Cheney *et al.* (1993) found that as windspeed increased, the headfire width required to reach a steady ROS also increased. Whittaker (1961) proposes that higher temperatures result from higher windspeeds, however Hobbs & Gimingham (1984) propose that higher windspeeds may result in faster fires that consume less vegetation and have lower temperatures. With the windspeed directly affecting the ROS of a fire, it can have an extreme influence on fireline intensity (see Chapter 4).

Temperature and relative humidity

Ambient temperature alone can be important in that a fuel at a higher temperature (all other factors being equal) requires less energy to raise it to ignition temperature. Whether a fuel is exposed to solar radiation has a great effect on its temperature (Teie, 1997; Pyne *et al.*, 1996), with topography therefore important in determining the heating effect of sunlight. Temperature also acts in conjunction with relative humidity (and other factors) to affect fuel moisture (see below), and in turn affects fire intensity.

Rainfall

Precipitation preceding a fire will affect the moisture content of the fuel. Long term precipitation will affect live fuel moisture, but dead fuels can be affected very quickly by low magnitude precipitation events (Teie, 1997). Precipitation also affects the ground moisture, which in turn will affect the moisture content of fuels in contact with the ground.

1.5.2 Site

Pyne *et al.* (1996) note that the main factors of topography that affect fire behaviour are altitude, aspect and slope. Altitude has a direct effect on the overall climate (notably decreasing temperature with increasing altitude), with subsequent effects on the vegetation and fuel present. Aspect can affect vegetation growth similarly, and increased insolation can result in fuels drying more quickly (Teie, 1997). Slope has a direct effect on flame length and rate of spread of surface fires, with greater pre-heating of fuels upslope of a fire.

1.5.3 Fuel

Amount

The amount of fuel (referred to as 'loading') can simply be expressed as mass per unit area. However, it is more commonly split into size classes, and in North America four size categories are commonly used (Teie, 1997), shown in Table 1.4. The smaller size classes are affected more quickly by environmental changes, as well as being the first fuels to ignite. In addition, care is usually taken to distinguish between live and dead fuels, as dead fuels also react quickly to environmental changes. The amount of fuel actually available to a fire (available fuel load) depends on the prevailing or given set of conditions, but it is generally less than the amount potentially available (potential fuel load), which is the maximum available given the most severe fire conditions.

Table 1.4. Fuel size class and response time categories used in North America. Compiled using data from Teie (1997).

Description	Diameter	Response time
Grasses and litter	0 to ¼ inch	1 hour
Twigs and small stems	¼ to 1 inch	10 hours
Branches	1 to 3 inches	100 hours
Large stems and branches	3 to 8 inches	1 000 hours

Type and distribution

Fuels can be categorised by species, or by plant parts (e.g. woody material and leaves). Johnson (1992) demonstrates how the heat of combustion (energy output per mass of fuel) can vary between species, and also within species, if different plant parts are sampled. A more important categorisation is into live and dead material - the dead material requires less heat input to ignite, and then burns faster (Teie, 1997). Catchpole, Catchpole & Rothermel (1993) noted that some fire models are unreliable in predicting fire behaviour in mixed fuels, and subsequent laboratory tests demonstrated different fire behaviour due to different types, sizes and distributions of fuel. The horizontal distribution of fuels affects the homogeneity of the fire, and areas particularly low in fuel may act as a firebreak. In a very patchy fuel environment, a fire will have a lower rate of spread and lower intensity (Cheney, Gould & Catchpole, 1993). Fuel can also be distributed vertically, most importantly in forest fires where 'ladder fuels' can provide a route for the fire from the surface into the canopy (Pyne *et al.*, 1996).

Size and shape

Fuel size and shape can be summarised by one important measure: the surface area to volume ratio. The higher the ratio, the quicker the fuel will dry, the less heat will be needed to ignite it, and the quicker it will burn (Teie, 1997).

Moisture content

Moisture must first be removed from a fuel before it can burn. If there is insufficient heat to do this, the fire cannot spread (Pyne *et al.*, 1996). Moisture content (expressed as % dry weight) can range from <5 % in dried grasses, to 300 % in live fuels (Teie, 1997), although Pyne *et al.* (1996) give a mean seasonal moisture content for bluebeard lily as 1 027 %. Surface litter with a moisture content of 45 % was found to be too wet to carry a surface fire set to reduce thinning slash fuel loads (McCaw, Smith & Neal, 1997). Anderson (1990) emphasises the importance of, and variation in, the response of fine litter moisture content to a changing environment, in particular changes in relative humidity. Response time (or timelag) is the time taken for a fuel to lose or gain approximately 63 % of the difference between the starting moisture content and the equilibrium moisture content (the steady-state moisture content for the new set of environmental conditions). Dead grass fuel can have a response time of as little as 12 minutes to a change in relative humidity from 90 to 20 %. The four commonly used fuel size-classes in North America also have associated response times, which are 1 hr, 10 hr, 100 hr and 1 000 hr (Table 1.4). However Anderson (1990) and Pyne *et al.* (1996) point out the errors that can be caused by such oversimplification - for example, the smallest size class (1 hr response time) fuel category incorporates both recently cast pine needles and dead grasses, which behave very differently to moisture changes.

1.6 The fire regime

An appreciation of the fire regime concept is essential in any fire ecology study. This involves consideration not only of single fire events, but rather the characteristics and effects of fires over a much longer timescale. Whelan (1995) has defined the following components of a fire regime:

- fire intensity;
- fire type;
- fire frequency;
- season of burning;

- extent of fires (including patchiness).

The effects of fire regime in a particular habitat are thus the cumulative effects of fire events over time. As well as little being known about individual fires in north-west Scotland, even less is known of the overall fire regime. Aerial photographs have been used to determine the extent and frequency of burning in dry heathland (Hester & Sydes, 1992), but the fast regrowth of grass and sedge species after a fire in the north-west makes these burns 'disappear' very quickly (Stevenson *et al.*, 1996). Very little (or no) records are kept of how and where fire has been used, but anecdotal evidence suggests that some areas are burnt very frequently. Goodfellow (1998) notes that *Molinia* dominated habitat on Dartmoor is burnt every 3 years or so, and this may also be the case in some areas in the north-west.

Mimicking the 'natural fire regime' is often the aim of a management burning programme, but the validity of this concept in north-west Scotland is questionable. Palaeoecological evidence described earlier in this chapter indicates that fire has been a part of the landscape almost continuously since glaciation, but we do not know the precise role fire played. Given that the presence of man was very quickly felt in Scotland after glaciation, there may never have been a settled 'natural' fire regime. The usefulness of this concept in defining a prescribed fire regime will be discussed later (Chapter 7).

1.7 Aims and objectives

This chapter has emphasised the importance of the blanket-bog habitat in agricultural, conservation and cultural terms, and the major role that fire plays in the management of this habitat over much of its area. We possess very little knowledge of either the effects of fire on the blanket bog habitat, or the characteristics of the actual management fires themselves. This thesis therefore addresses these two areas, with the broad aim that the results be applicable to land management policies, but also to guide future research.

The effects of fire on the *Sphagnum* layer is of prime concern, as *Sphagnum* is perhaps the most important and defining component of the blanket-bog habitat. Very little is known about the effects of fire on *Sphagnum*, and inspection of blanket-bog vegetation after fire (in 1995 and

1996) revealed that fire severity appeared to be spatially very variable. In particular, damage to *Sphagnum* appeared to be more severe where the remains of a shrub, or clump of shrubs (usually *Calluna*), were found. This study therefore focuses on this 'interface' between shrub and *Sphagnum*, and plot selection is stratified to include such plots, but also to represent plots at the other end of the fire severity spectrum, i.e. areas of *Sphagnum* with no shrub component. The study sites used, and the criteria for selecting both sites and the study plots within them are described in Chapter 2. The specific objectives for subsequent chapters are to:

- describe and quantifiy the fuels available on blanket-bog (Chapter 3);
- develop equations to predict fuel load, using non-intrusive techniques (Chapter 3);
- describe typical conditions under which management fires occur (Chapter 4);
- quantify the type and amount of fuel consumed in fires (Chapter 4);
- describe the fire temperature regime, both vertically and horizontally across the habitat (Chapter 4);
- quantify different measures of fire intensity (Chapter 4);
- compare measures of intensity and temperature measurements (Chapter 4);
- assess the suitability of fuel variables to predict fire intensity (Chapter 4);
- determine the effect of fire on the *Sphagnum* layer, in particular with respect to position, fuel, and fire characteristics (Chapter 5);
- determine the rate of recovery of *Sphagnum* after fire, and the effect of grazing (Chapter 5);
- determine whether fire does result in more *Calluna* and *Molinia* being available to herbivores, and whether burnt areas are grazed more than unburnt areas (Chapter 6).

The results from the areas of fire and fuel characteristics, and vegetation recovery, are brought together in Chapter 7, where the overall objectives for management fires are considered along with their actual effects. The possible advantages and disadvantages of management fires are discussed, and suggestions made for the formulation of management guidelines for burning on blanket bog. The different ways of characterising fires are discussed with respect to their effectiveness for achieving different objectives. The most important areas for further research, with regard to blanket-bog management and fire ecology in general, are highlighted.

Chapter 2 DESCRIPTION OF STUDY SITES AND PLOT SELECTION

2.1 Introduction

This chapter describes the main attributes of, and selection of, the study sites; the selection of study plots within each site; the methods of marking and re-locating the plots; and the exclosures used on some of the plots. All sites were burnt in the spring of either 1996, 1997 or 1998, with fires being set for management and/or experimental purposes. Sites are therefore referred to here using site name or number/letter, and the year of burn.

The sites used are located in the Coigach and Assynt areas in north-west Scotland, where the climate is described as hyperoceanic (Birse, 1971), and the study areas all experience between 225 and 250 rain days per year (Figure 1.1). This climate has resulted in peat formation over much of the landscape, with peaty soils on steeper slopes and deep peat deposits on flatter areas. Although outcrops of limestone do occur in the area (notably at Inchnadamph, NC2720, and Knockanrock, NC1909), most of the area is underlain by acidic igneous rock, and combined with the peaty nature of the soils results in a wet and nutrient-poor environment.

All sites are part of extensive hill grazings, with sheep kept by either the crofters or landowners. It was not possible to estimate the density of sheep on the sites, partly due to the sensitivity of obtaining such information, but mainly because stocking densities are usually arrived at using the total number of sheep and the total area available to them. However, at all times of the year, but especially during winter when supplementary feeding takes place, the sheep show strong preferences for certain habitats or areas. Even in summer, although the sheep range freely over large areas, some preference for roadside habitats, and drier habitats, is still evident. In addition, sheep numbers periodically decrease when pregnant ewes are kept on inbye land, sheep are sold, or some animals moved to the east of Scotland to over-winter. Stocking density figures derived from number of sheep and area of ground available therefore bear little resemblance to the actual grazing pressure experienced in any one particular habitat. Red deer also had access to all sites, but the deer grazing pressure is again unknown. Techniques such as dung counts could indicate animal usage of the sites used, but such work was outside the scope of this study. Observations of grazing pressure indicators are noted where appropriate in this study.

2.2 Site selection and vegetation type

The purpose of the study sites from each year are summarised below:

- 1996. Four sites were used to record vascular plant regrowth and recovery of the *Sphagnum* layer after fire. These sites were first visited between 2 and 6 days after they were burnt.
- 1997. Three sites were set up primarily to record maximum fire temperatures, fuel load, and effects of increased fuel load, but loss of samples and data meant that the only data available recorded the recovery of the *Sphagnum* layer.
- 1998. The aim of these sites was to record the temperature regime of fires and quantify fire intensity. Five sites were used, with some plots being harvested (to develop fuel loading equations) and others being burnt. *Sphagnum* recovery was also recorded on these sites.

The main criterion for site selection in all years was that they had 'typical' blanket bog vegetation for the north-west of Scotland. After examining blanket-bog habitat in this area, the most common vegetation type appeared to correspond to M17 *Scirpus cespitosus – Eriophorum vaginatum* blanket bog of the National Vegetation Classification (NVC), which is succinctly described by Rodwell (1991) as '........ a blanket bog community dominated by mixtures of monocotyledons, ericoid sub-shrubs and Sphagna, the two former groups of plants giving the vegetation its distinctive character when it is seen from a distance, but the last often occupying more of the ground, at least in wetter stands.' This vegetation type appears to correspond most closely to the 'Trichophoreto-Eriophoretum typicum' (Western blanket bog) from McVean & Ratcliffe (1962). The following, summarised from Rodwell, describe the environmental conditions under which M17 is commonly found:

- climate – extreme humidity, and mild and wet winter;
- altitude – usually below 500m, extending down to sea level in north-west Scotland;
- peat – typically 2 – 4 m deep, usually permanently waterlogged, pH 4 or less, nutrient-poor;
- situation – broad glen bottoms, low level plateaux, watersheds.

Rodwell notes that M17, although found over extensive areas in the Flow Country, in the north-west is usually restricted by the broken terrain to the small glens, plateaux and watersheds referred to above. The result is extensive areas of hill grazing made up of a mosaic of blanket bog and wet heath vegetation types. The above environmental criteria were of assistance in initial identification of potentially suitable areas of the 1996 burn sites, as they were not examined until after each fire event. On these sites, the remains of plants (including their spatial distribution) and the *Sphagnum* layer also helped in suitable site identification. For locating sites prior to burning (1997 and 1998 sites), the above criteria in conjunction with live vegetation characteristics were used. The commonest plant species found in the M17 community, and on all study sites, were:

- *Calluna*
- *Molinia*
- *Erica tetralix*
- *Trichophorum cespitosum*
- *Narthecium ossifragum*
- *Eriophorum angustifolium*
- *Eriophorum vaginatum*
- *Potentilla erecta*
- *Sphagnum capillifolium*
- *Sphagnum papillosum*

Species that were notable for being patchily distributed and/or occasionally dominant were;

- *Myrica gale*
- *Drosera anglica*
- *Hypnum jutlandicum*
- *Cladonia impexa* and *C. uncialis*
- *Carex echinata*
- *Polygala serpyllifolia*

In common with many habitats, there is usually a mix of community types present on a blanket bog. In the case of M17 in the north-west, it often appears to grade into M15 *Scirpus cespitosus – Erica tetralix* wet heath in drier areas, and into vegetation similar to M18 *Erica tetralix – Sphagnum papillosum* blanket bog in places where the vascular plant layer becomes sparser and shorter. To confirm community identification, five random 1 m^2 relevés were recorded prior to burning on each of the three 1997 study sites. Percentage cover of all vascular, bryophyte and lichen species were recorded, and the data entered into the computer program Comkey (Legg, 2000). This program compares either individual relevé data, or a community summary derived from more than one relevé, with NVC community data. The following matching criteria were used (in order of use and individually) for the community data: matching species; weighted species match; matched frequencies; frequency-weighted match. The matching criteria used for individual relevés were (in order of use): matching species; weighted species match; presence-weighted similarity. Each of the three community summaries, for all of the matching criteria, resulted in a close match with M17 blanket bog community. Twelve of the fifteen individual relevés also matched closely with M17. The remaining three matched closest with M15 (*Scirpus cespitosus – Erica tetralix* wet heath), with M17 being the second closest match. This illustrates the mosaic of vegetation types typically found over the blanket bog habitat. Changes from M17 to M15 commonly occur at abrupt and obvious limits at the edge of the bog habitat, but the topography of the bog can also result in a small-scale mosaic of vegetation types within the habitat.

As well as the topographical and vegetation selection criteria above, a further requirement was that the area was selected by the land managers for burning, without any reference to this study. The 1996 fires occurred prior to involvement with this study. For the 1997 fires, discussion with Nicky and David Davies of Inverpolly Estate during late 1996 identified the general areas of hill grazing that they wished to burn the following year. Suitable blanket-bog sites were then identified within these areas, and burning carried out to ensure that these sites were burnt in 1997. The 1998 burns were located beside a management burn. A final requirement was that a road had to be less than 1 km away, to allow field equipment to be carried easily to each site.

2.3 Study site locations

The grid reference of each site, date of burning, and an estimate of the area of each burn are given in Table 2.1. Areas are not given for the 1998 burns, as these were small experimental burns. The locations of each of the 1997 and 1998 burns and one of the 1996 burns are also shown on Figure 2.1. The remaining 1996 sites are located west of Figure 2.1 (Loch a' Chaoruinn and Mast) and to the north, in Assynt (Loch Poll). Two additional management fires, which were attended but not recorded for research purposes, are also shown on this map.

2.4 Study plots: 1996 and 1997 burns

2.4.1 Selection

The importance of the *Sphagnum* layer in the blanket-bog habitat was emphasised in Chapter 1. Observations of the effects of fire on blanket-bog vegetation indicated that the most severe effects on *Sphagnum* occurred where the *Sphagnum* carpet was interrupted by a shrub or clump of shrubs – referred to here as the shrub/*Sphagnum* interface. In such situations, the fire was apparently more intense, due to fuel amount and position. Plot selection was therefore not

Table 2.1. Study site summary showing names, date burnt, grid reference and burnt area.

Site	Date burnt	Grid reference	Burnt area
1996			
Badagyle	April 1996	NC 058 113	~ 25 ha
Loch Poll	April 1996	NC 099 321	~ 30 ha
Loch a' Chaoruinn	April 1996	NB 987 140	> 100 ha
Mast	April 1996	NB 999 117	~ 90 ha
1997			
Blar Garvie	26/4/97	NB 049 129	~ 15 ha
Creag na Braiste 1	16/4/97	NB 069 132	~ 30 ha
Creag na Braiste 1		NB 065 134	
1998			
Site A	18-19/4/98	NB 071 121	*All 1998 burns were very small, and the two 1997 Creag na Braiste sites were burnt as part of the same fire.*
Site B	22/4/98	NB 072 122	
Site C	18-21/4/98	NB 073 122	
Site D	19/4/98	NB 071 123	
Site F	19/4/98	NB 071 129	

random across each site but was stratified to focus on the shrub/*Sphagnum* interface, as well as including plots with no shrubs present, referred to as 'flat' plots.

Within each site a 40 m long transect (or two 20 m transects, where space was limiting) was marked out, so as to avoid any obvious habitat/vegetation changes or linear features such as the edges of peat cuttings. Random points were then located within an area extending up to 10 m either side of each transect by using random numbers to determine:

- distance along the transect;
- selection of either side of the transect;
- distance from the side of the transect (up to 10 m).

At each random point, the nearest patch of suitable vegetation was identified. This was either the shrub/*Sphagnum* interface described above or flat (no shrub) areas. Five shrub/*Sphagnum* plots on the 1996 sites, and ten shrub/*Sphagnum* plots on the 1997 sites were located in this manner. Random numbers were then used to generate a random bearing from each plot and distance between 2 and 5 m, and the closest suitable patch of vegetation identified beside this next random point. All shrub/*Sphagnum* plots were therefore located in pairs, with the within-pair distance always less than the smallest between-pair distance. The minimum distance of 2 m between the plots within a pair was maintained to lessen any effects of the cages (section 2.4.3)

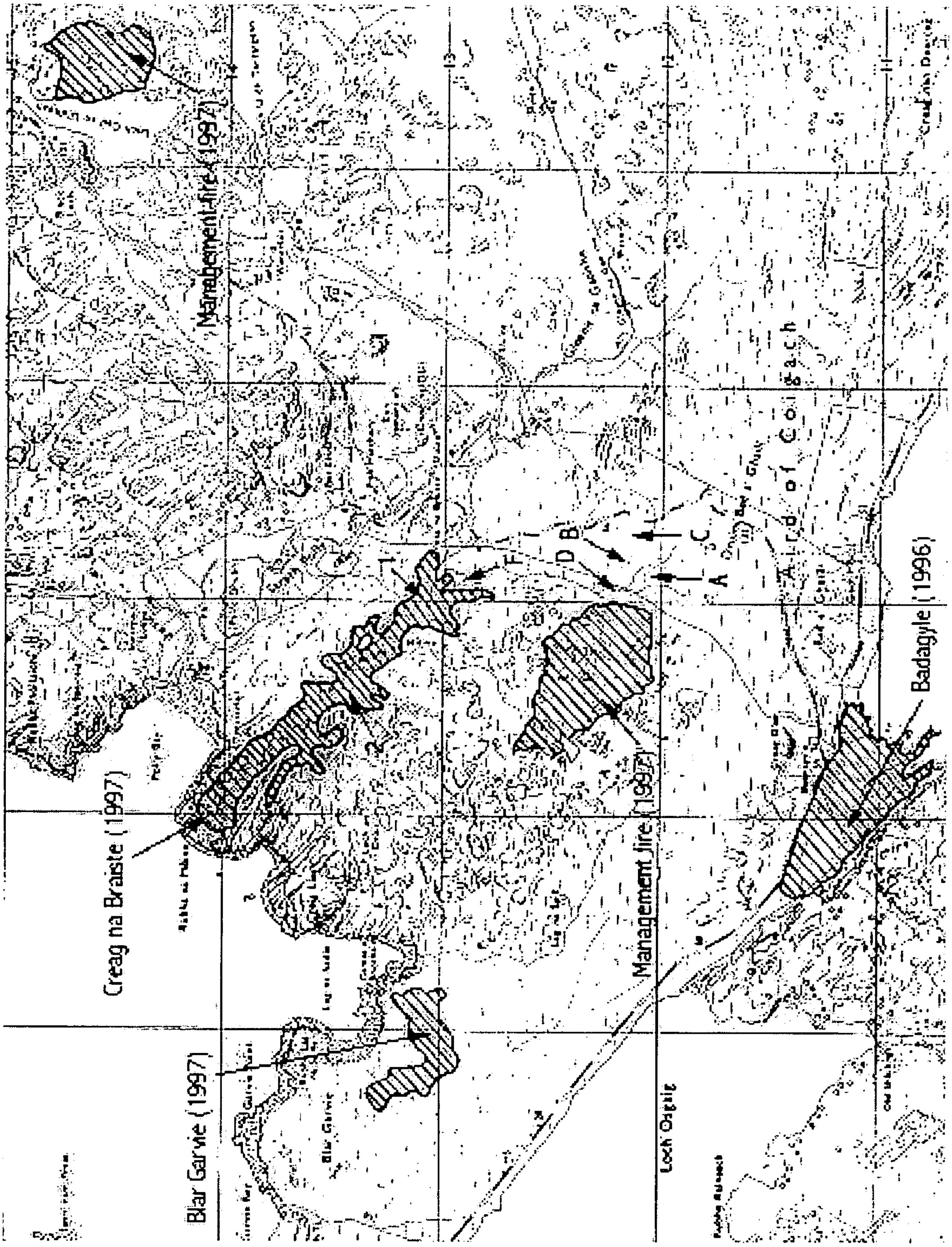

Figure 2.1. Map of the main study area on Inverpolly Estate, with study sites located by arrows. The numbers on the Creag na Braiste burn show the two separate sites, and letters indicate the 1998 sites. Two additional management fires from 1997 are also shown.

attracting animals (wool was sometimes found on the corners of the cages, presumably due to the sheep using the cages as scratching posts). Random number combinations that resulted in plot pairs being too close were discarded. On the 1996 burn sites, all plots were shrub/*Sphagnum* plots, but on the 1997 sites, approximately a quarter of the plots selected were flat. The flat plots on the 1997 sites were located singly (i.e. not paired), but again were further away than the largest within pair distance from any other plot. At each plot location, the depth of the underlying peat was checked using a rod to ensure it was at least 0.5 m.

2.4.2 Plot marking and recording

At each plot location, metal marker pegs were positioned at the opposite corners of a 25 cm x 25 cm quadrat. The pegs were made from 2.4 mm diameter mild steel welding rod, cut into 25 cm lengths, bent at the top to form an inverted 'L' shape, and given one coat of black Hammerite rust-prevention paint. The pegs were pushed into the peat so that the upper part was flush with the peat or moss. This made the pegs unobtrusive to avoid attracting animals, however the pegs became harder to re-locate with successive years of vascular plant and *Sphagnum* growth. They could usually be re-located by feeling in the moss by hand, but for the last recording visit to all sites in April 1999, a metal detector was required to locate some markers.

At each plot, 35 mm slides were taken on each recording date, weather conditions permitting. In order to minimise the potential impact of trampling on each site, a set route was walked between plots, and each plot recorded from the driest side, as the wetter the area the more susceptible the habitat is to damage.

2.4.3 Grazing exclosures

One of each pair of shrub/*Sphagnum* plots on the 1996 and 1997 sites was randomly selected as a 'no grazing' plot and caged, with the other left open to grazing animals. All of the flat plots on the 1997 sites were caged. Each cage was made from angle iron (20 mm by 20 mm by 3 mm thick), cut and bent to form an inverted 'U' shape ('⊓'). Two of these pieces formed opposite sides of a single cage, with the bars at the top being 50 cm long, and the legs 70 to 80 cm long. The two sides were joined by 50 cm long pieces of flat bar (20mm by 3 mm thick), with nuts and bolts used to secure the crossbars to the cage sides. All cage sides and crossbars were given one coat of Hammerite to inhibit rusting. Cage construction took place on each field site, and the legs of each assembled cage were simply pushed into the peat to a depth of 20 – 30 cm. Each

25 cm by 25 cm caged plot therefore had a buffer zone around it (12 cm on either side to the cage sides), to minimise any environmental effects of the cages.

Netlon nylon fruit cage netting (19 mm x 19 mm mesh size) was used to cover the sides and top of each cage. The netting was secured to the cage frame by twisting small pieces of plastic coated electrical wire through the netting and around the frame. The top and each side were separate pieces of netting, allowing sides to be adjusted to take into account topography and vegetation, and the top could easily be 'flipped' open to allow access from one side. These cages proved very resistant to interference by grazing animals – both deer and sheep were commonly observed around cages, and at one point a herd of cattle was seen on the Badagyle site. The result of the attentions of the cattle was simply that the cages were pushed further into the peat. Despite some frames being bent in places, the cages never collapsed, and the netting still protected the plants from grazing. Although sheep and deer could presumably bite through the netting easily, neither this, nor the results of severe grazing, was ever observed. In some cases, the top of the cage was found pulled back to some extent, but as this was never done completely the grazing effects on the plants in the cage were observed to be negligible. Five cages were located on each of the four 1996 burn sites, and fifteen cages on each of the 1997 burn sites.

2.5 Study plots: 1998 burns

The selection of these plots was done with very different experimental aims to the previous years plots, but with the same habitat and vegetation selection criteria. As the areas to be burnt were small, the six sites chosen could be quite close together. Time did not permit one of the six chosen sites to be burnt, so only five sites are shown on Figure 2.1.

On sites A, B and C, fourteen 1 m^2 plots were selected, and seven plots selected on sites D and F, by laying out either one 40 m transect or two 20 m transects. Random numbers were again used to determine distance along and to the side of each transect, although plots were kept within 3 m of the transect line, as it was initially planned that several plots would be burnt at once. Plot selection was stratified so that either shrub/*Sphagnum* plots or flat plots were selected. Plots were not paired on these sites. After selection, all plots were marked using metal pegs at each corner, as well as a metal peg in the exact middle of the plot to record location of the thermocouples used. Canes marked the beginning and end of each transect line, and no exclosures were put out on these plots.

Chapter 3 FUEL PREDICTION AND LOADING

3.1 Introduction

The study of fuel and fire characteristics has been neglected in the UK, despite the wealth of information available from overseas demonstrating the importance of these characteristics in determining fire behaviour and effects. Basic texts about prescribed burning (Bunting, Kilgore & Bushey, 1987), fire-fighting/control (Teie, 1997) and fire ecology (Pyne *et al.*, 1996; Whelan, 1995) either start with an explanation of fuel and fire characteristics or assume such knowledge. This is regarded as necessary background information required before the use, control and effects of fire can be explored and understood, and should be part of any fire ecology study (Johnson & Miyanishi, 1995).

Fire behaviour is dictated by the fire environment, and relevant variables are summarised in the 'fire environment triangle' (Figure 3.1), which emphasises the importance of fuel, weather and topography.

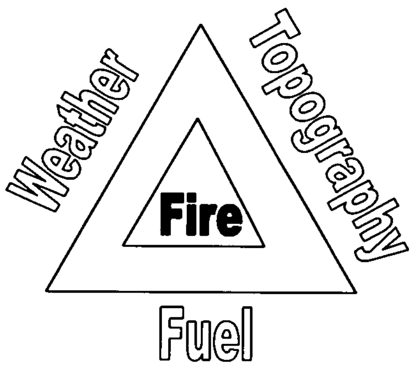

Figure 3.1. The fire environment triangle, which stresses the importance of fuel, weather and topography in influencing fire behaviour. The inclusion of fire itself in the middle indicates that fire can itself influence the fire environment. From Pyne (1996).

An understanding of fire and its effects in north-west Scotland starts with an understanding of the fuels involved – collectively referred to as the fuel complex. Many field-based methods have been used for quantifying fuel, for example straightforward biomass harvesting (Allchin, 1997), line intersection methods (Van Wagner, 1968), or by measuring attributes of the fuel itself such as plant stem length or diameter, or measuring plot-level variables such as canopy cover or stem density (Halpern, Miller & Geyer, 1996). Brown, Oberhue & Johnston (1982) summarise methods applicable to surface fuels, including those used in this study. Data generated using such techniques are often then used to model fuel loading or other fuel attributes using, for example, simple biometric relationships (Pereira, Sequeira & Carreiras, 1995), remote sensing (Keane *et al.*, 1998), or incorporating a GIS to model spatial aspects of fuels (Ball, 1997; Perry, Sparrow & Owens, 1999). The above techniques produce estimates of important fuel characteristics such as total biomass (Halpern *et al.*, 1996), dead to live fuel ratio (Johnson, 1986), surface area to volume ratio (Fernandes & Rego, 1998), or fuel moisture levels (Ball, 1997). The biometric approach to predicting fuel characteristics is widely used because of the prohibitive time and effort required for repeated direct harvesting of fuels. Once predictive equations have been developed for a fuel type they are then easily used, subject to further testing and refinement as required. This method of quantifying fuel can involve the use of one variable to predict biomass (Telfer, 1969) through to the measurement and use of several independent variables (Halpern *et al.*, 1996). It can be applied to several types of fuel at once, or in detail to one fuel type, where the plant species in question constitutes an important part of the fuel complex. For example Frandsen (1983) modelled *Artemisia tridentata* (big sagebrush) in the USA, developing equations capable of predicting biomass within different fuel size classes, highlighting an important fuel characteristic, the size-class distribution. The smaller the fuel size, the quicker it dries, the easier it ignites and the faster and more intensely it burns (Teie, 1997).

The different types of fuel available are also important in determining fire characteristics and effects. The surface fuel present in northern (boreal) ecosystems is not a single fuel type, nor is it spatially continuous (Van Wagner, 1983). Three surface fuel types are identified by Van Wagner: dead material, moss or lichen, and fine shrubs. These fuel types can be recognised on blanket-bog in north-west Scotland, where the shrub component is mainly *Calluna,* with *M. gale* locally important. The dead fuel mixture is often dominated by *Molinia* litter, but includes *E. vaginatum*, *T. cespitosum*, and any other sedges and grasses that may be present. The moss and lichen component is dominated by *Sphagnum* in various forms (lawn, hummock, pool) and (hypnoid) mosses such as *H. jutlandicum*, typically in hummocks. The degree to which these different fuels are available for a fire depends to a great extent on their moisture content, which can vary between fuels even in a common environment. Different types of fuel can also vary in other characteristics, including size-class as discussed above. An obvious example of the result of such differences is demonstrated by comparing grass fuel and fine woody fuel – under given field conditions the grass fuel will dry quicker, ignite sooner and burn faster than woody fuel, so the amount of grass fuel may be very important in determining fire ignition and spread.

Fire ecology studies in the UK have concentrated on post-fire vegetation recovery, with very little being done on the pre-fire conditions (fire environment and fuels) and the fire itself (fire behaviour and characteristics, which are discussed in the next chapter). When fuel has been taken into account in studying heath fires, it has been common to use the age or height of *Calluna* as a proxy measure of the amount of fuel available. This was the approach adopted by Whittaker (1961) and Kenworthy (1963), and is the method recommended in the Muirburn Code (Phillips *et al.*, 1993). However, this does not take into account the other fuel types that may be present, and which may be important in affecting fire behaviour. This lack of appreciation of fuel characteristics is reflected in the few studies that have addressed fuel attributes. Hobbs & Gimingham (1984) harvested a small number of 0.25 m^2 quadrats (one per stand burnt), and divided the vegetation into different components. These biomass values were then used to calculate fire intensity values, however the small sample size reveals no details about within-stand and within-fire variability in fuel load, and therefore variability in fire characteristics. Allchin (1997) estimated fuel by harvesting 0.25 m^2 quadrats before experimental fires in lowland heath in Dorset, and separated the fuels by species. Although only one quadrat per experimental area was harvested, replicated plots ($n = 4$) resulted in mean and standard error estimates for fuel load, which showed the clear difference between the 'high' and 'low' fuel load used. In contrast, Currall (1981) did not deal with fuel characteristics at all, although he studied fire in wet heath. Only Hobbs & Gimingham (1984) highlight the possible importance of vegetation (and therefore fuel) structure in dictating fire characteristics, a view further emphasised later by the same authors (Hobbs *et al.*, 1987). None of these studies have differentiated between potential and available fuel, nor how the amount of the latter varies with changing conditions. In all cases, there is a noticeable lack of information about how the fuel load may vary across the particular habitat. A recent review of blanket bog fire ecology only discusses fuel in terms of age or height of *Calluna* (Shaw *et al.*, 1996), again showing the lack of information about the variation in fuel and therefore fire characteristics possible. It is clear that if we are to fully understand the use of fire as a management tool in the UK, we must first develop a better understanding of the fuels involved.

The work described in this chapter addresses some of the issues raised above concerning blanket bog fuel characteristics. Equations to predict the biomass of different fuel types, derived from plant and plot-level attributes, are presented. The results from applying these equations to experimental plots emphasis the spatial variation in fuel loading, and highlight sampling difficulties involved in quantifying the fuel complex.

3.2 Methods

3.2.1 Plot layout

The sites used were 1998 burn sites A, B and C. These sites, and plot selection within them, are described in Chapter 2. Ten 1 m x 1 m plots (referred to here as experimental plots) were selected within each of the three sites and were used for experimental fires described in Chapter 4. A further four plots (referred to as fuel assessment plots) were located in the same manner at the same time on each site, and were used as the basis for assessing fuel loading.

3.2.2 Assessing fuel attributes

Each site was subjectively scored (before being quantitatively assessed) as having either 'low', 'medium' or 'high' amounts of fuel available (scored as 1, 2 or 3). Site A was assessed as 'high' fuel load (score 3) and sites B and C as 'medium' (score 2). These scores were based mainly on the size of *Calluna* present and amount of litter. At one extreme was *Sphagnum* dominated bog with few, small, very scattered *Calluna* plants and scattered litter (low fuel), and at the other areas where the *Sphagnum* surface was mostly obscured by a litter layer up to 15 cm deep, and the *Calluna* was much taller (up to 0.5 m). It was decided not to use any areas with the lowest score due to such areas being unlikely to burn under typical spring burning conditions.

The 'fine shrub' and 'dead material' fuel categories identified by Van Wagner (1983) were present on all sites, although spatially patchy. These categories correspond to shrubs (mainly *Calluna*, but including *M. gale* and *E. tetralix*), and what is referred to here as 'fine litter'. The latter mainly consists of dead stem and leaf material of *Molinia* but may also include dead *E. angustifolium*, *E. vaginatum* and *T. cespitosum*, where present. The small amount of live grass, sedge and herb material was also included in this category, as the amount of live material (typically 5 to 10 g m^{-2}) was very little compared to dead material. If fuel sampling were to be carried out in habitats with more live material, or within bog habitats at different times of the year (e.g. to assess summer or autumn burns), then a separate category for live material is recommended. Such fuels would have different moisture contents, and different ignition and burning characteristics to the equivalent dead material.

For all plots (experimental and fuel assessment) several variables were recorded during late March and early April 1998, before burning or harvesting. These variables, shown in Table 3.1 (pre-harvest measurements), were selected as they were thought likely to relate to the biomass on each plot. The height of *Calluna* and depth of fine litter were measured using a ruler, and the percentage cover values by visual assessment.

Table 3.1. Pre and post-harvest measurements made on the 30 experimental and 12 fuel assessment 1 m x 1 m plots.

PRE-HARVEST MEASUREMENTS
Qualitative site fuel score (Three-point scale: 1 = low, 2 = medium, 3 = high)
% cover of *Calluna*
Average height of *Calluna* (cm)
% cover of fine litter
% cover of fine litter, and depth of fuel (measured in cm)
POST-HARVEST MEASUREMENTS
Fine litter biomass (g)
E. tetralix biomass (g)
M. gale biomass (g)
Calluna biomass (g) – divided into dead and alive plants, and then all plants divided into diameter classes (0-2; 2-4; 4-6; 6-8; 8-10; 10-12 mm): Height measured (cm) and shape of plant assessed (5 categories, ranging from tall & thin to short & bushy)

The biomass considered available in spring management fire was then removed from each fuel assessment plot. Observation of management fires in north-west Scotland (in 1996 and 1997) suggested that in most situations only material above the moss layer (or above the peat in the absence of moss) was burnt, with minimal amounts of moss consumed. All vascular plant material was therefore clipped at ground or moss level and removed – this material can be considered the typical 'available' fuel for spring management fires. Not all potential fuel was removed, as the mosses (*Sphagnum* and others) can burn in dry conditions, as noted by Van Wagner (1983) who listed moss/lichen as a surface fuel type. In the laboratory, harvested fuels were sorted into different categories: fine litter; *E. tetralix*; *M. gale*; live *Calluna*; dead *Calluna*. The *Calluna* material was further sub-divided into height and diameter classes. In the case of plants with a basal diameter greater than 2 mm the whole plant was divided into 2 mm diameter size classes (Table 3.1) with the smallest class, 0-2 mm, containing all the leaf material. The division into the diameter classes was done using pre-set calipers and garden clippers.

The height of each *Calluna* plant was recorded, along with a subjective score of the shape of the plant. Five common shapes were identified (ranging from very tall and thin, to short and bushy), as it was expected that this information would be an important factor in predicting plant biomass. The dimensions of the canopy were also recorded, but compression resulting from transportation and storage of material made these data unreliable (this was also thought to affect the shape data to some extent). All plant matter was then dried at 80 °C for two days (Mackey & Neal, 1993) and the dry weight recorded.

3.2.3 Post fire measurements – experimental plots

Within 2 weeks of the experimental fires (18th – 21st April 1998), all remaining above-ground plant material (as defined above) was removed from each of the 30 experimental fire plots. The material in a 25 cm x 25 cm quadrat centered on the middle of the plot (where the thermocouples were located, see Chapter 4) was removed separately. In the laboratory all material was separated into the categories described above and oven dried at 80 °C for two days. *Calluna* was divided as before prior to drying. Examination of this material showed that *Calluna* stems (at least the lower few centimetres) survived the fire with no obvious damage and the bark material intact, allowing a precise estimate of the basal diameter to be made prior to drying. This measurement was the basis for estimating the pre-burn biomass of each plant. All analysis in this and subsequent chapters was carried out using MINITAB Release 11.21 (McKenzie, Schaefer & Farber, 1995). All biomass values given, except where stated otherwise, refer to g m^{-2}.

3.3 Results

3.3.1 Analysis and fuel prediction equations

Data from the fuel assessment plots were used to develop equations to predict fuel biomass and *Calluna* size-class distribution, using linear, multiple and polynomial regression. The small number of harvested plots containing *M. gale* and dead *Calluna* material made meaningful analysis of the data for these fuel types impossible, and unnecessary in any case due to the small amount they contributed to the overall fuel biomass. All biomass values quoted in this study refer to ovendry weight.

E. tetralix and fine litter

Stepwise multiple regression was used to relate fine litter and *E. tetralix* biomass from the 1 m^2 plots to the pre-harvest measurements (Table 3.1). The percentage fine litter cover by depth class data did not contribute to explaining the fine litter or *E. tetralix* biomass, and so were excluded from further analyses. The two resulting equations, shown in Table 3.2, are highly significant, with both explaining over 85 % of the variation in the datasets.

Table 3.2. Equations to predict fuel biomass (g) from pre- and post-harvest measurements. The fine litter, *E. tetralix* and small *Calluna* equations predict biomass over 1 m^2 plots. The remaining *Calluna* equations predict biomass of individual plants. Diameter values are measured in mm, heights in cm. In the equation for small *Calluna*, 'L' refers to the log$_{10}$ (large *Calluna* biomass plus 1), and the result is log$_{10}$ (small *Calluna* biomass plus 1). 'Site score is explained in section 3.2.2.

	Equation	R^2	*F* value	*P* value
Fine litter	93 (site score) – 1.48 (*Calluna* avg. height) + 0.613(fine litter % cover) - 119	0.865	$F_{3,8} = 17$	<0.001
E. tetralix	20 (site score) + 0.631 (*Calluna* % cover) + 0.464 (fine litter % cover) – 61.8	0.897	$F_{3,8} = 23$	<0.001
Small *Calluna* Log$_{10}$ (biomass + 1)	**(Whole plant <2 mm diameter)** $0.147 + 1.359L - 0.138L^2 - 0.154L^3$	0.777	$F_{3,8} = 9.3$	<0.001
Calluna	**(Large plants, >2 mm maximum diameter at base of stem)**			
Total biomass				
Site A	$(0.753 + 0.303 \text{ diameter})^3 - 1$	0.905	$F_{1,79} = 764$	<0.001
Site B	$(0.694 + 0.266 \text{ diameter})^3 - 1$	0.880	$F_{1,62} = 453$	<0.001
Site C	$(0.756 + 0.240 \text{ diameter})^3 - 1$	0.783	$F_{1,43} = 155$	<0.001
All sites	$(0.656 + 0.304 \text{ diameter})^3 - 1$	0.875	$F_{1,188} = 1320$	<0.001
<2 mm diameter biomass				
Site A	$(0.877 + 0.221 \text{ diameter})^3 - 1$	0.855	$F_{1,79} = 466$	<0.001
Site B	$(0.751 + 0.229 \text{ diameter})^3 - 1$	0.878	$F_{1,40} = 287$	<0.001
Site C	$(0.824 + 0.196 \text{ diameter})^3 - 1$	0.742	$F_{1,43} = 124$	<0.001
All sites	$(0.801 + 0.229 \text{ diameter})^3 - 1$	0.846	$F_{1,166} = 918$	<0.001

Small (whole plant <2 mm diameter) Calluna

This fuel category refers to individual plants with a basal diameter <2 mm (hereafter referred to as 'small *Calluna*'). The importance of the contribution of such small plants to the fuel available (in some plots) was not fully appreciated until the data were examined, so the pre-harvest variables had not targeted this fuel type. The biomass of small *Calluna* varied widely (Figure 3.2A), but was generally only at its greatest in the low to middle range of large *Calluna* biomass. This may be because the plots dominated by large *Calluna* typically had a deep fine litter layer, and combined with the shading from the large plants would result in very few small *Calluna* plants. In plots with little or no large *Calluna* plants, the apparent lack of a suitable environment for this species explains the lack of smaller plants. The $\log_{10}$ of all data were taken (after adding 1 to all values to avoid negative results), and are plotted in Figure 3.2B with a 3rd order polynomial regression line fitted, and the equation is shown in Table 3.2.

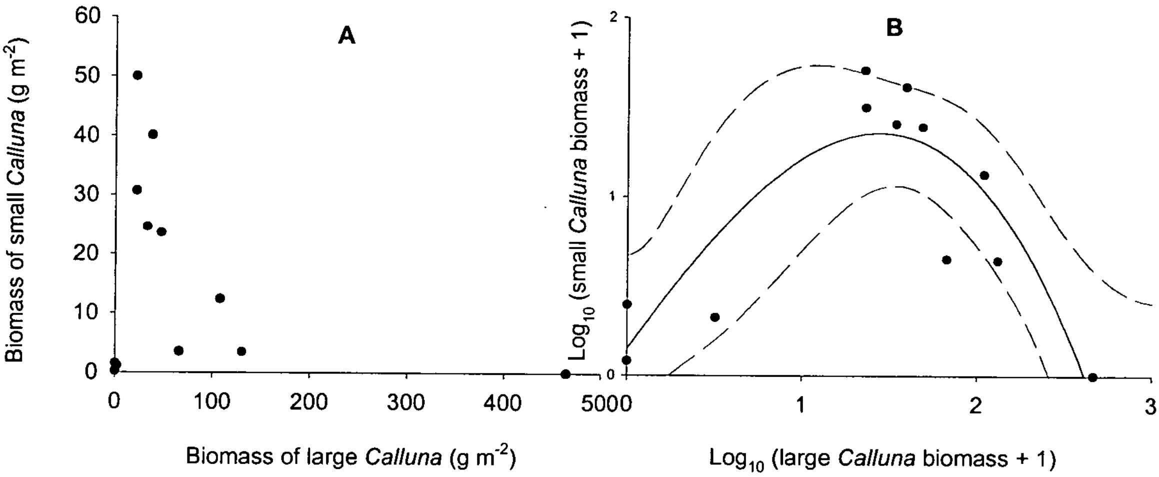

Figure 3.2. The relationship of small *Calluna* biomass to large *Calluna* biomass. Fig A: biomass in g m^{-2} on both axes. Fig B: both axes, $\log_{10}$ (biomass +1), with fitted 3rd order regression line (see Table 3.2) and 95 % confidence intervals shown.

Large (>2 mm diameter) Calluna

The height and shape data did not contribute to predicting the biomass of the larger *Calluna* plants, therefore these data were not used. The stem diameter data from individual *Calluna* plants were plotted against the corresponding cube root of the biomass, with the latter used because it is linearly related to the stem diameter. Biomass values less than 1 (which would have resulted in very small numbers) were therefore avoided by adding 1 to each value. Linear regression resulted in equations to predict *Calluna* biomass from stem diameter values for all three sites (Table 3.2). Normal probability plots of residuals were examined to confirm the suitability of the data for this technique. The regression lines are shown in Figure 3.3.

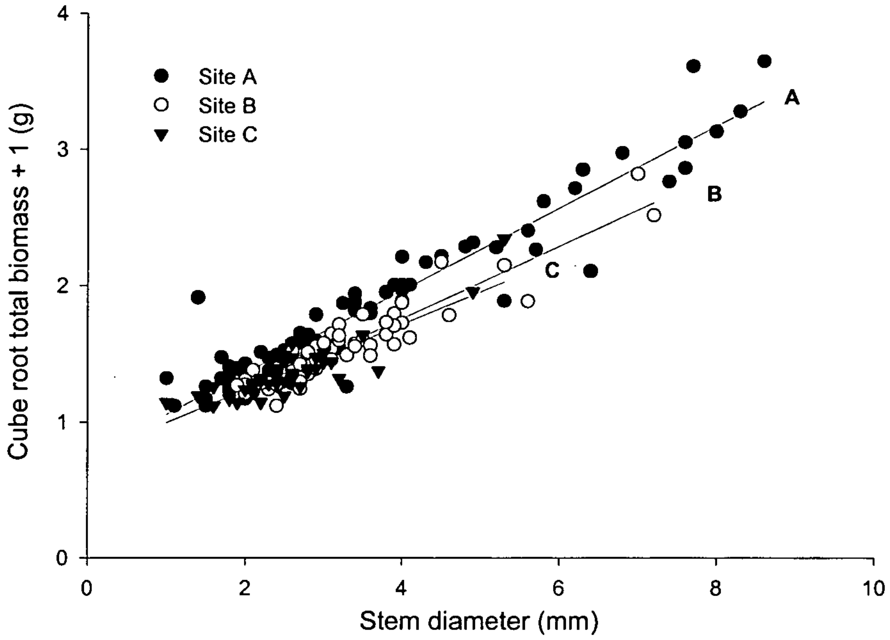

Figure 3.3. *Calluna* stem diameter and biomass by site. All data points shown, and regression lines fitted for individual sites (see Table 3.2).

The most important fuel size class in a fuel complex is the smallest, because that is the fuel which potentially dries out quickest, carries the fire, and in moderate fires can make up most of the fuel consumed. Linear regression was therefore used to develop equations for predicting the biomass of the <2 mm fuel size category. The equations for the three sites are also shown in Table 3.2 and the pooled equation (using the data from all three sites) has been used to plot the <2 mm regression line in Figure 3.4. This figure also shows the pooled regression line for total biomass. The <2 mm category forms the major proportion of the total biomass at all times, although this proportion decreases with increasing basal stem diameter. This is to be expected, with larger plants having a greater proportion of larger diameter (woody) material, and therefore proportionally less smaller material.

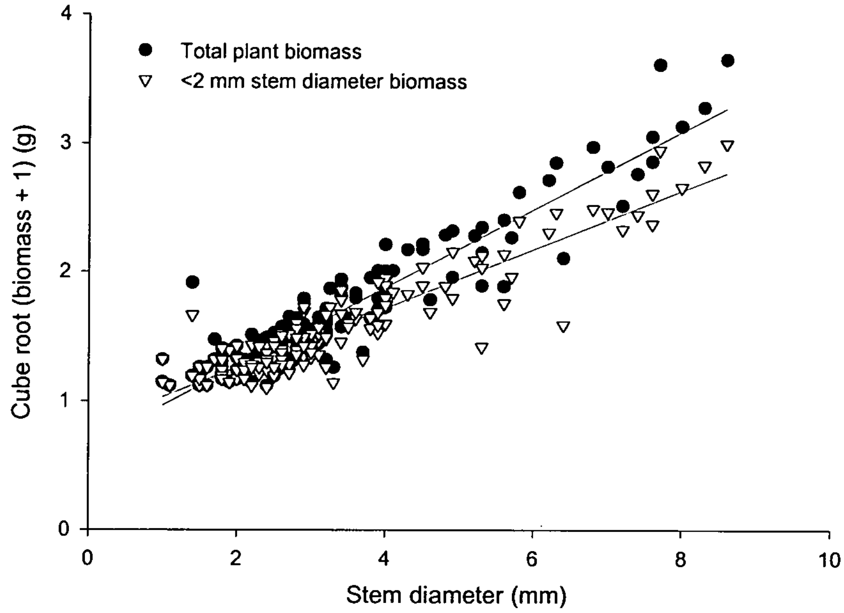

Figure 3.4. *Calluna* stem diameter and biomass by size-class. All data points shown, and regression lines fitted for pooled data (see Table 3.2).

3.3.2 Pre-fire fuel composition

The equations shown in Table 3.2 were used to predict the pre-fire fuel in the 30 experimental plots, based on the pre-fire survey (Table 3.1) and the stem diameters of *Calluna* plants removed after the fires. The pooled equations (combining data from all sites) were used to predict *Calluna* biomass values. All resulting predicted biomass values were positive, with the exception of the predictions for *E. tetralix* in plots C7 and C9. Slightly negative values resulted here (-8.1 and –0.2 g respectively), as the input variables were outside the range of those used to develop the equation. These predicted values were set to zero. All results are given in Table 3.3, showing the four predicted fuel types as well as the total for each experimental plot. The results from the harvested plots are also shown for comparison, as these values are the result of direct measurement. The data from the experimental plots are also displayed in Figure 3.5. The variability of all fuel types both within and between the sites is apparent, in particular the amount of large *Calluna* on site A differs markedly between *Calluna* dominated plots and non-*Calluna* plots. The amount of fine litter is consistently different between the high fuel (A) and medium fuel (B and C) sites, despite the marked within-site variation in both large *Calluna* and total biomass values. The amount of small *Calluna* in all plots is consistently low, however this

Table 3.3. Fuel biomass (g m^{-2}) in the experimental and harvested plots. Values for the experimental plots have been calculated from equations in Table 2, those for harvested plots (prefix 'H') were measured directly. The fuel categories are: sC = small *Calluna*; lCv = large *Calluna*; Et = *E. tetralix*; L = fine litter; T = sum of all categories. Values all rounded to nearest integer. Some harvested plot totals are bigger than the sum of values shown, due to the presence of some dead *Calluna* or live *Myrica*. Statistics are calculated from all plots in a site.

	SITE A					SITE B					SITE C				
	sC	lCv	L	Et	T	sC	lCv	L	Et	T	sC	lCv	L	Et	T
1	3	228	170	64	**465**	15	70	74	12	**172**	14	77	93	22	**207**
2	8	4	189	41	**241**	9	114	86	19	**228**	20	42	104	29	**195**
3	3	227	174	68	**472**	16	65	99	25	**206**	22	28	99	24	**173**
4	0	369	166	77	**612**	20	43	95	20	**178**	20	42	115	22	**200**
5	0	424	160	51	**634**	7	144	95	28	**274**	6	149	91	38	**284**
6	0	0	211	37	**249**	15	70	107	23	**215**	11	103	86	26	**225**
7	4	2	217	42	**265**	19	14	101	17	**151**	9	4	86	0	**100**
8	6	3	200	41	**249**	16	63	92	26	**198**	2	240	83	30	**355**
9	2	1	216	44	**263**	20	41	110	32	**203**	19	14	70	0	**103**
10	6	160	175	50	**390**	22	29	96	18	**165**	15	9	82	7	**113**
H1	0	0	226	51	**280**	40	38	66	29	**175**	50	22	118	27	**228**
H2	3	130	181	45	**365**	3	66	91	17	**188**	31	22	100	20	**174**
H3	0	464	150	61	**707**	1	0	114	28	**144**	1	2	92	7	**104**
H4	24	48	146	39	**259**	12	108	111	24	**255**	25	33	75	9	**145**
	Mean				**389.4**					**196.6**					**186.1**
	SD				**163.0**					**37.4**					**73.6**
	Maximum value				**707**					**274**					**355**
	Minimum value				**241**					**144**					**100**

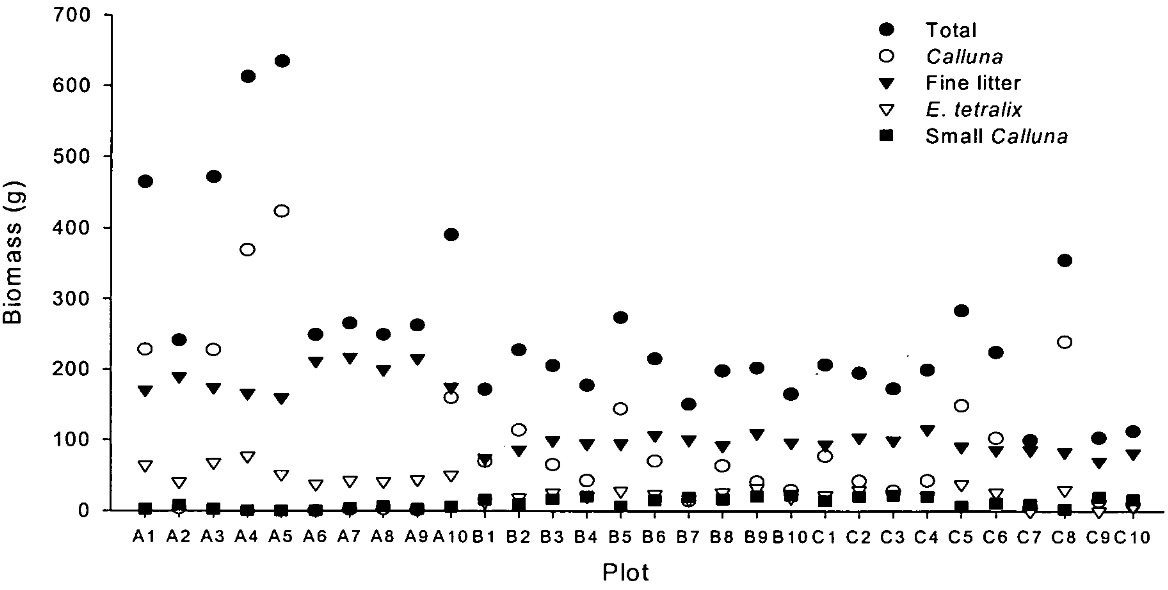

Figure 3.5. Predicted biomass (g m^{-2}) for the thirty experimental plots, using data shown in Table 3.3. The different fuel types and the total are shown for each plot.

fuel type may constitute an appreciable part of the fuel complex where the total fuel load is very low (sites B and C). In all cases, the major contributor to the total fuel biomass is either large *Calluna* or fine litter.

3.3.3 Errors associated with predicted values

Although the results shown in Table 3.3 are the 'best estimates' using the equations developed, there is of course a degree of uncertainty associated with these values. In order to quantify the possible effects of such uncertainty, the 95 % prediction interval (PI) associated with each regression line can be used to calculate the associated 'upper' and 'lower' predicted values. The 95 % PI limit amounts of fine litter and *E. tetralix* were calculated for each individual estimate, and are shown in Figure 3.6 as error bars to either side of the 'best estimate' values. These results again clearly confirm the initial (subjective) assessments of 'high' fuel loading for site A, and 'medium' for sites B and C.

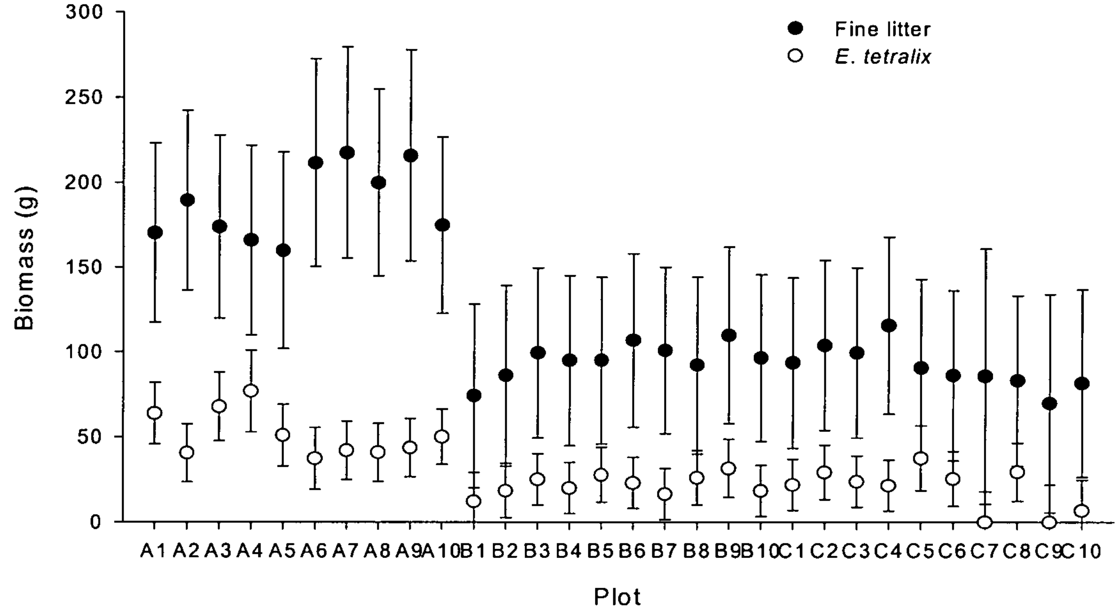

Figure 3.6. Mean and error bars showing 95 % prediction intervals for estimates of fine litter and *E. tetralix* biomass.

Complications arise when considering the errors associated with predicting large *Calluna* biomass. The same procedure as above can also be applied to each individual *Calluna* plant, using the 95 % PI shown in Figure 3.7. However, the prediction of *Calluna* is not plot based, but plant based; i.e. the equation is applied to each individual plant in a plot, and the outcomes summed over the plot. If a plot contained one individual, the calculation of the 95 % PI value would therefore be equivalent to the calculation of fine litter or *E. tetralix.* However where a plot contains more than one individual, the chances of each individual, in turn, being sampled at the extreme of the prediction interval decreases with repetition. Thus each individual prediction for a plant correctly estimates the upper and lower 95 % PI values for that individual, but the chance of sampling all individuals in a plot at the extremes of the PI's decreases with increasing numbers of individuals.

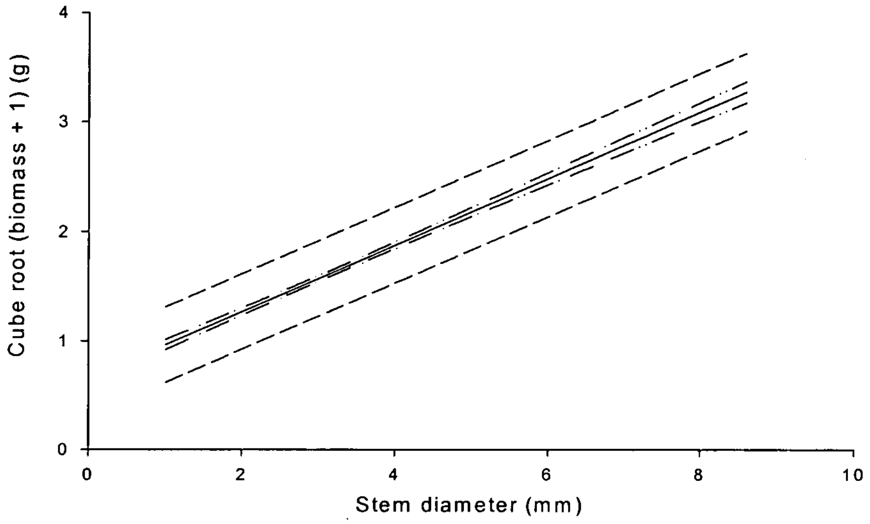

Figure 3.7. 95 % confidence and prediction intervals (inner and outer sets of lines respectively) shown for the regression equation used to predict the biomass of individual *Calluna* plants from stem diameter.

Small *Calluna* is predicted on a plot-basis, as with fine litter and *E. tetralix*. However, the predictor used is the biomass of large *Calluna* – itself a predicted value. The result is that the uncertainty attached to the *Calluna* prediction transfers to the prediction of small *Calluna*. Despite these issues, the most extreme values of both types of *Calluna* were calculated, and for each plot the extreme values (high and low) of all fuel types (including those for individual *Calluna* plants) were summed. It must be stressed that the results from this process do not represent the 95 % prediction interval of the whole fuel complex – but rather the sums of individual 95 % prediction interval values. These extreme values from the summation process are shown in Figure 3.8, as error bars either side of the straightforward predicted value. A second (upper) x-axis shows the number of individual *Calluna* plants in each plot. As a rough guide, the larger the number of *Calluna* plants, the more unlikely it is that the most extreme values will be obtained for the whole plot. Even for a plot with no *Calluna* plants (A6), the lower and upper limits shown are still reliant upon two consecutive extreme predictions; those of fine litter and *E. tetralix*..

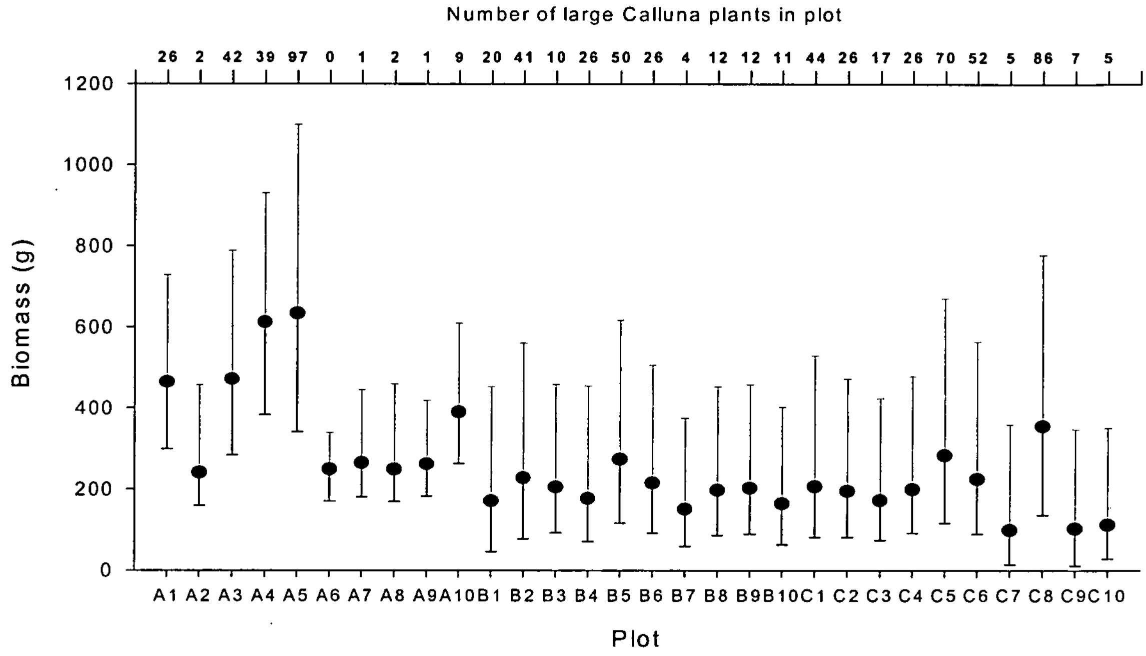

Figure 3.8. Variability possible in total biomass of fuel (g m^{-2}), using the regression equations in Table 3.2 and the associated prediction intervals. Refer to the text for a discussion of these results.

3.4 Discussion

The ability of simple regression equations to accurately and precisely estimate biomass parameters have been demonstrated many times elsewhere. Telfer (1969) presents equations to predict above-ground biomass from stem diameter for 22 species, with R^2 values ranging from 0.74 to 0.99. Similarly, Halpern *et al.* (1996), in a comprehensive treatment of vegetation in western Oregon, present equations for 38 tree, shrub and herb species, and conclude that 'simple measures of plant abundance….or size….can be used to accurately predict the above-ground biomass'. In that study, not only were plant-level attributes used (stem diameter, stem length) but plot-level as well, such as canopy cover or plant density. Plot-level attributes alone were used by Mosley (1987) to predict vegetation biomass, however potential sampling issues regarding relating frequency to yield were highlighted. A combined approach allowed Kauffman (1990) to develop equations to predict detailed partitioning of biomass within individual species. For certain species of tall shrubs, plot-level regression equations were sufficient for biomass predictions in the two years after a fire, but the use of stem-diameter based equations were required for later years (Halpern *et al.*, 1996). Ideally, fuel assessment techniques for use in the field would be as simple and efficient as possible, suggesting that the use of plot-level attributes only would be desirable. However, the incorporation of data from both plant and plot-level would seem necessary, based on the experience of workers overseas and the techniques for fuel sampling developed. For example, the techniques detailed and recommended by Brown *et al.* (1982) involve measurements at both the plot and plant level for satisfactory results.

This study has assessed fuel at both the plant and plot-level. The plot-level approach has been adopted to predict the biomass of *E. tetralix* and fine litter, and the plant-level approach adopted to predict *Calluna* biomass. The results from this study show that simple and effective regression equations to predict different blanket-bog fuel types can be developed. The high R^2 and significance levels obtained for the equations indicate that the use of these equations, across the sites they were developed for, is a very appropriate method of fuel prediction. In contrast, the time taken to harvest plots and sort and measure the fuel types make extensive use of this alternative approach impractical.

The spatial variation in fuel load across the blanket bog habitat is very obvious from the results obtained by both prediction and harvesting. Wallen (1987) notes that the position of *Calluna* on a bog is strongly related to water level, in that there is much more *Calluna* on hummocks than in hollows. This spatial variation was most obvious on site A, with a clear difference in biomass between *Calluna* dominated plots and others. This was also apparent on sites B and C, although to a much lesser extent. This variation has consequences for the prediction of fire characteristics (next chapter), and fuel sampling must therefore be capable of quantifying the range of biomass in the habitat. This study used a total of 12 plots to develop the regression equations, and a further thirty plots across three sites to predict the fuel load. In contrast, in previous UK studies where the fuel load has actually been sampled (Table 3.4), estimates are based on only one or a few samples, although most of this work to date has been in the much more homogeneous dry heath habitat. Other studies, concerned with vegetation production, also estimate biomass parameters, often with a larger sample size. However, there is obvious variation in biomass estimates both between and within habitats, and it is at times unclear what impact the different sampling methodologies have on this variation. There is thus a clear need for standardising fuel description and quantification.

Despite the amount of work done on the effects of management fire in the UK, only three studies quantified the amount of fuel before burning (Table 3.4). Hobbs & Gimingham (1984), working in dry heathland in eastern Scotland, showed the variation in fuel available in this habitat. They stratified their sites by identifying different stages in *Calluna* growth (pioneer, building, mature, degenerate), and showed that biomass of *Calluna* (and total plant biomass) increased with *Calluna* age, until decreasing into the degenerate phase. However the single sample per fire site gives no information about within-site fuel variation. Barclay-Estrup (1971), working in the same habitat found broadly similar results, but Allchin (1997) working in Dorset heath obtained much lower results for her mature *Calluna* stands. The small sample sizes makes valid comparison difficult. Results from biomass sampling done in blanket (or ombrotrophic) bog habitats in Sweden are broadly comparable with results presented here. However, the results from studies on Moor House NNR in north England are much higher than this study. This may be because the definition of 'blanket bog' varies between studies, and the Moor House site is actually degraded bog/wet heath, with a vegetation depauperate in moss cover, but higher in vascular species than undegraded blanket-bog.

Direct comparisons of fuel loads between studies in Table 3.4 must be made with care. There is ambiguity concerning the division of biomass into fuel types, and some question over the choice of sampling area: has the sampling been random?; how was the sampled vegetation divided? This again emphasises the need for a clear and unambiguous methodology. In all the UK fire studies cited above there is inadequate quantification of the variation in fuel biomass. The equations presented in this study all have associated confidence and prediction intervals, but the difficulty in quantifying errors when multiple equations are used is apparent. However, the high R^2 and P values associated with the equations make the use of straightforward predicted values acceptable for the purposes of this study.

Table 3.4. Summarised total fuel load and *Calluna* fuel load data from different studies. Studies prefixed with '*' are those where the sampling took place to quantify fuel. The growth stages of *Calluna* are indicated by P (pioneer) B (building) M (mature) and D (degenerate). All values shown are for g m^{-2} dry matter.**

STUDY DETAILS		Total live *Calluna*	Total fuel load (all species)
*****Kayll (1966)**			
Dry heath, NE Scotland.			
Six 0.5 m^2 plots in 15 yr. old Calluna, ten 0.5 m^2	15 yr.	**1096**	**1592**
plots in 25 yr. old Calluna.	10 yr.	**1840**	**2334**
Forrest (1971)			
Blanket bog, Moor House NNR, N England.		**665 ± 35**	**979 ± 42**
Ten 0.5 m^2 plots per sampling period.			
Means and 95 % confidence intervals given			
Barclay-Estrup (1971)	**P**	**287**	**889**
Dry heath, NE Scotland.	**B**	**1508**	**1702**
Ten 0.25 m^2 plot per stage of *Calluna* growth	**M**	**1924**	**2305**
	D	**1043**	**1561**
Forrest (1975)			
Blanket bog, Moor House NNR, N England.		(356-665) **533**	(599-979) **863**
Four repeats of fifteen 0.5 m^2 plots per sampling period			
Mean values shown - ranges given in brackets.			
Vasander 1981 (cited Wallen, 1987)	**Hu**	**90**	
Ombrotrophic bog, in Sweden.	**Ho**	**25**	
Values shown for hummock (Hu) and hollow (Ho).			
*****Hobbs & Gimingham (1984)**	**P**	(434-674) **518**	(882-1042) **1021**
Dry heath, NE Scotland.	**B**	(466-872) **1380**	(1050-1934) **1524**
One 0.25 m^2 plot per stand burnt (total 18 stands)	**M**	(604-1980) **1218**	(1692-2740) **2159**
Divided stands by stage of *Calluna* growth.	**D**	(704-782) **743**	(1855-2070) **1962**
Mean values shown - ranges given in brackets.			
Wallen (1987)			
ombrotrophic bog, S Sweden.	**Hu**	**~250**	
Six 2 m transects, 10 contiguous 0.04 m^2 plots per transect.	**W**	**~50**	
Values for hummock (Hu) and water level (W).			
*****Allchin (1997)**	**M**		**1278 & 1245**
Dry heathland, S England.	**D**		**1791 & 2215**
Two plots per category			
Divided stands by stage of *Calluna* growth.			
***** THIS STUDY**	Site A (all plots)	(0-464) **151**	(241-707) **389**
Blanket bog, NW Scotland.	Site B (all plots)	(1-144) **77**	(144-274) **197**
Fourteen 1 m^2 plots per site.	Site C (all plots)	(3-242) **72**	(100-355) **186**
Mean values, with ranges in brackets			

3.4.1 Methodology issues

Calluna is probably the main fuel type encountered in the vast majority of UK management fires, ranging from blanket-bog habitat in the Western Isles to dry Dorset heath. Predictive equations to estimate biomass must however be used with care, for example the stem diameter / biomass relationship may vary with size of plant. Halpern *et al.* (1996) note that plants can change form with successional stage, and that a range of predictive equations may therefore be required. Although the equations developed here provide acceptable estimates over the range of *Calluna* sizes studied, these may not be applicable in all situations. In addition, different forms of *Calluna* exist in different habitats (e.g. comparing dry heath and *Sphagnum*-dominated blanket bog). Fuel modelling over a range of habitats, or in the same habitats over a geographical range, must take these issues into account. There is also the impact that different levels of grazing can have on fuel availability, as even under 'biologically sustainable' grazing, 40 % of the new growth can be removed from *Calluna* (Grant *et al.*, 1982). Not only will this reduce the total amount of fuel available, but the material removed is also in the smallest size-class category, and thus potentially the most important fuel in a fire.

The basis of this study has been observations of what did and did not burn in previous spring management fires, and the fuel amounts calculated are thus representative of available fuel under 'typical' management fire conditions. Calculation of *Calluna* biomass has relied upon the lower part of the plant stems surviving the fire, and complete combustion of stems (if it occurred at all) was not quantified. However, the surviving moss layer seems to contribute to protecting the stems, and only the survival of the smallest stems is considered questionable.

The potential amount of fuel in this habitat has not been addressed, due to the flammabililty of the entire habitat in extreme conditions. The amount of available fuel will depend upon the prevalent conditions (such as moisture, vegetation composition and structure), and this work has been within a 'window' of possible conditions (considered representative for north-west management fires). For example, the contribution of moss to the fuel complex clearly depends mainly on the prevailing moisture conditions. In the experimental plots burnt, there was some loss through burning of hypnoid mosses (mainly *H. jutlandicum*), but the moss biomass consumed is thought to be very small in comparison to the biomass of other fuels. Under drier conditions, for example during a severe summer fire, the moss component (and perhaps the peat, and below-ground parts of the vascular plants) may contribute significantly to the fuel load, and will thus assume increasing importance with increasing severity of fire. In addition, the presence of damp moss hummocks may have an effect on fire behaviour by absorbing radiative energy, thus reducing the energy available for drying and ignition of other fuels.

3.4.2 Further fuel sampling and modelling

In the methods presented here for *Calluna*, knowledge of the diameter of all stems in the plot is required. This information must be gathered either immediately before the fire, or immediately afterwards (assuming little/no losses of stem bases). Such work is very time consuming, and in order to develop more usable models of *Calluna* biomass the following steps are recommended:

1. develop plant-level predictive equations
    refine as required for plant size
    refine as required for habitat;
2. integrate results with plot-level attributes as required (e.g. canopy cover, stem density);
3. develop simple and effective field methods to predict fuel load;
4. conduct verification and testing as required at all stages.

There probably already exist some suitable datasets that could be re-analysed to provide some of the above information, not only from fire studies, but also from work on vegetation productivity, e.g. Forrest (1971). Access to the raw data in such cases would be desirable and probably necessary. Fuel assessment methods developed would have to include predictions in different fuel size-classes, as emphasised by Frandsen (1983) and Pyne *et al.* (1996). Although the development of such techniques would be less advanced than the fuel modelling techniques described by Burgan (1987), they would provide much needed information for predicting fire behaviour. If further fuel modelling was then deemed necessary, existing models and techniques should be examined. For example, the surface fuel sub-models currently used in the BEHAVE fire prediction model (Pyne *et al.*, 1996) could be tested to assess their suitability for alteration to accommodate UK fuels and conditions. The BIOPAK methodology for estimating plant biomass could be used (Means *et al.*, 1994; Means *et al.*, 1996), with the advantage that the output would be applicable to existing fire models. Methodologies for gathering and arranging area-specific fuel information and for insertion in an existing fire model (including GIS development), are described by Keane *et al.* (1998). However, the majority of management fires in the UK occur within a relatively simple fuel complex (dry heathland) compared to the situations north American or Australian fuel models are designed for, and there is a much lower likelihood of severe wildfire. We should therefore not embark on a course of complex fuel modelling when simple models suffice, and when simple models would in any case make collecting field data and fuel prediction more straightforward.

3.4.3 Conclusions

This work has demonstrated that simple and accurate equations to predict different fuel types can be developed for fuels in the blanket-bog habitat. The results from these equations to predict pre-fire loading emphasise the variability in fuels across the habitat, and thus the need for more than 'spot' sampling of fuels, as has been the general practice in UK fire studies. The equations presented here can be applied in similar habitats, subject to testing, and with further work it is possible to develop methods to allow fuel prediction over a range of habitats and fuel types. The ability to predict the amount of fuel available to a fire is vital to quantifying the characteristics of the fire, and the results from this chapter are used directly in the next, which deals with fire and fire environment characteristics.

Chapter 4 FIRE CHARACTERISTICS AND FUEL CONSUMPTION

4.1 Introduction

There is a lack of attention paid in management fire studies to fire behaviour and the subsequent effects (Johnson *et al.*, 1995) with fire characteristics often being defined in very imprecise and vague terms. Qualitative terms such as 'cool', 'hot' or 'severe' are often used (Alexander, 1982), even though such terms cannot precisely describe a fire. There are several variables that are commonly used to characterise a fire (section 1.4.2) and these include temperature, flame length, rate of spread, length of fire-front and various measures of intensity. Alexander (1982) stresses the importance of the fire intensity concept, and in particular describes the commonly used fireline intensity (Byram, 1959). Such characteristics can be used to define the severity of fire for control purposes, and help predict the effects of fire on the vegetation and environment, and subsequent vegetation recovery. By defining standards for such characteristics, precise fire prescriptions can be set and the success of management fires judged by measurement of the relevant variables.

The previous chapter contained a discussion of the importance of understanding the characteristics of the potential fuels available to a fire. However, fuel is only one aspect of the fire environment, as weather and topography are also important. Bessie & Johnson (1995) discuss the relative importance of fuel and weather attributes, and conclude that weather sets upper and lower severity 'thresholds' – below the lower, fires cannot occur, and beyond some upper threshold, severe fires occur. They do not dispute the importance of fuels in fire behaviour, but rather argue that fuel attributes can be 'overwhelmed' by weather fluctuations. Temperature, relative humidity and precipitation affect the moisture content of the fuels (and thus change the amount of available fuel), and along with windspeed, slope and aspect, affect fire behaviour (Pyne *et al.*, 1996).

In situations where fire and its effects are well understood, both the environment necessary to achieve prescribed fire characteristics, and those characteristics themselves, are well defined. For example, Bunting (1987) describes the procedures necessary to plan and execute management fires in sagebrush-grass vegetation in the western USA, summarised in Table 4.1. This emphasises that the required information for correct execution of a controlled burn spans several timescales – from yearly monitoring of fuel loads to hourly monitoring of weather variables.

Table 4.1. Suggested timetable and activities for planning management fires. Adapted from Bunting (1987).

ACTIVITY	TIMESCALE
Development of burning plan	Year prior to burn
Sample monitoring plots	Growing season prior to burn
Weather and fuel moisture monitoring	Begin 10 days prior to burn, or as required
Prepare firebreaks	End of growing season prior to burn, or just before fire
Determine ignition and fire control details	Day prior to burn
Review burn plan with all involved	Day of burn
Monitor weather	Hourly, day of burn (or as required)
Evaluation of burn plan	Postburn
Sample monitoring plots	Yearly, or as required

For prescribed burns to reduce fuel loads in forests in south eastern Australia, Buckley (1993) defines the desired burning environment and fire characteristics. Pro-forma tables allow personnel conducting burns to define and collect necessary information before the burn (e.g. desired fire intensity, fuel load information, topographic details,) and on the day of the burn (e.g. weather variables, fuel moisture details, rate of fire spread, tree scorch height). Use is made of 'lookup tables', for example using various measures of fuel moisture content to determine if the fuel is either too moist or too dry to permit controlled burning.

Although we have a long history of using fire as a management tool in Scotland, we do not yet possess the information to define or carry out burns with the precision of the examples above. With the notable exception of the work by Thomas in the 1960's and 1970's, (e.g. Thomas, 1971), little use has been made of the concepts and techniques associated with fire characteristics. Any fuel and fire information gathered has generally been subsidiary to the vegetation aspects of the study. Whittaker (1961) measured maximum temperatures only, and Kenworthy (1963) presented a small number of temperature profiles. Similar profiles were augmented by a few fire intensity measurements by Kayll (1966). Valuable information about fire intensity and other fire characteristics is given in Hobbs & Gimingham (1984) and Hobbs, Currall & Gimingham (1984), including a model which predicts maximum fire temperature from vegetation height, fire width and windspeed. However these results are based on a small number of fires with a small sampling effort per fire. More recently, Allchin (1997) studied the effects of fuel load on temperature and intensity of lowland heath fires, requiring the measurement of fuel variables (loading and moisture content) and fire characteristics (temperatures and intensities). Almost all of the above work has taken place in dry heathland, and the only fire study to focus on wetter habitats was that by Currall (1981) on wet heath. In that study only the maximum temperatures reached were recorded for four experimental fires, and no fuel load or fire intensity measurements were made. In most cases where one or more fire characteristic has been measured, there appears to be a lack of appreciation of the different information conveyed by the different characteristics. For all measures of intensity or temperature, a 'higher' number is taken to imply a more 'severe' fire. However, there has been little discussion about what the different characteristics actually mean, and therefore which type of measure should be considered for which purpose. The difference between knowing the value of variables that may be important for fire control, and those that may be less important for fire control but have a large ecological impact, is an issue that has not been addressed in this country. Even in North America, where a much better appreciation of fire characteristics exists, it has been said that 'as a consequence of inadequately describing fuel and fire in quantitative terms, knowledge of the ecological role of fire is limited because of the difficulty in comparing results of different studies' (Sapsis & Kauffman, 1991). There is therefore much work to be done in quantifying all relevant aspects of fire behaviour, not only for management fires in the north-west of Scotland but for fires in all habitats. In addition, a fuller appreciation of the different uses for different fire characteristics must be developed.

The results from this chapter, in conjunction with those from the previous chapter, provide the fuel and fire context within which the later vegetation results may be interpreted. At this scale of study it is not possible to quantify all aspects of management fires, but the main fire and fire environment characteristics are addressed. The amount of fuel consumed is used to calculate fire intensity values, and these are related to temperatures reached, duration of temperatures, and cumulative heat recorded. These different ways of characterising fire (temperature, and measures of intensity) are compared, and their usefulness discussed. The environment within which these fires occurred is also summarised. More intense fire and subsequently most damage to the moss layer is likely to occur where there is the most fuel (i.e. the shrub/*Sphagnum* interface), therefore the surface fire environment is described in detail. The sites used have been described in Chapter 2, and the calculation of fuel loads in Chapter 3.

4.2 Experimental fire methodology

4.2.1 Experimental layout

The selection of study plots is described in Chapter 2. In summary, ten 1 m x 1 m experimental plots were used within each of three sites (Table 4.2). In addition to the three main sites, two further sites (D and F) with five experimental plots in each were also used. Full and comparable fuel results are not available for sites D and F, but temperature data from them have been used in some of the analysis in this chapter.

Table 4.2. Summary of plots burnt (experimental) and harvested (fuel assessment) at each burn site.

Site	Fuel assessment	Fuel assessment plots	Experimental plots
A	High	4	10
B	Medium	4	10
C	Medium	4	10

4.2.2 Temperature measurement

Temperatures were recorded in the centre of each experimental plot using Type K (nickel alloy) thermocouples made from 5 m lengths of fibreglass insulated wire, with the final 1 cm of wire bared and twisted together. This wire is rated for continuous usage to 480 °C, and for short periods to 1 260 °C. Within each plot, a thermocouple was located at each of the following positions:

- on the surface of peat or moss;
- in the middle of vegetation (measured as half the vertical height of the vegetation at that point);
- at the top of vegetation;
- 20 cm above the top of the vegetation.

The latter three thermocouples were held in position using a retort stand pushed into the peat leaving 1 m protruding (Figure 4.1). The wires were taped to the retort stand and each run through 20 cm of glass tubing held horizontally with wire to a clamp. The tubing protected the most vulnerable wire (held horizontally in the fire), with the last 5 cm (including the bare junction) protruding. The clamps could then be moved to the height required. Damp *Sphagnum* was used to protect the short horizontal length of wire at the stand end of the glass tubing. The wires from each set of four thermocouples were run along the ground through damper areas where possible, or where high temperatures seemed likely damp *Sphagnum* was spread over the wire (2-3 cm wide). The wires were connected using Type K miniplugs to a Pico Technology TC-08 thermocouple input device. This was in turn connected to a laptop computer running the PicoLog data logging program which recorded the temperature from each thermocouple once every 5 seconds (the time taken for the logger to sample all four thermocouples sequentially). Each reading was an average temperature over approximately half a second for that particular thermocouple. Results are not available for plot A8, due to a procedural error during burning.

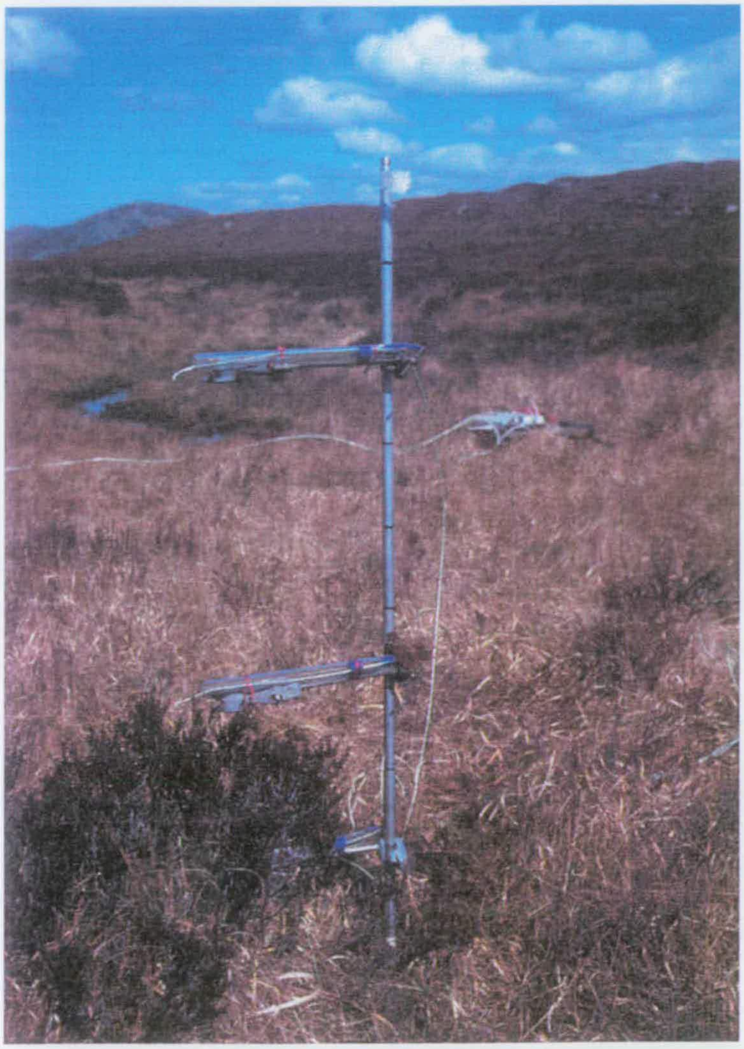

Figure 4.1. Plots on site A prior to burning, showing the retort stand and glass tubing used to protect and support the thermocouple wires.

Prior to each days burning the temperatures recorded by all thermocouples were checked using boiling water and ice water. Between individual burns on a particular day, all thermocouples were checked against each other in recording ambient temperature and body temperature by holding the junction. Where there were discrepancies this appeared to be due to fire residues on the junction disturbing contact. This was easily fixed by untwisting and wiping the wires before re-twisting, or in a few extreme cases cutting off the junction, baring a further 1 cm of each wire and re-twisting. Soldering or braising the junctions was considered, but neither was done due to the high temperatures expected and the ease of fixing problems using the simpler approach above. The accuracy of the thermocouples at higher temperatures was checked in muffle furnaces in the laboratory, but this provided only a rough confirmation of high temperatures recorded as the fibreglass insulation caught fire at sustained high temperatures.

Three aspects of the temperature data collected from each thermocouple in each fire are analysed in this chapter. The first is maximum temperature reached, which many studies recording temperature have focused on. However, the maximum temperature is only one aspect of the temperature regime of a fire, and another is the duration of temperature. The data are therefore analysed to give the duration of temperatures greater than 55 °C. This temperature was chosen because the thermal death point for cells of typical mesophytic plants is between 50 and 55 °C (Hare, 1961; Larcher, 1995). Lastly, it is possible obtain an estimate of the heat output at a particular thermocouple position by calculating the product of temperatures above 55 °C and their duration (i.e. multiplying each temperature measurement above 55 °C by 5, the number of seconds until the next reading) and summing the output. The result is a value for each thermocouple position in units called here ‘degree-seconds’ (in this case above 55 °C).

4.2.3 Burning technique

Test fires were lit on 17/4/98, and all experimental fires were conducted between 18/4 and 22/4/98. Fires were started using matches and dry litter approximately 2 m upwind from each experimental plot along a front approximately 2 m wide, and were controlled using a standard firebeater. Initially, some plots were burnt using a single fire, i.e. a fire was allowed to run through three plots in a row, and the logger/laptop connected to each thermocouple set in turn. However, problems with fire control resulted, and most plots then were burnt individually. Where plots were adjacent and the wind direction appropriate, the furthest downwind plot was burnt first, then the next upwind, using the previously burnt plot as a firebreak, and so on. Although these fires were very small in area and length of fire front, they are thought to be representative of management fires in this habitat, which are typically very discontinuous. The rate of spread of each fire was recorded by timing the fire front between canes placed 2 m apart. Figures 4.2 and 4.3 show experimental fires burning through a medium fuel plot and a high fuel plot. The site C plot was one of the first to be burnt (after a period of rain), and this is reflected in the fire seen in Figure 4.2. The experimental fires were not representative of more severe fires, where increased severity is due not only to variables such as higher windspeed and drier fuel, but also to different fire behaviour and characteristics resulting from a more uniform, larger and more intense fire front. For an example of the importance of fire front length see Hobbs & Gimingham (1984), and Cheney *et al.* (1995) for a discussion of the relationship of fire front length to the rate of forward spread.

Figure 4.2. Fire going through a medium fuel plot (site C) on the first day of burning (18/4/98). Note the small flame height and the discontinuous nature of the fire-front.

Figure 4.3. Fire going through a high fuel plot (site A) on the second day of burning (19/4/98). Note the much larger flame height compared to Figure 4.2 above, but again the discontinuous fire-front.

4.2.4 Fuel and environmental recording

The above-ground biomass remaining on each experimental plot was removed within 2 weeks of the fires. Using the biomass values estimated for each plot (Chapter 3) and the amount left after each fire, the biomass and type of fuel consumed were estimated. These values then formed the basis for estimating fire intensity values.

Environmental variables were also recorded, either on a daily basis by the nearest meteorological station at Knockanrock, 11.5 km ESE (inland) of the study sites, or before/during each fire itself. Although Strathpolly meteorological station is only 1 – 1.5 km from the sites, the station was not operating properly during this period. During each fire, windspeed was measured at 2 m using a hand-held anemometer. Samples to determine fuel moisture were taken before the first fire each day by sampling pieces of *Molinia* leaf litter and sealing them in plastic bags. *Molinia* litter was sampled as observations of previous fires had shown the importance of this fuel type in 'carrying' a fire, and it also appeared to be the first fuel type to dry out. Samples were taken from three distinct positions in the vegetation: ground litter in contact with lawn *Sphagnum*; ground litter not in contact with the *Sphagnum* (i.e. from the upper layer of the litter); and aerial litter that had been blown into the *Calluna* and held off the ground. In the laboratory, moisture content values were calculated (percentage of ovendry weight), by weighing the samples before and after drying at 80 °C for 2 days (Mackey *et al.*, 1993). Any excess moisture in the bag after transportation to the laboratory was absorbed using tissue paper, and the mass of water absorbed calculated after drying as above, and added to the value obtained from the fuel itself.

4.2.5 Calculation of fire intensity variables

There are several ways of calculating fire intensity, each of which conveys different information about a fire. Heat release per unit area gives an indication of the total amount of heat either potentially or actually released over the duration of the whole fire event via flaming combustion. In contrast, quantification of a heat flux (or heat release rate) gives information about the energy released per unit time.

The measures of fire intensity used in this study all make use of the heat of combustion of the fuel involved (H). This is the amount of energy released by complete flaming combustion from a given amount of fuel, with units of kJ kg^{-1}. This value can be reduced to take into account energy losses, in particular for two reasons. Firstly, the value of H will be reduced by latent heat losses when the water of reaction (water produced as a by-product of volatilisation) is vapourised. H is then referred to as the low heat of combustion. Secondly, a reduction is required to take into account the moisture content of the fuel. Other possible losses may be due to radiation and incomplete combustion, but the usefulness of including these factors, and indeed whether they can be reliably estimated, is debatable (Alexander, 1982). As a result these factors are not dealt with in this study.

Potential and actual energy release per unit area

The hypothetical maximum amount of energy (heat) that can be released by a fire given a particular fuel load is called the potential heat energy (H_w). This is the product of the high heat of combustion of the fuel and the mass of that fuel over a given area, resulting in a value with units of kJ m^{-2}. A high heat of combustion of 22 400 kJ kg^{-1} was used for the *Calluna* fuel types (ITE Merlewood Analytical Chemistry Section, cited Allchin, 1997). For the other fuel types (fine litter and *E. tetralix*) a value of 21 400 kJ kg^{-1} was used, which was calculated as a mean heat of combustion of 43 fuel types by Susott (1982). To calculate the actual energy release (H_A) from each plot the mass of fuel consumed must be multiplied by the corrected value(s) of H. The low heat of combustion varies so little from fuel to fuel (approximately ± 10 %) it can effectively be thought of as a constant, and a value of 18 700 kJ kg^{-1} is used, (Alexander, 1982). Further corrections for fuel moisture are then normally required, but the mix of fuels in north-west blanket bog habitats, and the extreme gradients in fuel moisture present (see results) made quantification of fuel moisture for all fuel types and positions impractical. The low heat of combustion given above (18 700 kJ kg^{-1}) was therefore used.

Fireline intensity

One of the most commonly used measures of fire intensity, the 'fireline intensity' (I_B), was defined by Byram (1959). It is calculated as follows:

$$I_B = H * w * r$$

I_B = energy output per unit length of fire front per second (kJ m^{-1} s^{-1} or kW m^{-1}).
H = corrected (low) heat of combustion of fuel (kJ kg^{-1}).
w = mass of fuel consumed per unit area (kg m^{-2}).
r = rate of spread of fire (m s^{-1}).

The mass of fuel consumed is the total value for each plot and the rate of spread of the fire-front was estimated at the time of each fire. The low heat of combustion value of 18 700 kJ kg^{-1} was used in this study.

4.3 Results – environment and fuels

4.3.1 The burning environment

Experimental burning commenced on 18/4/98, the second dry day after several days of rain (Figure 4.4). A small amount of rain fell on the study sites on 20/4/98, but this did not stop subsequent burning. Figure 4.4 also shows the lack of any appreciable change in relative humidity over this period, although as these measurements were taken at 0900 their relevance to individual fire events (which took place from 11am to 4pm) may be limited. Figure 4.5 shows the changes in various temperature measures over the same period. The burning period is again apparent, showing as a rise, starting mid-month, in all temperatures measured except the fluctuating grass minimum (the lowest temperature recorded at ground level over a 24-hour period). These fluctuations may be because this temperature is recorded at 0900, and the periods of clear weather experienced during the burning period resulted in low morning temperatures.

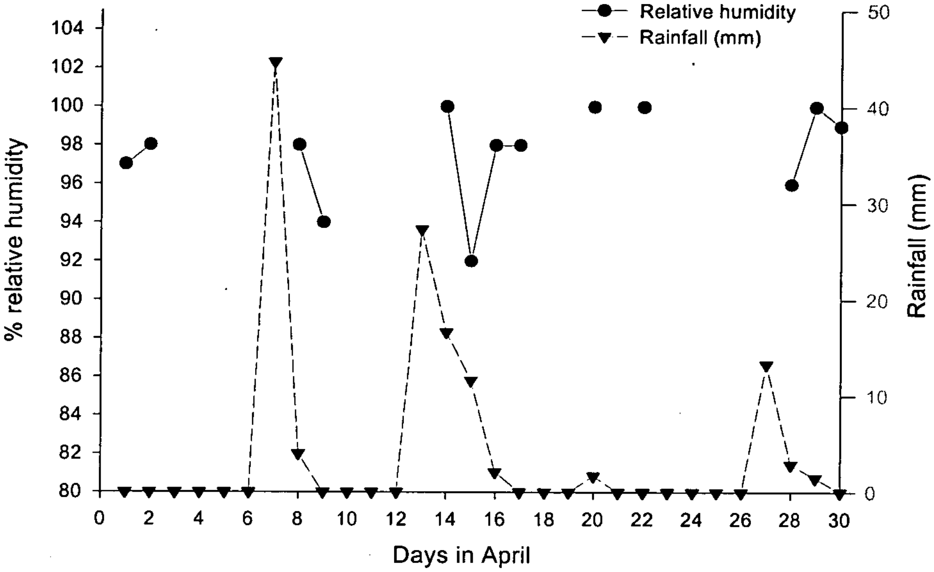

Figure 4.4. Daily precipitation and humidity during the month of April, 1998. Data from Knockanrock meteorological station. Humidity readings were not available for all days.

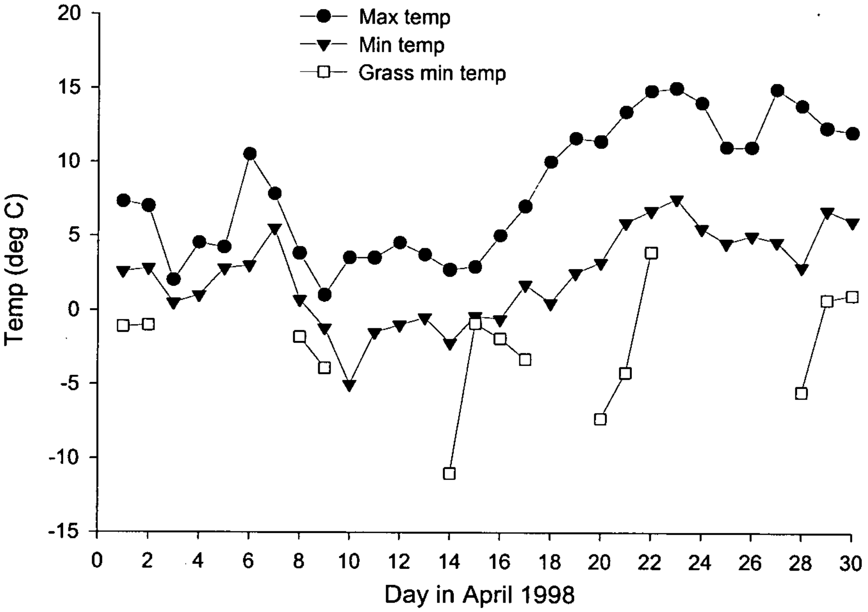

Figure 4.5. Temperature variation (maximum, minimum, grass-level minimum) during the month of April 1998. Data from Knockanrock meteorological station. Only maximum and minimum data were available for all days.

The available weather data for each burning day are summarised in the lower half of Table 4.3, which also shows the number of experimental plots burnt each day.

Table 4.3. Environmental variables for the days of experimental burning. Numbers in the upper half of the table indicate the number of plots burnt per site per day. '-' indicates data unavailable. Relative humidity was measured at 0900, windspeeds are averages.

Fuel	**Date**					
Level	**Site**	**18/4/98**	**19/4/98**	**20/4/98**	**21/4/98**	**22/4/98**
High	**A**	5	5			
	D		5			
Med	**C**	5		3	2	
	F		5			
	B					10
Knockanrock meteorological Station. (Lat 58.03N; Long 5.08W; altitude 244 m; Grid Ref: NC187088)						
Max temp (°C)		10	11.6	11.4	13.4	14.8
Min temp (°C)		0.5	2.5	3.2	5.9	6.7
Rainfall (mm)		0	0	1.7	0	0
Relative humidity		-	-	100	-	100

4.3.2 Fuel moisture

Fuel moisture was calculated as a percentage of the ovendry weight. Insufficient samples were taken in order to quantify any day to day, fire to fire or site to site variation, nonetheless the results demonstrate the extreme vertical moisture gradient present in this fuel type in the bog habitat. The raw data from the three litter layers sampled displayed heteroscedasticity, and were therefore transformed ($\log_{10} x + 1$). One-way ANOVA was highly significant ($F_{2,24} = 71$, $P < 0.001$), with significant differences between all three groups (Tukeys Multiple Comparison test). Figure 4.6 shows that the aerial fuel moisture contents were very consistent, with the magnitude and variance of fuel moisture content increasing towards the surface of the bog.

4.3.3 Fuel biomass remaining and consumed

The amounts of the four main fuel types (*Calluna*, small *Calluna*, fine litter, and *E. tetralix*) remaining within each plot after each experimental fire are shown in Figure 4.7. Although the total biomass remaining varied considerably (from 23 to 267 g m^{-2}), this variation is mainly due to the widely differing amounts of *Calluna*. The amounts remaining of the other fuel types are all less than 50 g m^{-2}.

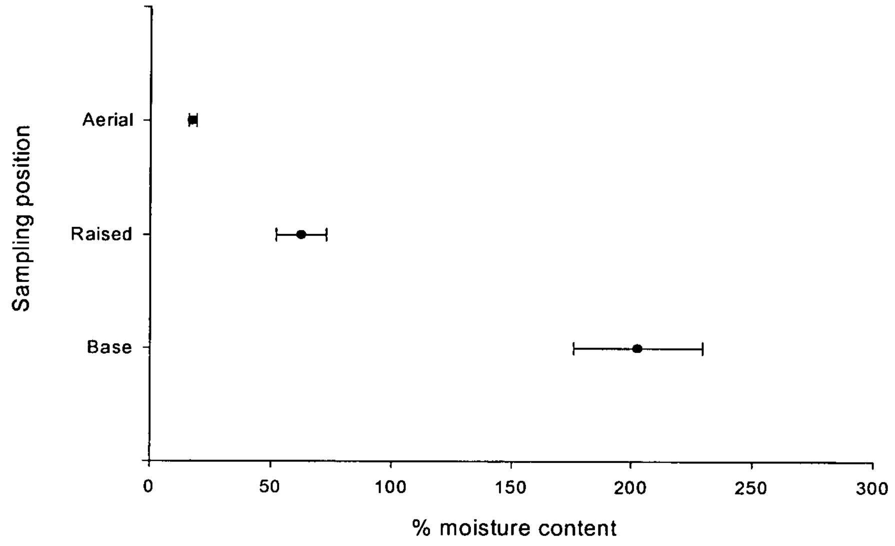

Figure 4.6. Mean and standard error of moisture content of *Molinia* leaf litter (fine litter category) recorded at three positions in the vegetation, at the start of each burning day. Moisture content is expressed as a percentage of the ovendry weight of the fuel.

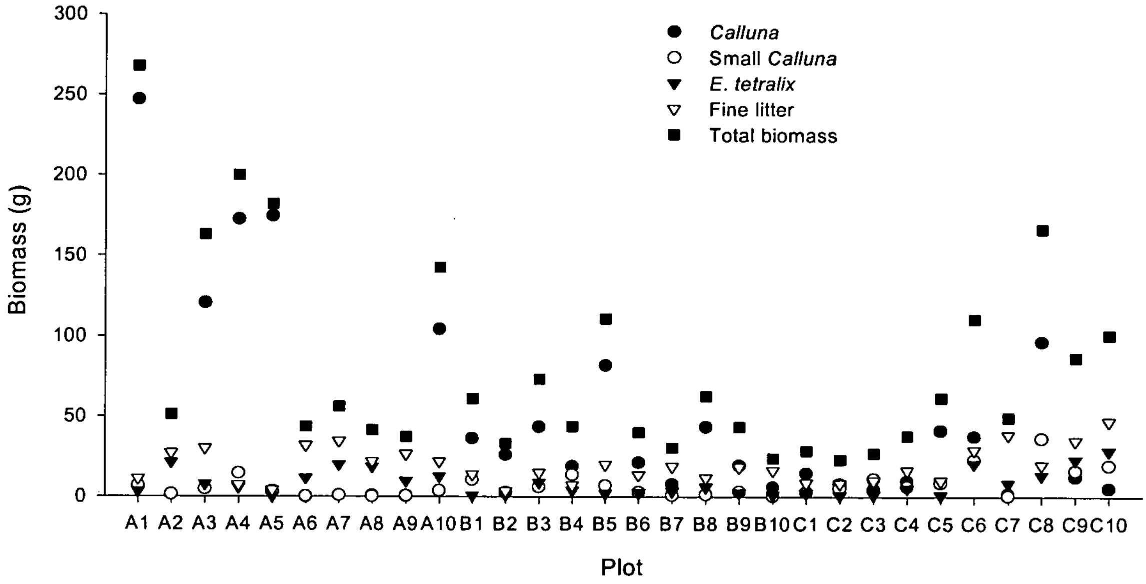

Figure 4.7. Biomass (dry weight, g m^{-2}) of different fuel types remaining in each experimental plot after burning.

The biomass consumed for each fuel type was then calculated using the equations presented in Chapter 3, but in a few cases the amount calculated was actually less than the amount remaining after the fire. These results are principally due to the error associated with the estimates of pre-fire biomass (Chapter 3), and similar problems in fuel prediction were encountered by Allchin (1997). Negative predictions were obtained three times in estimating *E. tetralix* biomass (-8.3, to -23.2 g m^{-2}) and nine times in small *Calluna* estimates (-0.3, to -24.2 g m^{-2}). All of the *E. tetralix* negative values and three of the small *Calluna* negative values were predicted for plots C6 – 10. The majority of these errors are small compared to the overall fuel biomass, and this type of result never occurred with the most important fuel types – *Calluna* and fine litter. There are two possible explanations for obtaining these errors:

1. there were small amounts of these fuels before burning, with very little consumed in the fire, and the predictions have slightly underestimated these amounts; or
2. there were large amounts of these fuel types before burning, and the predictions have severely underestimated these amounts. This implies that a large amount of these fuel types were consumed in the fires.

Given that the fires observed on these plots were very small (see Figure 4.2), and site C was not a high fuel site, it is clear that explanation 1 is correct. The amount of fuel consumed in the negative cases was therefore set to zero, to reduce the effect on the estimates overall biomass. The corrected results are illustrated in Figure 4.8, which shows the estimated biomass for each fuel type in each plot, divided into biomass remaining and biomass consumed. The amount of fine litter remaining after burning across all plots is similar, with the notable exception of plots C6, 7, 9 and 10. These were the first to be burnt after the prolonged wet period mentioned above, and although these plots suffered from the problems in estimating some fuel types discussed above, field notes describe these plots as 'barely burnt', 'barely burnt', 'reasonably well burnt', 'mostly untouched' and 'barely burnt' (see Figure 4.2). Those plots with a large amount of *Calluna* before burning also have a large amount remaining afterwards, which is the larger diameter woody material not consumed in the fires.

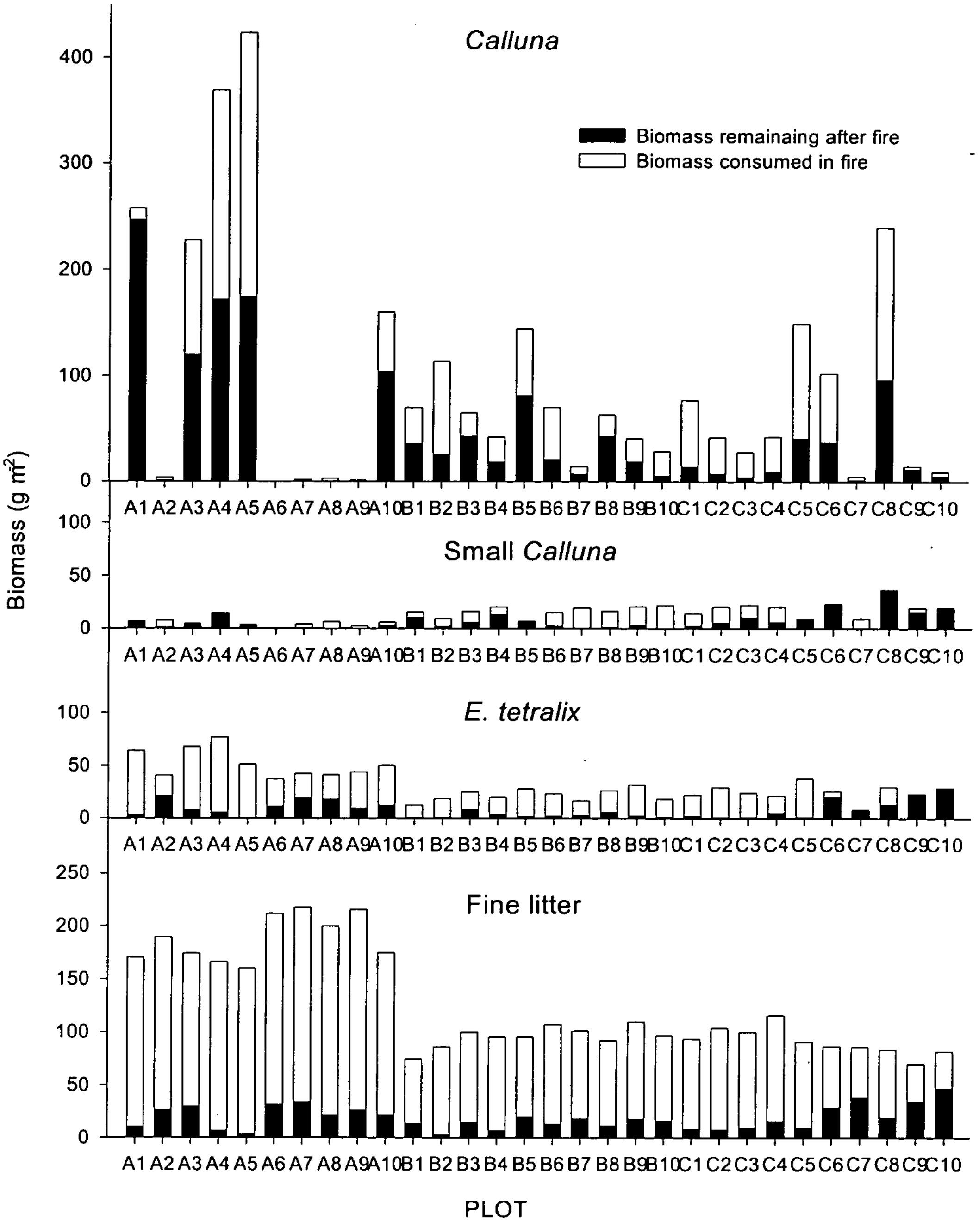

Figure 4.8. Biomass (dry weight, g m^{-2}) consumed and remaining after fire, for the four main fuel types. All biomass (y) axes are on the same scale.

The relationships between initial biomass and consumed biomass for each fuel type are shown in Figures 4.9A and B. These show that the biomass of fuel consumed is positively related to the biomass available, as found by Allchin (1997) for dry heath fires.

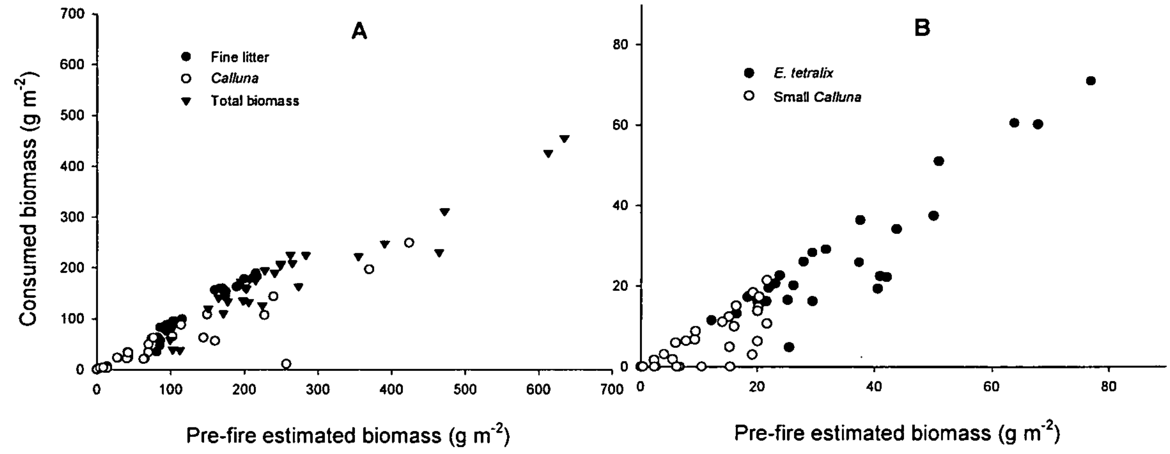

Figure 4.9. Biomass of each fuel type consumed plotted against biomass available. Fig. A shows fine litter, *Calluna*, and total of all fuels; Fig. B shows small *Calluna* and *E. tetralix*.

The main fuel types are fine litter and *Calluna*, so the biomass of *Calluna* consumed is plotted against the proportion of fine litter consumed in Figure 4.10. The proportion of fine litter consumed is relatively constant, the exceptions being the five plots on site C (plots 6-10) that were the first to be burnt, which have the smallest proportions of fine litter.

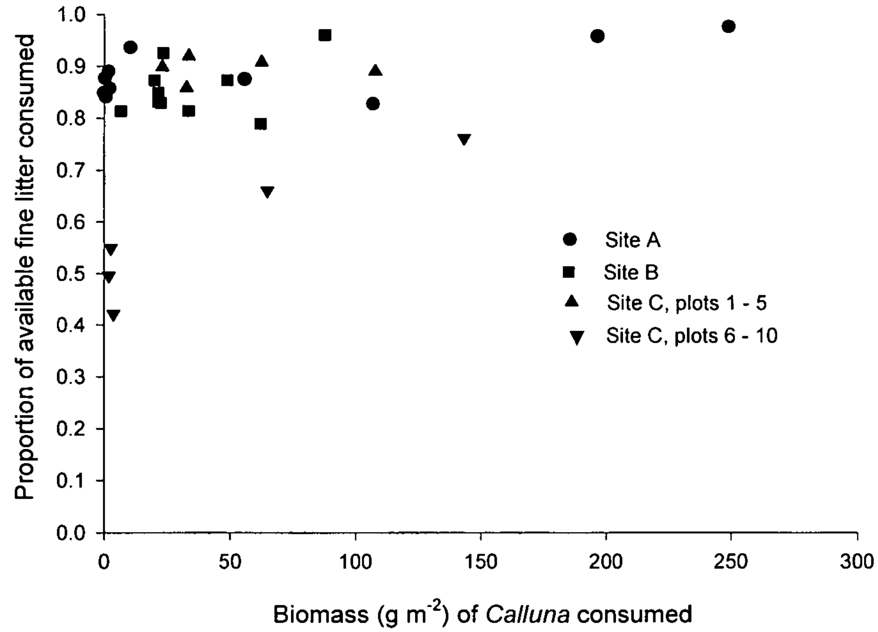

Figure 4.10. Proportion of fine litter consumed against the biomass of *Calluna* consumed.

4.4 *Results - fire temperature*

4.4.1 GLM analysis of temperature data

The three temperature datasets (maximum temperature, time above 55 °C, and total degree seconds) were analysed using the Generalised Linear Model (GLM) procedure in Minitab. The data were first $\log_{10}(x + 1)$ transformed, and GLMs constructed using site and thermocouple position as factors in each model, and *Calluna* height (at the location of the thermocouples) as a covariate. The latter was included as a term in the model as it was considered a proxy measure of total fuel available in the centre of the quadrat, and was therefore considered to have an effect on temperature variables. The results from the three GLMs are shown in Table 4.4 below, and they demonstrate that there are significant differences between the thermocouple positions in terms of maximum temperature and total degree seconds, but not in duration of high (>55 °C) temperatures. There is a significant difference between sites for all three temperature variables, but there is no interaction between sites and thermocouple position. In all three cases, *Calluna* height is a highly significant covariate.

Table 4.4. Results from GLM procedures carried out on the three temperature datasets. 'Position' refers to the thermocouple position, total no. of plots = 39, no. of sites = 5.

	FACTOR		INTERACTION	COVARIATE
	Site	**Position**	**site*position**	***Calluna* height**
MAXIMUM TEMP	$P < 0.05$ $F = 2.89$	$P < 0.001$ $F = 9.87$	NS	$P < 0.001$ $F = 15.12$
TIME OVER 55 °C	$P < 0.05$ $F = 3.29$	NS	NS	$P < 0.001$ $F = 13.08$
DEGREE SECS	$P < 0.05$ $F = 3.17$	$P < 0.05$ $F = 2.88$	NS	$P < 0.001$ $F = 13.99$

Multiple comparison tests were then carried out, and the results showed that site C was significantly different from all the others, having lower maximum temperatures, less time at temperatures above 55 °C, and fewer total degree seconds. The middle thermocouple position was found to be consistently different to the others in experiencing higher maximum temperatures, and more total degree seconds than the above and top of canopy positions.

4.4.2 Maximum temperatures

The maximum temperature recorded at each thermocouple position in each plot are shown in Figure 4.11. This shows the highly significant difference between the thermocouple positions, with the highest maximum temperatures tending to be in the middle of the vegetation, and the lowest above the vegetation canopy or at the surface.

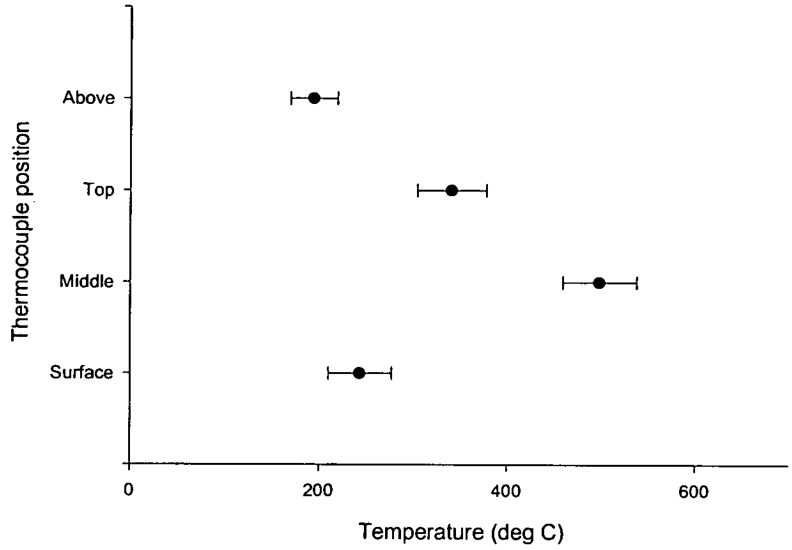

Figure 4.11. Maximum temperatures recorded at the four thermocouple positions, for all plots from all sites (*n* = 39). Mean and standard errors are shown.

4.4.3 Time over 55 °C

Figure 4.12 shows the duration of temperatures above 55 °C, and it can be seen that such temperatures tend to last longer at the surface thermocouple position. However, the greater variance of the data means a non-significant difference to other positions (Table 4.4).

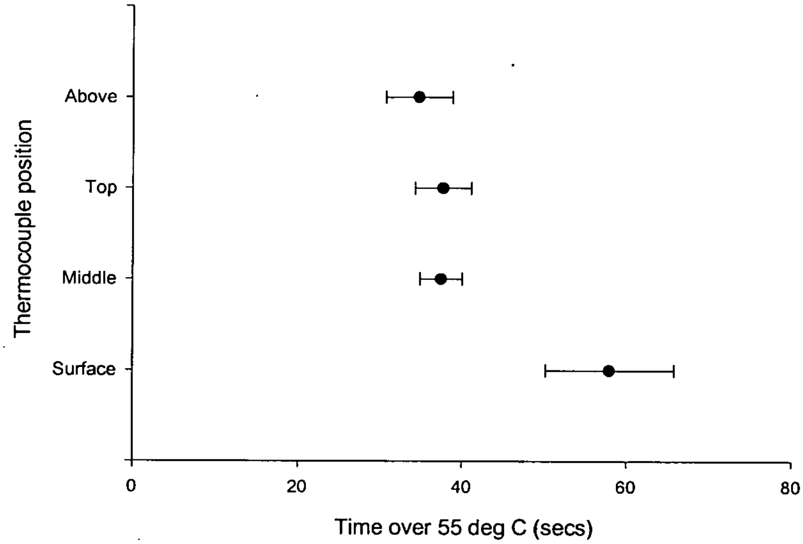

Figure 4.12. Duration in seconds of temperatures above 55 °C recorded at the four thermocouple position for all plots (*n* = 39). Mean and standard errors are shown.

4.4.4 Cumulative degree-seconds

In Figure 4.13A the degree-second data are plotted by thermocouple position, and this shows lower degree-seconds above the canopy and larger degree-seconds accumulated at the middle and surface positions, but also the greater variation at the surface. This is clarified in Figure 4.13B, which shows the time above 55 °C plotted against maximum temperature. The middle thermocouple position stands out as having the highest maximum temperatures, however the surface position is distinct due to part of the distribution being shifted to the right hand side of the graph, and also that it shows a clearer relationship between maximum temperature and time above 55 °C. Thus the surface environment, although not experiencing the highest temperatures, often has the greatest energy input due to duration of temperature.

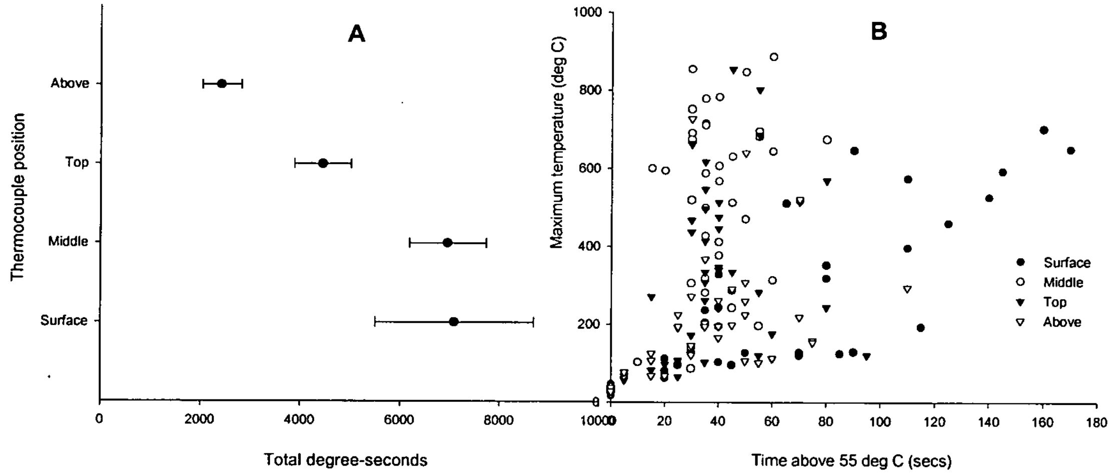

Figure 4.13. A. Total degree seconds recorded at the four thermocouple position for all plots (*n* = 39). Mean and standard errors shown. Fig. 4.13B. Time above 55 °C against maximum temperature.

4.5 Results - measures of intensity

4.5.1 Potential and actual energy release per unit area

Estimates for the amount of potential heat energy (H_w) for all plots (including both harvested and experimental plots), are shown in Figure 4.14. This shows the consistent amounts of energy available at each site from the fine litter and *E. tetralix* fuel types, which is the result of the fairly homogeneous distribution of these fuels across each site (although the differences between site A and sites B and C are apparent). In contrast, the amount of H_w for *Calluna* shows greater variation, particularly on site A, and this in turn has a large effect on H_w for the total fuel load.

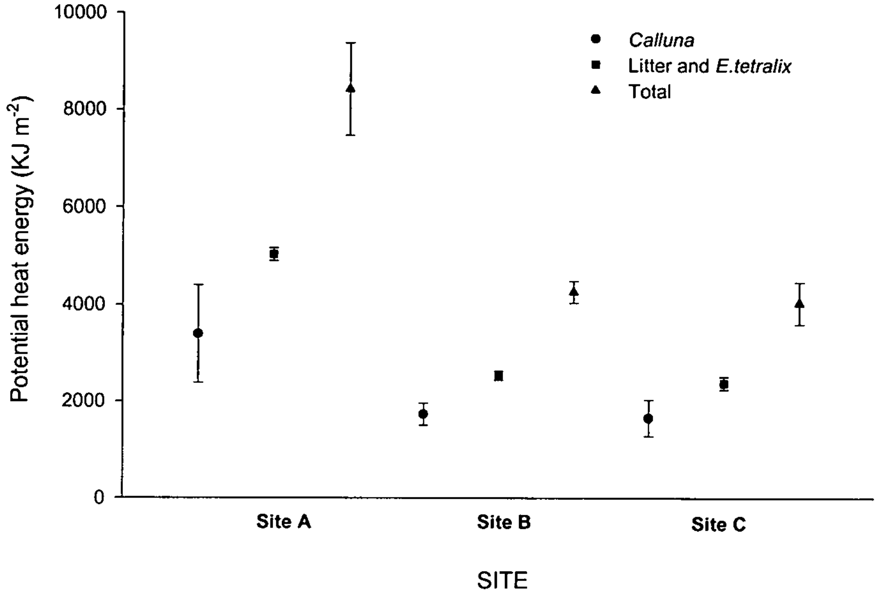

Figure 4.14. Potential heat energy release (H_w) over the three study sites, measured in kJ m^{-2}. Mean and standard errors are shown for *Calluna*, litter & *E. tetralix*, and total fuel biomass. *N* = 14 for each site.

The estimates of actual heat energy release (H_A) are shown in Figure 4.15 for each experimental plot alongside the total potential heat energy release (H_w). The biggest differences between H_w and H_A are in those plots that contained a lot of large *Calluna*. H_w in these plots included the potential contribution from the larger diameter (woody) material, but as this material was generally not consumed in the fire, H_A was therefore much lower than H_w.

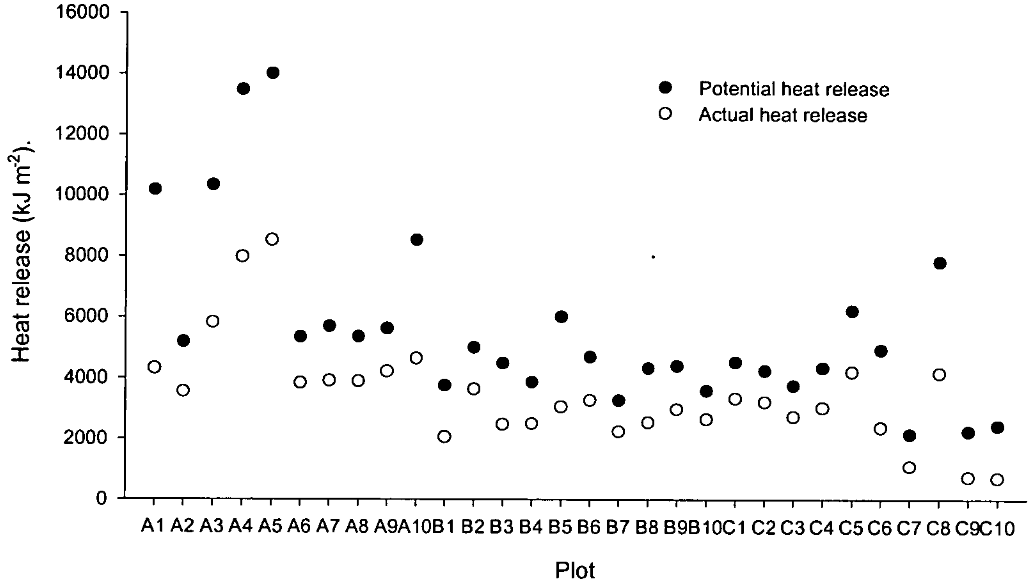

Figure 4.15. Predicted (H_W) and actual (H_A) energy release for each experimental fire plot.

4.5.2 Fireline intensity

Fireline intensity estimates are plotted against actual energy released estimates in Figure 4.16. These results demonstrate the variation within and between sites, and from fire to fire. The lowest I_B values (y-axis) are associated with the site C plots that were burnt first (C6 – 10), which also have the lowest H_A values. However, the highest I_B values are not associated with plots where the most fuel was consumed (plots A3, 4 and 5, firespeeds of 0.85 m min^{-1}), but rather with those plots where the fire moved a lot faster (plots B5, 6, 9 and 10, firespeeds of 2.5 – 3 m min^{-1}). In site A plots 3, 4 and 5, although more fuel was burnt than in the site B plots, the time taken to consume the fuel was much longer than for the site B plots, resulting in a lower rate of energy release compared to site B plots.

The average windspeeds recorded are plotted against the ROS of the fires in Figure 4.17. This figure is based on a sample size of 30, however it was only possible to estimate ROS and record average windspeed within a few categories, hence the smaller number of points on the graph. The ROS recorded ranged from 0.85 m min^{-1} to 3 m min^{-1}, and the regression line shows the linear relationship between ROS and windspeed over the range of values recorded. However, the relationship between ROS and windspeed outwith the range recorded is unknown.

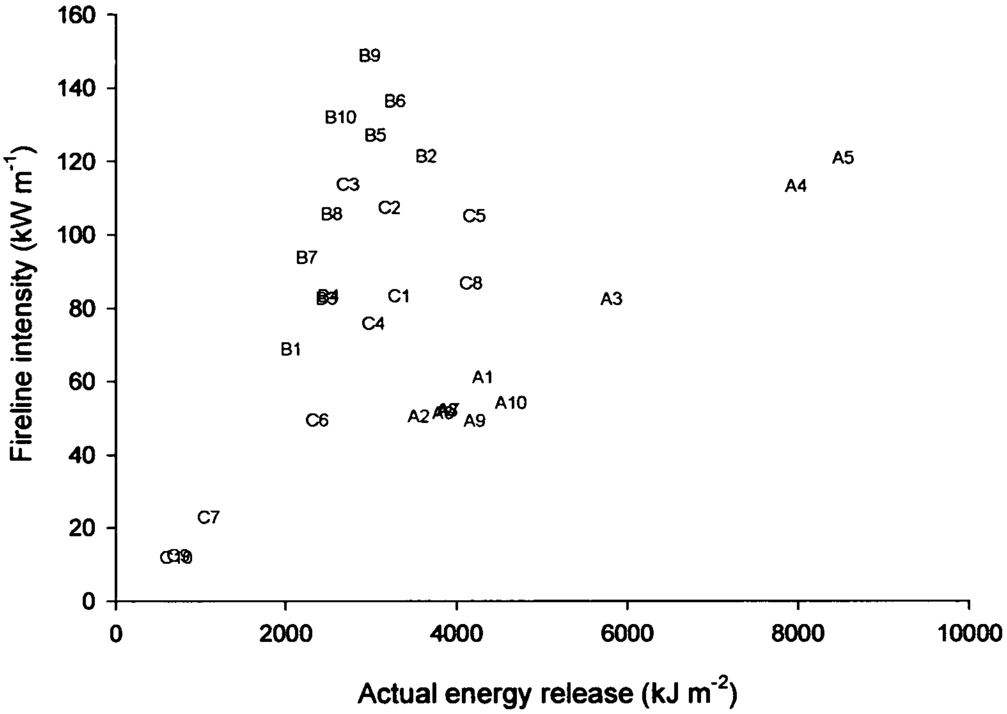

Figure 4.16. Fireline intensity (I_B) values against actual energy release values (H_A).

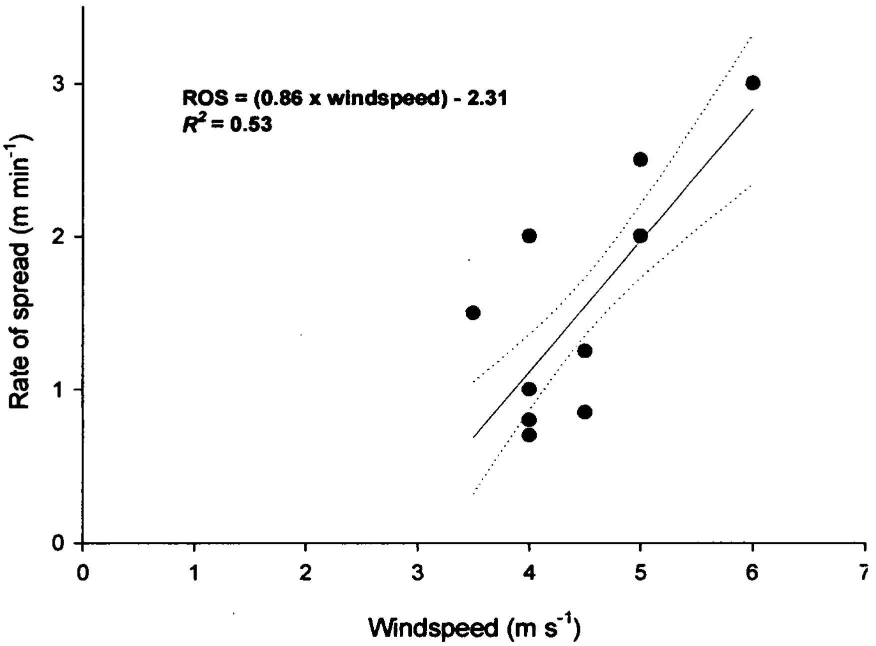

Figure 4.17. Windspeed plotted against ROS, with linear regression line and 95 % confidence intervals shown.

4.5.3 Relating fire intensity, heat release, temperature and fuel variables

Possible relationships between the above variables were examined using linear regression, with fuel variables (pre-fire biomass values, post-fire biomass values) and temperature variables (maximum temperature, time over 55 °C, total degree seconds) used individually as predictors for fireline intensity (I_B) and actual energy released (H_A) values. Consumed fuel values were not used as predictors, as these were used to estimate I_B and H_A. The H_A data required square root transformation before analysis. The results from all analyses are shown in Table 4.5.

Overall, although many of the results are significant, most have low R^2 values, indicating a very weak linear relationship between the intensity measure and the explanatory variable. The following very strong relationships can be seen:

- pre-fire *E. tetralix* and total fuel load are positively related to H_A.

The following relationships can be considered strong:

- pre-fire *Calluna* is positively related to H_A;
- post-fire litter and *E. tetralix* are negatively related to I_B;
- middle thermocouple, time >55 °C, is positively related to H_A.

The following relationships, although not particularly strong, are nonetheless notable:

- pre-fire small *Calluna* is negatively related to H_A;
- overall, pre-fire biomass gives better estimates of H_A compared to I_B.

All of the temperature variables are significantly, but generally very weakly, positively related to H_A. Similar results are seen between the temperature variables and I_B, (although two are non-significant) but the relationship are generally much weaker, with the exception of the middle thermocouple result noted above. These relationships are discussed later.

Table 4.5. Results from linear regression analysis relating temperature and fuel variables to fireline intensity and actual energy release values. Temperature variables are grouped by thermocouple position; '>55 °C' refers to duration (s) of temperatures >55 °C; 'total DS' refers to total degree seconds; 'mid-litter' refers to fine litter from 25 by 25 cm quadrat in middle of plot; 's-*Calluna*' refers to small *Calluna*. All regression lines have a positive slope, except those marked 'NEG'.

	FIRELINE INTENSITY (I_B)				ACTUAL HEAT RELEASED (H_A)			
	R^2	Significance			R^2	Significance		
Pre-fire biomass								
Calluna	0.08		NS		0.53		$F_{1,28} = 33.45$	$P < 0.001$
Litter	0.01		NS		0.33		$F_{1,28} = 15.63$	$P < 0.001$
E.tetralix	0		NS		**0.76**		$F_{1,28} = 94.84$	$P < 0.001$
s-*Calluna*	0.03		NS		0.42	NEG	$F_{1,28} = 22.07$	$P < 0.001$
TOTAL	0.02		NS		**0.80**		$F_{1,28} = 113.8$	$P < 0.001$
Post-fire biomass								
Calluna	0		NS		0.36		$F_{1,28} = 17.4$	$P < 0.001$
Litter	0.54	NEG	$F_{1,28} = 34.69$	$P < 0.001$	0.20	NEG	$F_{1,28} = 8.31$	$P < 0.01$
E.tetralix	0.59	NEG	$F_{1,28} = 42.71$	$P < 0.001$	0.08		NS	
s-*Calluna*	0		NS		0		NS	
mid-litter	0.25	NEG	$F_{1,27} = 10.5$	$P < 0.01$	0.16	NEG	$F_{1,27} = 6.49$	$P < 0.05$
TOTAL	0		NS		0.16		$F_{1,28} = 6.6$	$P < 0.05$
Surface temperature variables								
Maximum	0.01		NS		0.17		$F_{1,27} = 6.59$	$P < 0.05$
>55 °C	0.12		$F_{1,27} = 4.95$	$P < 0.05$	0.29		$F_{1,27} = 12.39$	$P < 0.01$
Total DS	0.01		NS		0.16		$F_{1,27} = 6.53$	$P < 0.05$
Middle temperature variables								
Maximum	0.12		$F_{1,27} = 5$	$P < 0.05$	0.36		$F_{1,27} = 16.62$	$P < 0.001$
>55 °C	0.49		$F_{1,27} = 27.8$	$P < 0.001$	0.52		$F_{1,27} = 31.81$	$P < 0.001$
Total DS	0.19		$F_{1,27} = 7.62$	$P < 0.01$	0.37		$F_{1,27} = 17.39$	$P < 0.001$
Top temperature variables								
Maximum	0.13		$F_{1,27} = 5.13$	$P < 0.05$	0.15		$F_{1,27} = 5.9$	$P < 0.05$
>55 °C	0.19		$F_{1,27} = 15.3$	$P < 0.001$	0.48		$F_{1,27} = 26.61$	$P < 0.001$
Total DS	0.34		$F_{1,27} = 7.73$	$P < 0.01$	0.22		$F_{1,27} = 8.85$	$P < 0.01$
Above temperature variables								
Maximum	0.12		$F_{1,27} = 4.83$	$P < 0.05$	0.37		$F_{1,27} = 17.24$	$P < 0.001$
>55 °C	0.19		$F_{1,27} = 7.67$	$P < 0.01$	0.19		$F_{1,27} = 7.69$	$P < 0.01$
Total DS	0.11		$F_{1,27} = 4.34$	$P < 0.05$	0.22		$F_{1,27} = 9.15$	$P < 0.01$

4.5.4 The fire environment at the surface

Previous results (section 4.4) showed that the surface thermocouple position tended to have a greater mean and variability in time over 55 °C (Figure 4.12), with a similar trend seen in total degree seconds (Figure 4.13B). One of the assumptions behind the selection of study plots was that the presence or absence of *Calluna* will have an effect on the fire environment at the surface, and a subsequent effect on the damage to, and recovery of, the *Sphagnum* layer. The plots were therefore divided by the presence/absence of *Calluna*, and are shown in Figure 4.18

with maximum temperature and total degree-seconds plotted for the surface thermocouples only. This shows the clear difference in both maximum temperature and total degree-seconds between plots with and without *Calluna*. In the one plot without *Calluna* that has high maximum temperature and degree-second values, the moss in that plot actually caught fire, and smouldered for a considerable time after the flames had died down. In general, although plots with *Calluna* exhibit a wide range of temperature values, the plots without *Calluna* were almost exclusively restricted to the lower ends of the ranges of these variables.

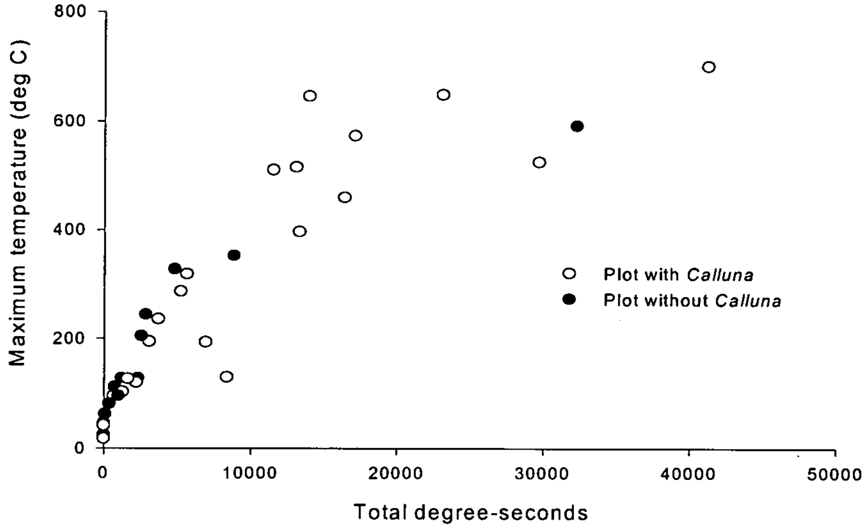

Figure 4.18. Surface total degree-seconds and maximum temperatures.

4.6 Discussion

4.6.1 Fire environment and fuel consumed

The environment results (Figures 4.4 and 4.5) show that at least part of the fuel complex in the blanket-bog habitat can dry out, enough to permit burning, very quickly after rain. The first test fires were lit the day after the last rain event, and flame lengths of 1.5 – 2 m were observed from the test plots (in a high fuel area). An easterly wind is considered best for drying out the vegetation prior to burning (D. Davies, pers. comm.), as the more common westerly winds are associated with rain. For two sites on Skye, Currall (1981) estimated an average number of suitable burning days per year of 28 and 38. However, the criteria Currall used took no account of excessively windy days, nor frost or snow-lie, and he proposes that the actual number is less than 20. Even that number may be an overestimate, indeed some years there are no suitable burning days. When gaps in the weather occur (Figures 4.4 and 4.5), burning must be organised and undertaken very quickly to take advantage of what may be a very short-lived change in conditions.

The fuel moisture results show that, as expected, the aerial fuel dries out first of all, with fuels lower down drying out more slowly. The fuel in the lowest positions will be influenced not only by precipitation but also, to varying degrees, by the wetness of the bog surface. As noted in Chapter 1, dead grass fuel can have a response time of as little as 12 minutes to a change in humidity from 90 to 20 % (Anderson, 1990), and the aerial fine litter on the blanket bog are in a position to respond quickly to such changes in the environment. Buckley (1993) gives fuel moisture values for south-eastern Australia showing a similar vertical gradient, as well as increased moisture content with shading. Increased variance with increased moisture content was also found by Buckley, similar to the results of this study. The distinction between elevated and surface fuels is emphasised, as given common conditions, the moisture content varies considerably between the two groups. The mean aerial fuel moisture in this study (16 %) is less than mean value of any fuel type from dry heathland studies by Hobbs & Gimingham (1984). The raised (surface) fuel mean (62 %) is very similar to the mean values for *Calluna* shoot and surface litter fuels from dry heathland, but the base fuel mean (202 %) is considerably less than the moss mat mean (320 %) from dry heathland. The effects of the larger moisture content of the moss mat is often observed after a dry heathland fire, with the moss layer remaining relatively unburnt. In Dorset heathland, Allchin (1997) found a mean of 30 % fuel moisture for the vegetation, and 60 % for the litter layer. With further studies of fire behaviour and fuel moisture values, it should be possible to set maximum thresholds of fuel moisture for burning, and further to correlate fire characteristics (and effects) with fuel moisture values. Such information would provide a quantitative basis for prescribed burning.

The biomass of the different fuel types left after each fire is small (under 50 g m^{-2}), with the exception of *Calluna*. As the amount of potentially available *Calluna* increases, so the amount of *Calluna* left after the fire increases, and this remaining *Calluna* is the larger diameter woody material. Management fires under these conditions do not produce a 'clean burn', although under more favourable fire conditions (e.g. drier, windier, or during summer), more *Calluna* fuel can be expected to be consumed. The proportion of fine litter consumed is very consistent (except in the site C plots discussed earlier). This consistency is maintained across all plots and sites and also over 5 days of burning, where an increase in proportion consumed might be expected with drier conditions. The proportion always left behind may be the results of the blanket-bog surface keeping a certain amount of the fuel (in contact with the surface) damp enough not to burn, despite the varying fire intensities and temperatures. This damp litter layer (very often observed after fire in bog habitats as a layer of semi-burnt material lying on the bog surface) may be very important in limiting the effects of fire on the *Sphagnum* layer.

The total amount of fuel consumed in the fires in this study, ranging from less than 50 g m^{-2} to 450 g m^{-2}, are considerably less than values from dry heathland fires. Hobbs & Gimingham (1984) showed a range of fuel consumption of 868 to 2 048 g m^{-2}; Allchin (1987) a range of 1 246 to 2 557 g m^{-2}; and Kayll (1966) a range of 650 to 1 484 g m^{-2}. Although the bog habitat is expected to have lower fuel availability and consumption, the values quoted for this study are affected by the scale of the sampling and the scale of the fuel patchiness. From personal observations, some small areas of thick, old *Calluna* are likely to have a biomass of *Calluna* approaching that of dry heathland. This fuel patchiness has implications for fire intensity characteristics, discussed later.

4.6.2 Temperature characteristics

Analysis of the temperature data showed that significant differences between the sites was due to site C having lower means for all three temperature characteristics, and this can be attributed to half of the plots on this site being the first to be burnt. There is, however, a great degree of variability apparent both within and between sites. This variability is also shown by other studies measuring temperature, with a maximum canopy temperatures recorded of 220 – 840 °C (Whittaker, 1961); 940 °C (Kenworthy, 1963); 250 °C (Kayll, 1966); 800 °C (Currall, 1981); 340 – 790 °C (Hobbs *et al.*, 1984); 204 – 704 °C (Allchin, 1997). The mid-canopy range recorded in this study is 31 – 886 °C for all plots, and 103 – 886 °C for plots with *Calluna*. Although there are methodology differences in comparing the above studies, all the results emphasis that the temperature regime of fires can be extremely variable.

The pattern of temperature characteristics found between the four thermocouple positions was consistent across all sites, with the highest maximum temperatures found in the middle of the vegetation. The highest total degree-seconds are also found at this position and at the surface, although the surface data showed high variation. The variation at the surface was also apparent in the temperature duration data, and although the differences were non-significant, they nonetheless indicate the different temperature regime at the surface. This difference is also apparent between those plots with and without *Calluna*, and confirms one of the basis for plot selection on all sites (Chapter 2), that the fire characteristics and effects will vary with presence or absence of *Calluna*. The maximum surface temperatures recorded ranged from 18 – 702 °C, with the lowest maximums being recorded in the site C plots that were first burnt. Hobbs & Gimingham (1984) recorded a surface maximum temperature range of 140 – 840 °C. Overall, the temperatures reached in blanket-bog fires can get as high as dry heathland fires, but with a greater proportion of lower temperatures recorded. All fires seem to show a great deal of within and between fire temperature variation, but this variation is more pronounced in the blanket-bog habitat due to the heterogeneity of the fuel arrangement and fuel moisture content.

4.6.3 Fire intensity and energy measures

Van Wagner (1983) suggests five main kinds of fire in northern boreal ecosystems, with the following fireline intensity ranges:

- deep smouldering fires (<10 kW m^{-1})
- surface backfires (100-800 kW m^{-1})
- surface headfires (200 - 15 000 kW m^{-1})
- crown fires (8 000 - 40 000 kW m^{-1})
- spotting fires (up to 150 000 kW m^{-1})

Comparison of the above with the fireline intensity values obtained in this study would indicate that surface headfires on blanket bog are much less intense than the range given for surface fires above, and even lower than backfire values. Lower values may be expected, as the fires in this study are in a very wet habitat, and those values given by Van Wagner are presumably for drier habitats with a much greater total fuel load (although with similar fuel types).

The range of fireline intensity values calculated in this study is 11 to 120 kW m^{-1} (again, the very low values coming from the site C plots first burnt). Hobbs & Gimingham (1984), in dry heathland, estimated a range of intensities of 43 – 1 112 kW m^{-1}, and 2 430 kW m^{-1} was estimated for an uncontrolled dry heathland fire (Kayll, 1966). The values in this study therefore appear very low in comparison, but there is an additional consideration. The spatially variable nature of management fires was emphasised by both the small experimental fires described in this chapter and observation of larger fires. In the high fuel plots (sites A and D), flame lengths of 1.5 to 2 m were commonly observed, coming from older and larger *Calluna* patches with *Molinia* litter. It is possible to estimate fireline intensity using flame length only using the following equation from Byram (1959):

$$I_B = 259.833(L)^{2.174}$$

where I_B is fireline intensity (kW m^{-1}) and L is flame length (m). Large flames were limited in area (to the size of the patch of *Calluna*) and relatively short-lived, however they indicate transient I_B values of 627 to 1 173 kW m^{-1}. Such intensity values were not estimated from the fuel data collected in this study due to the spatial patchiness of the fuel. This patchiness can therefore cause problems in estimating I_B values from plot-level fuel estimates. This undoubtedly results in underestimates of the highest intensity values, and overestimates of the lowest values (i.e. an averaging out of fuel load and therefore intensity estimates occurs).

The lack of a clear relationship between the measures of fireline intensity and heat release per unit area demonstrate that these two measures convey different information about the fire. The fireline intensity value gives an average energy output over a second, for the time the fire is resident in the plot. The actual energy release value gives the total energy output, i.e. the sum of energy output for the time the fire is resident in the plot.

4.6.4 Fire characteristics relationships

The results presented in Table 4.5 may at first appear to be confusing or contradictory, but their meaning becomes clear with consideration of the ecology of the fire and vegetation. The positive relationship of the pre-fire fuel biomass with the area energy release is expected – the more fuel available, the more burnt, and the more heat given off. However, the biomass of small *Calluna* is negatively related to the area energy release. This could in part be due to errors in the prediction of small *Calluna* (the study did not initially include this fuel type for prediction), but it may also be because where the *Calluna* is small and stunted, the environment is too wet for the growth of large or many vascular plants (and any fuel in such an area may have a higher fuel moisture content). The lack of any relationship between pre-fire fuel biomass and fireline intensity highlights the different scales at which different measures operate. The pre-fire fuel variables are plot-level measurements, as is the area energy release measurement with which the relationships are found, In contrast, fireline intensity is a measure of the energy output over one second, and is more strongly influenced by the speed of the fire rather than by fuel characteristics.

The biomass remaining after the fire is more consistently related to both measures of intensity, with a negative relationship found for litter, *E. tetralix* and mid-litter. These are small fuel types, and will therefore be consumed first in a fire. The negative relationship is expected; the more intense the fire, the greater the proportion of such small fuel types are consumed. In contrast, the *Calluna* and total biomass fuel types show a positive relationship with area energy output. In situations where the *Calluna* biomass remaining after a fire is very high (and this fuel type is the major component of the fuel remaining), such a plot also contained a lot of fuel (large and small diameter) before the fire. The larger diameter woody material is mostly left behind, but the extra smaller material would have been burnt, contributing to the higher energy output.

The overall stronger relationships obtained between the temperature variables and H_A (in comparison to I_B) indicate that the H_A may be ecologically more meaningful than the latter, if temperature regime is considered important to vegetation damage and recovery. The common measurement and use of fireline intensity overseas is probably due to the fact that it contains information relevant to fire-fighting. Overseas fires (wild and management) are generally larger and more intense than those encountered in the UK, and thus fireline intensity information is more relevant.

4.6.5 Conclusions

The fire characteristics results (temperature, intensity) are broadly comparable to those obtained from previous studies in heathland habitats in this country, but with a greater proportion of lower values. This variability is a key feature of all fires, but in particular those in blanket bog, and demonstrates that fire cannot be treated as a uniform event. Fires may be broadly categorised, but the variation that accompanies each fire must be appreciated and quantified. The main reason for fire variability is the spatial patchiness of the fuel complex, and to a lesser degree the extreme moisture gradients encountered in the fuels. Although the latter have not been quantified fully they undoubtedly vary with position, in particular along a vertical gradient, and also in relation to the topography of the bog surface.

The results given here also emphasis the differences between the different ways of characterising a fire. This has not been appreciated in UK fire studies to date, and prior to collecting any fire characteristic data, the questions being addressed should be considered carefully. If the aim is a detailed study of the response of individual plants to fire, then temperatures reached by the meristems will be important, in conjunction with the shielding effects of the *Sphagnum* layer. If a larger-scale estimate of fire intensity is required, then actual energy output (kJ m^{-2}) may be appropriate. This would have to take into account fuel (and therefore fire) spatial heterogeneity. If intensity details are required for fire control purposes and/or fire behaviour prediction, then fireline intensity (kW m^{-1}) would be more appropriate, as is commonly used abroad, again taking into account fuel variation.

Chapter 5 RECOVERY OF *SPHAGNUM* AFTER FIRE

5.1 Introduction

The *Sphagnum* layer may be considered the most important living component to the bog system, and it is often the main constituent of peat. It is the 'substrate' through which the vascular species often grow, and the *Sphagnum* layer defines to a large extent the vegetation and hydrological characteristics of the habitat. Loss of the *Sphagnum* layer can cause fundamental changes to habitat structure and can also have far reaching consequences. In the Peak District, reservoirs have silted-up due to deposition of eroded peat, which is a result of a lack of cover of *Sphagnum* or vascular plants on upland blanket-bog habitat (Anderson, Tallis & Yalden, 1997). Although the lack of *Sphagnum* cover in this area is thought to be due to atmospheric pollution, it does indicate the possibly severe consequences of a lack of vegetation cover on a bog. When bare peat is exposed, there is also the possibility of large quantities of carbon being released into the atmosphere due to oxidation of the peat, thereby contributing to global warming.

Observations of the immediate effects of management fires in 1995 and 1996 in the north-west of Scotland showed that the effects of fire on the *Sphagnum* varied spatially across sites. The *Sphagnum* beside and around shrubs (mainly *Calluna*) appeared to be affected more severely by the fire. There are several possible explanations for this: increased fuel biomass present in such positions; different fuel arrangement; or drier fuel and *Sphagnum* (*Calluna* is often associated with a slight hummock). This observed difference was the basis for plot selection (Chapter 2). Spatial variation in the effects of fire may be expected as a consequence of the different species of *Sphagnum* present in a bog habitat, and in particular because of the habitat preference of the different *Sphagnum* species. Hummock species will have a lower moisture content than hollow species, and will therefore catch fire easier. The effects of the presence of a shrub and a hummock of *Sphagnum* are therefore interlinked – the hummock provides slightly drier conditions, which suit shrub growth, and in turn the presence of the shrub may provide a 'climbing frame' for the *Sphagnum* (Malmer, Svensson & Wallen, 1994).

A fire can have one of three broad effects on *Sphagnum*:

1. the fire has little or no impact, with the *Sphagnum* recovering quickly and with little effect evident on the cover, growth rate or species composition. Fire may even encourage *Sphagnum* growth under some circumstances;
2. cover, growth rate and species composition are affected to some extent for a time after the fire, but recovery occurs before the next fire event;
3. the *Sphagnum* is either killed by the fire, or affected to an extent that bare peat is exposed, and recovery before the next fire event is not possible. Ongoing degradation of the habitat takes then takes place if *Sphagnum* cannot re-establish.

The third outcome can be the result of severe fire. Similar results are seen when the bog habitat is changed in some other way to make it unsuitable for *Sphagnum* colonisation and growth, such as the pollution example noted above, or when peat harvesting takes place, or when drainage lowers the water table below the level required by *Sphagnum*. The default opinion of the effects of management fire on *Sphagnum* of many conservation bodies (reflected in the burning guidelines summarised in Table 1.2) is that it causes ongoing degradation.

However, there is very little information available about the recovery of *Sphagnum* after fire. Foster (1984) notes that 'scorched' ridge and hummock *Sphagnum* in Canada is invaded by *Polytrichum* and *Cladonia* species, but that *Sphagnum* eventually re-establishes dominance. Also in Canada, Kuhry (1994) noted complete vegetation recovery within a few decades of peat surface fires in boreal peatlands in western Canada. However, these fires appear to be more severe than the management fires dealt with in this thesis, since the *Sphagnum* apparently had to re-colonise bare peat.

In the UK, our understanding of the response of *Sphagnum* to fire is based on conjecture and informal observation more than established fact. One opinion is that management fires have very little effect on *Sphagnum*, as the fire passes through the vegetation on the bog surface (Barkman, 1992; Daniels, 1991). An alternative is that fire is harmful to blanket-bog, and therefore presumably harmful to the *Sphagnum* component (see Table 1.2). Interestingly, the latest and most definitive bog-management handbook (Brooks & Stoneman, 1997) makes no mention of the effects of fire on the *Sphagnum* component of the bog, which is in contrast to the wealth of detail regarding other management activities aimed at creating or maintaining the correct habitat for *Sphagnum*. This reflects the lack of definitive published information regarding fire effects on *Sphagnum* and the subsequent recovery of the *Sphagnum* layer.

This lack of information leaves many questions unanswered. This chapter looks at the damage done to *Sphagnum* by fire, in particular regarding fire temperature and intensity, and position on the bog in relation to fuel available. Recovery over time is recorded, and the possible positive effects of management fire on *Sphagnum* growth discussed. This chapter therefore addresses two broad questions:

1. How does the damage to *Sphagnum* vary with position on the bog surface, fuel loading, fire temperature and fire intensity?
2. What are the effects of grazing on the recovery of *Sphagnum*, and how quickly does the *Sphagnum* layer recover over time?

5.2 Methods

The recording of *Sphagnum* condition took place on the management burn sites from 1996 and 1997 and the experimental burns from 1998. The identification of *Sphagnum* species was difficult, due to the damage caused by the fires, and also to the very small size of any new shoots coming through the damaged moss layer. The *Sphagnum* component on all study areas was dominated by *Sphagnum capillifolium* and *S. papillosum*, with scattered *S. subnitens*, *S. tenellum* and *S. imbricatum*, and *S. cuspidatum* in the wetter hollows. In the plots selected for this study, the *Sphagnum* layer was dominated by *S. capillifolium* and *S. papillosum* in different proportions, and a mix of these two species is commonly found on blanket bogs. This chapter therefore makes no reference to the identity of individual species in the plots, and the results can be regarded as being applicable to a 'typical' blanket-bog mix of *S. capillifolium* and *S. papillosum*. Analysis of plots where species identification was confirmed supported the general conclusions of the results presented here.

5.2.1 Sites

The plot layout on all sites is described in Chapter 2, but is also summarised here.

1996 and 1997 burns

The following plots were located on the 1996 burn sites at Badagyle, Loch Poll, Loch a' Chaoruinn and Mast, and on the 1997 burn sites at Creag na Braiste and Blar Garvie:

- the four 1996 burn sites each had 5 pairs of 25 cm x 25 cm plots, one of each pair caged to exclude grazing animals;
- the two 1997 burn sites each had 10 pairs of 25 cm x 25 cm shrub/*Sphagnum* plots (centred on the shrub/*Sphagnum* interface), with one of each pair caged to exclude grazers. In addition, each site had 5 flat plots (no shrub present), all caged. On each site half of the pairs of plots, and half of the individual flat plots, received 200 g (dry weight) of extra fuel, scattered evenly over an area 0.5 x 0.5 m centred on the plot.

The extra fuel consisted of dried birch twigs, up to a maximum of 0.5 cm in diameter. However, most of this fuel was unburnt, with consumption ranging between 30 to 60 %, and an average of 40 % consumed (the fuel remaining after the fires was collected, however the samples were later lost). The fuel arrangement (with the twigs laid horizontally on the ground) and fuel type and size were thought responsible for the lack of consumption of the extra fuel.

Within each plot, *Sphagnum* condition was recorded within an area of 0.25 cm x 0.25 cm. This area was divided by a 5 cm–square grid into 25 recording squares. When recording was carried out in these plots, a metal grid was used to divide the recording area. This grid was made in two halves, each half consisting of two adjacent sides of the quadrat, with parallel 'prongs' forming half the interior grid. The two halves were then fitted together at right angles to form the complete grid; this enabled the arms of the grid to be put through the vegetation. This was necessary because the density and uneven-ness of the vegetation precluded the use of a quadrat on the top of the vegetation. Despite the use of this method, after more than a year of vascular plant regrowth, it was very difficult at times to form the grid in the correct position and to even see the *Sphagnum*, and for the final record made on the 1996 burn sites (in 1999, Table 5.1), all above-ground vascular plant material had to be clipped and removed. Metal pegs located at the corners of each plot allowed the recording grid to be re-located in the same position each time.

1998 burns

On each of the three main 1998 sites (A, B and C), ten 1 m^2 uncaged plots were burnt (see Chapter 4 for details), with five plots burnt on the other two sites. These plots were mainly used for fuel and fire characteristic studies (Chapters 3 and 4), but before and after burning in April 1999 the condition of the *Sphagnum* within a 2 cm radius of the centre of each plot was recorded. This was done at the same place as the surface thermocouple was located for fire temperature measurements. The amount of *Calluna* at the centre of the plot was also recorded before burning, and was scored as either: 1 (dense *Calluna*); 2 (sparse *Calluna*); 3 (no *Calluna*). Table 5.1 summarises the sites and recording dates of *Sphagnum* condition monitoring.

Table 5.1. Summary of sites and dates of post-fire *Sphagnum* condition recording.

Sites	Recording dates				Plot no. & type
1996 burns (4 sites)					
Badagyle **Loch Poll** **Loch a' Chaoruinn** **Mast**	**Sept 1996** All sites, all plots	**Oct 1997** All sites, grazed plots only	**Apr 1999** All sites, all plots, except Loch Poll,		Each site, 5 pairs of plots, one of each pair caged
1997 burns (2 sites)					
Blar Garvie **Creag na Braiste**	**Apr 1997** Both sites	**Jul 1997** Both sites	**Nov 1997** Both sites	**Apr 1999** Blar Garvie only	Each site, 10 pairs of plots, one of each caged, plus 5 'flat' plots, all caged. Half of all plots with additional fuel
1998 burns (5 sites)					
All sites	**Apr 1999**	Three sites (A, B & C) with 10 plots, two sites (D & F) with 5.			

5.2.2 Scoring *Sphagnum* condition

A semi-quantitative method of scoring *Sphagnum* condition was developed, based on identifiable categories. The following categories of *Sphagnum* condition were used after observation of *Sphagnum* on several sites and at various times since the last fire:

- healthy (full and normal colour, no damage apparent);
- bleached (very pale or white, often with no other damage apparent);
- singed (plants usually bleached, but with tips of branches and capitulum singed brown or black);
- burnt (all visible *Sphagnum* burnt, and black or brown in colour);

- decaying (usually only seen more than ~1 year after burning; apparently caused by the breakdown of dead *Sphagnum* and the absence of any recovery or regeneration. The *Sphagnum* takes on a semi-decomposed 'mushy' appearance).

Each 5 cm x 5 cm grid square that was scored contained *Sphagnum* that corresponded to either one, or at the most a mix of two, of the above categories. If two categories were present, then the proportion of each category was recorded. As this chapter is concerned with changes in the amount of healthy *Sphagnum*, all data were converted to give a condition score that indicated the proportion of healthy *Sphagnum* in each grid square. The resulting range of scores, and the approximate percentages of healthy *Sphagnum* they represent, are shown in Table 5.2.

Table 5.2. *Sphagnum* condition scores used in the analysis, and the approximate proportions of *Sphagnum* within each grid square that they represent.

Percentage of healthy *Sphagnum*	0		25		50		75		100
Condition score	0	1	2	3	4	5	6	7	8

One estimate of *Sphagnum* condition (in the centre of the plot) was made before and after burning on the 1998 sites. No definitive data are available on the condition of the *Sphagnum* layer on the 1996 burn sites prior to burning. On the 1997 and 1998 burn sites, the vegetation did not allow detailed scoring of *Sphagnum* condition before burning, but examination of each plot revealed only healthy *Sphagnum*. The pre-fire score for *Sphagnum* condition is therefore taken to be 8 on all sites, but this assumption will be discussed later.

Figure 5.1 shows plot 5A (ungrazed) from Blar Garvie before and after burning. The top image shows that the *Sphagnum* layer is obscured by the vascular vegetation (alive and dead) before burning. In the middle image, the *Sphagnum* layer is predominantly bleached. The final image illustrates both the fast recovery of the vascular plants (which have been removed from the plot to show the *Sphagnum*), but also the healthy condition of *Sphagnum* 17 months after burning.

5.2.3 Data analysis

For the 1996 and 1997 burn data, the grid scores (up to a total of 25) from each plot were converted to a single condition score for the whole plot by summing and dividing by the number of grid squares in which *Sphagnum* was recorded. This resulted in, for each plot at each

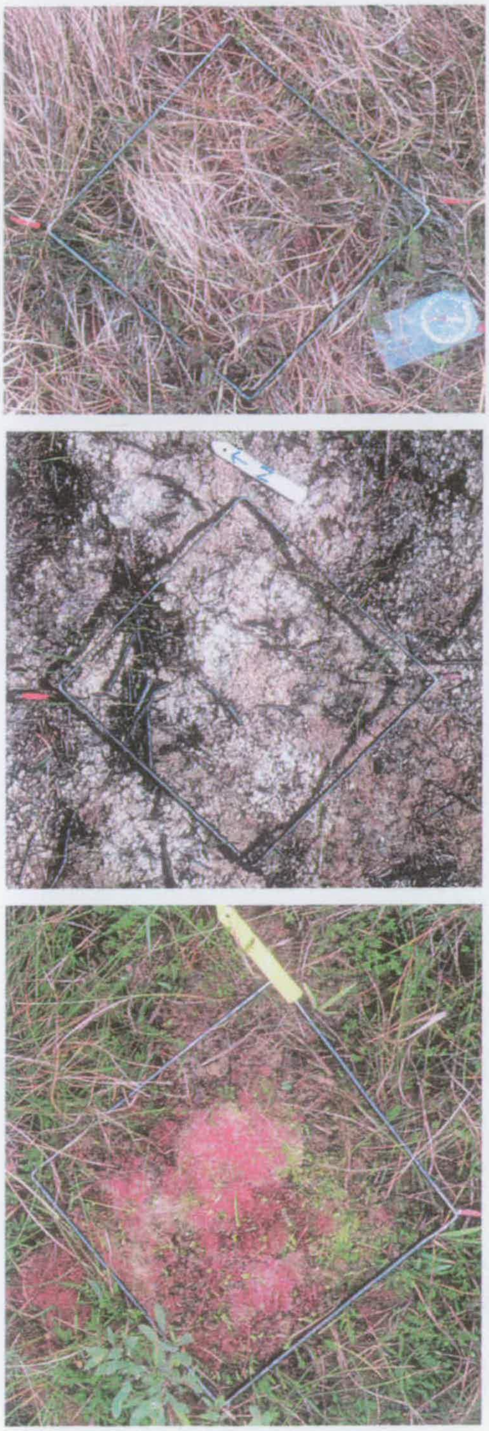

Figure 5.1. Photos of 25cm x 25 cm plot 5A on Blar Garvie. The top image was taken on 6-4-97 (before burning on 18-4-97), the middle image on 31-5-97 (showing the bleached *Sphagnum* layer, and remains of extra fuel added to the quadrat) and the bottom image on 10-9-98 (after removal of the vascular plants), showing healthy *S. capillifolium.*

recording time, a single measure of overall condition. Transformation before analysis was not necessary for the 1999 burn data, but in order to meet analysis requirements (normality, homoscedasticity) the 1996 and 1997 burn data were transformed by taking $\log_{10}(x + 1)$.

5.3 Results

5.3.1 Effects of position, fire temperature and fire intensity on *Sphagnum*

The data from the 1998 burn plots were used to quantify the effect of site and amount of *Calluna* on the condition score of the *Sphagnum* in the centre of each plot one year after burning. GLM analysis was used with post-fire *Sphagnum* condition score as the dependant variable, site as a factor and *Calluna* amount as a covariate. Site did not have a significant effect on post-fire condition score ($F_{4,33} = 2.60$, $P = 0.055$), but the P value indicates that a larger sample size might have shown a significant effect. The site condition scores are shown in Figure 5.2A. The *Calluna* covariate was highly significant ($F_{1,4} = 17.61$, $P < 0.001$), indicating increasing damage to the *Sphagnum* layer with increasing amounts of *Calluna* (Figure 5.2B). The mean condition score in plots with dense *Calluna* was 0.727, which was significantly different from the mean scores for plots with sparse *Calluna* and no *Calluna* (scores of 3.615 and 4.923 respectively).

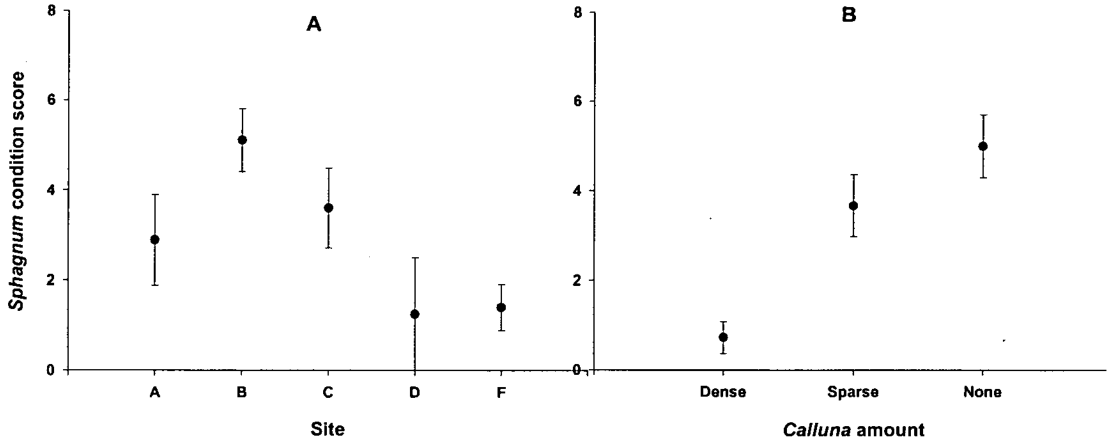

Figure 5.2.. *Sphagnum* condition scores in centre of 1998 experimental burn plots, one year after burning. Fig. A shows variability between sites ($F_{4,33} = 2.60$, $P = 0.055$), and Fig. B the variability between *Calluna* categories ($F_{1,4} = 17.61$, $P < 0.001$). *Calluna* categories are: 1 = dense; 2 = sparse; 3 = none. Mean and standard errors shown.

The effects of fire and fuel attributes on the condition of *Sphagnum* were examined in more detail by performing linear regressions of the 1998 burn post-fire condition scores from all sites against the fuel and fire attributes (Chapters 3 and 4), shown in Table 5.3. Only plots containing *Calluna* were included in the *Calluna* height analysis, and only plots from sites A, B and C could be included in those analyses involving fire attributes. The results show that all three temperature variables are negatively related to *Sphagnum* condition, although the relationships are weak in all cases. The fireline intensity (I_B) values are not related to *Sphagnum* condition, but there is a weak (but again significant) negative relationship with actual energy release (H_A).

Table 5.3. Regression equations predicting *Sphagnum* damage 1 year after burning. H is the condition score explained in the text; the temperature variables are explained in Chapter 4; I_B is fireline intensity; H_A is actual energy released.

Variable	Equation	ANOVA results	R^2
***Calluna* ht (cm)**	H = 5.99 – 0.144 (*Calluna* height)	$F_{1,18} = 8.86, P < 0.01$	0.32
Max temp (°C)	H = 4.56 – 0.0064 (max temp)	$F_{1,33} = 9.48, P < 0.001$	0.22
Time > 55 °C (s)	H = 4.79 – 0.0034 (time > 55°C)	$F_{1,33} = 12.14, P < 0.001$	0.27
Total DS	H = 3.96 – 0.000144 (total DS)	$F_{1,33} = 8.47, P < 0.01$	0.20
I_B (kW m^{-1} s^{-1})	NS	NS	NS
H_A (kJ m^{-2})	H = 6.40 – 0.000830 (H_A)	$F_{1,24} = 10.25, P < 0.01$	0.30

5.3.2 Effects of increased fuel load and grazing on *Sphagnum* recovery

The results described in the previous section show that the amount of *Calluna* (as measured by the score value and height) has a significant effect on the condition score of the *Sphagnum*. This question was also addressed by the 1997 burns, with half the plots having extra fuel added. Differences between the two sites (Blar Garvie and Creag na Braiste) were first of all examined by a GLM using post-fire *Sphagnum* score as the dependant variable, and site and recording date as factors. Data from 1997 only were used, as 1999 data were only available for Blar Garvie. The results showed a highly significant increase in *Sphagnum* condition between July and October 1997 on both sites ($F_{1,93} = 32.64$, $P < 0.001$), but also that the condition score was consistently higher on Creag na Braiste compared to Blar Garvie ($F_{1,93} = 5.04$, $P < 0.05$). The data from the two sites are therefore analysed separately.

Creag na Braiste: The data sets from the two recording dates in 1997 (July and October) were analysed separately, using a GLM with grazing and addition of fuel as factors and *Sphagnum* condition score as the dependant variable. On both dates, neither factor nor the interaction effect had a significant effect on the *Sphagnum* condition scores.

Blar Garvie: Employing the same analysis as described in the previous section, there was no significant effect from either factor or the interaction in the July 1997 data, although the fuel addition factor was close to significance ($F_{1,21} = 4.14$, $P = 0.055$). Neither factor nor the interaction were significant from the October 1997 data.

The 1999 data from Blar Garvie were also analysed using the same GLM procedure, and again the effects of both grazing and fuel addition, and the interaction, were found to be non-significant ($P = 0.177$, 0.228 and 0.752 respectively). However, examination of the interaction plot (Figure 5.3) reveals trends in the data. Overall, there is a lower condition score under grazing compared to no grazing, and also higher condition scores are associated with plots with no extra fuel added, in comparison to plots with additional fuel. These trends are also apparent, although not as pronounced, in all the interaction plots for the 1997 results from Blar Garvie, and from one of the two interaction plots from Creag na Braiste. This suggests that both grazing and fuel addition have significant effects on *Sphagnum* condition which may be revealed in a larger study.

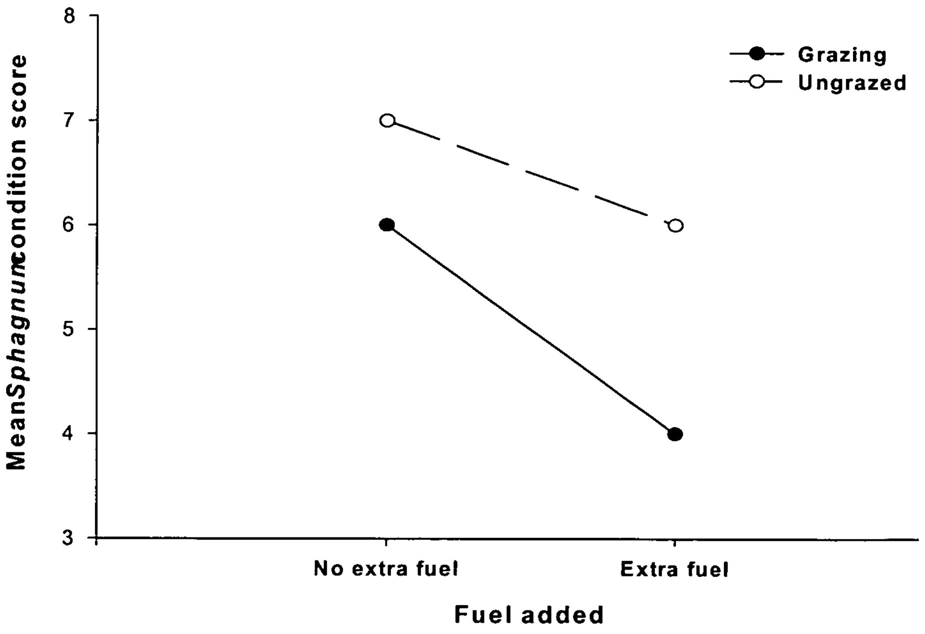

Figure 5.3. Interaction plot for the effects of fuel addition and grazing on the mean 1999 *Sphagnum* condition scores from Blar Garvie (burnt in 1997).

5.3.3 Sphagnum condition recovery

1996 burns

The 1996 burn sites were recorded over a period of three years after the fires. The data collected were not balanced as no data from the caged plots were collected in 1997 due to the density of the vascular plant regrowth, and no Loch Poll data were collected in 1999. The data for each year were therefore analysed separately. For 1996 data, a GLM using site and grazing as factors (and including the interaction) showed no significant results. A similar GLM using 1997 data had only site as a factor, and showed the Badagyle condition score to be significantly higher than the other three sites ($F_{3,16} = 6.56$, $P < 0.01$), as illustrated in Figure 5.4. However, analysis of the 1999 data, again using site and grazing as factors (and including the interaction) showed no significant differences between sites or between grazing treatments.

The data from all sites over the three recording dates are shown in Figure 5.4, which shows an increase in *Sphagnum* condition score from 1996 to 1997 on all sites. However, the rate of recovery differs markedly between sites, with Badagyle showing the greatest recovery over this period and Loch Poll the least. A drop in mean *Sphagnum* condition score between October 1997 and April 1999 on Badagyle and Loch a Chaoruinn, although not significant at either site, can be seen. Possible reasons for this will be discussed later. The remaining site recorded in 1999 (Mast) shows a continual recovery, but in none of the three sites recorded in 1999 does the mean condition score get to 8, the assumed pre-fire score.

1997 burns

Similar analysis was also carried out using the data from Blar Garvie and Creag na Braiste. The results showed highly significant increase in *Sphagnum* condition score for Blar Garvie ($F_{2,66} = 39.56$, $P < 0.001$) and for Creag na Braiste ($F_{1,45} = 13.64$, $P = 0.001$). The data from both sites on all recording dates are shown in Figure 5.5. Unlike the 1996 data (Figure 5.4), there is no downward trend in condition score on either site, although the total recording period for these sites is one year less than that for the 1996 sites.

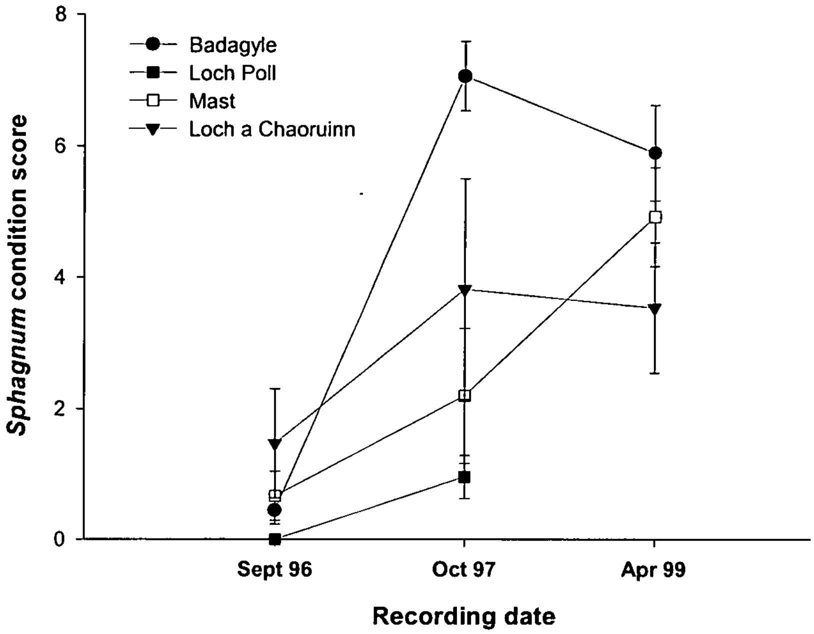

Figure 5.4.. *Sphagnum* condition scores (mean and standard errors) from 1996 burn sites, over the three years after burning. Sept 96 includes all site and all plots; Oct 97 is for caged plots only; Apr 99 does not include Loch Poll data.

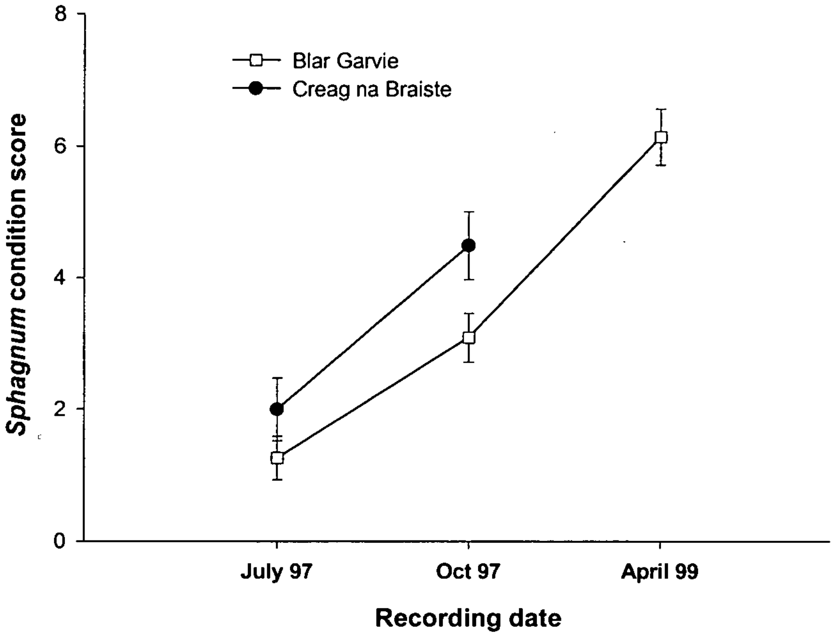

Figure 5.5. *Sphagnum* condition scores (mean and standard errors) from the 1997 burn sites.

1996 and 1997 sites together

The data from the 1996 and 1997 burns are displayed on the same graph in Figure 5.6, where the x-axis shows the number of months since the fire occurred. The variability between sites is very pronounced. There is a wide scatter in the condition of the *Sphagnum* in the first 6 months after the fire, but up to 18 months after fire all sites show recovery in *Sphagnum* condition to varying degrees. Subsequently two of the four sites with data available past 18 months, show continued condition recovery, whilst the other two show slight (but not significant) declines in *Sphagnum* condition.

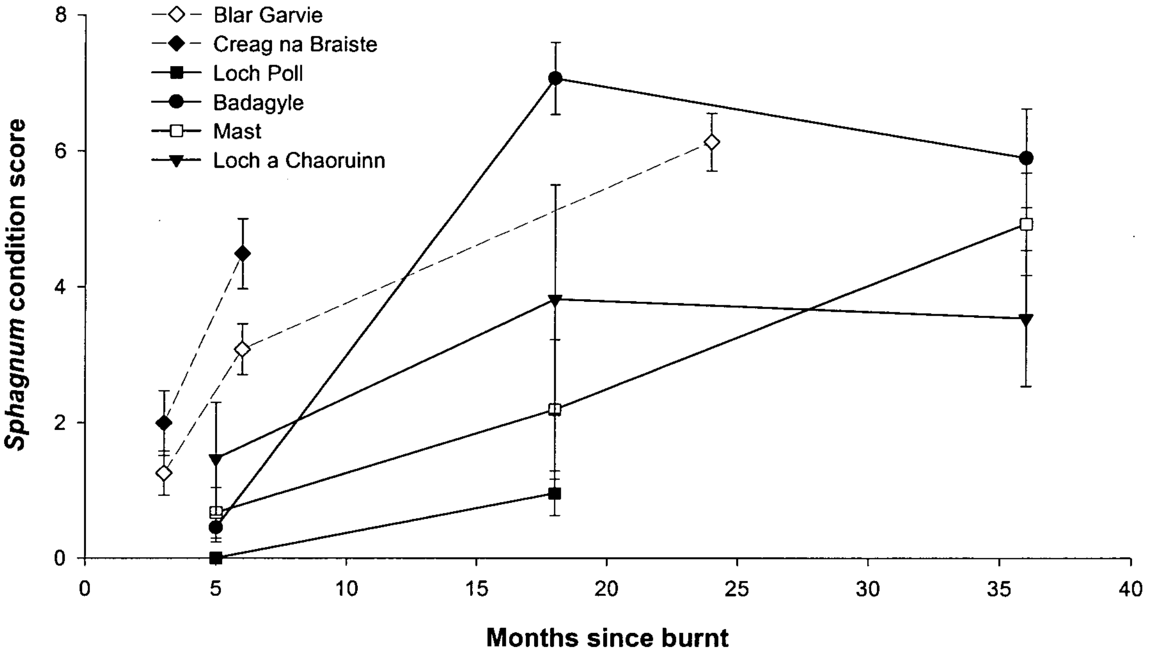

Figure 5.6. Changes in *Sphagnum* condition scores over time, for 1996 and 1997 burns. The x-axis shows the number of months since each fire occurred relative to each recording date, regardless of the actual date of burning. Means and standard errors shown.

For each of the burn years (1996 and 1997), data from all sites burnt in any one year were combined for each recording date, and plotted in Figure 5.7. In this figure, the x-axis shows actual dates, and a pre-burn initial condition score of 8 has been assumed. The resulting line for the 1996 burns shows continual recovery over the whole recording period, which is a consequence of the evening-out of between-site differences. The shape of the recovery curve for the 1997 burns is very similar, although the 1997 fires appear to have had less initial impact on *Sphagnum* condition (see also Figure 5.5), and have recovered more quickly and to higher condition scores. This indicates that the more severe the initial impact of the fire on the *Sphagnum*, the slower the rate of *Sphagnum* condition recovery over time, as would be expected.

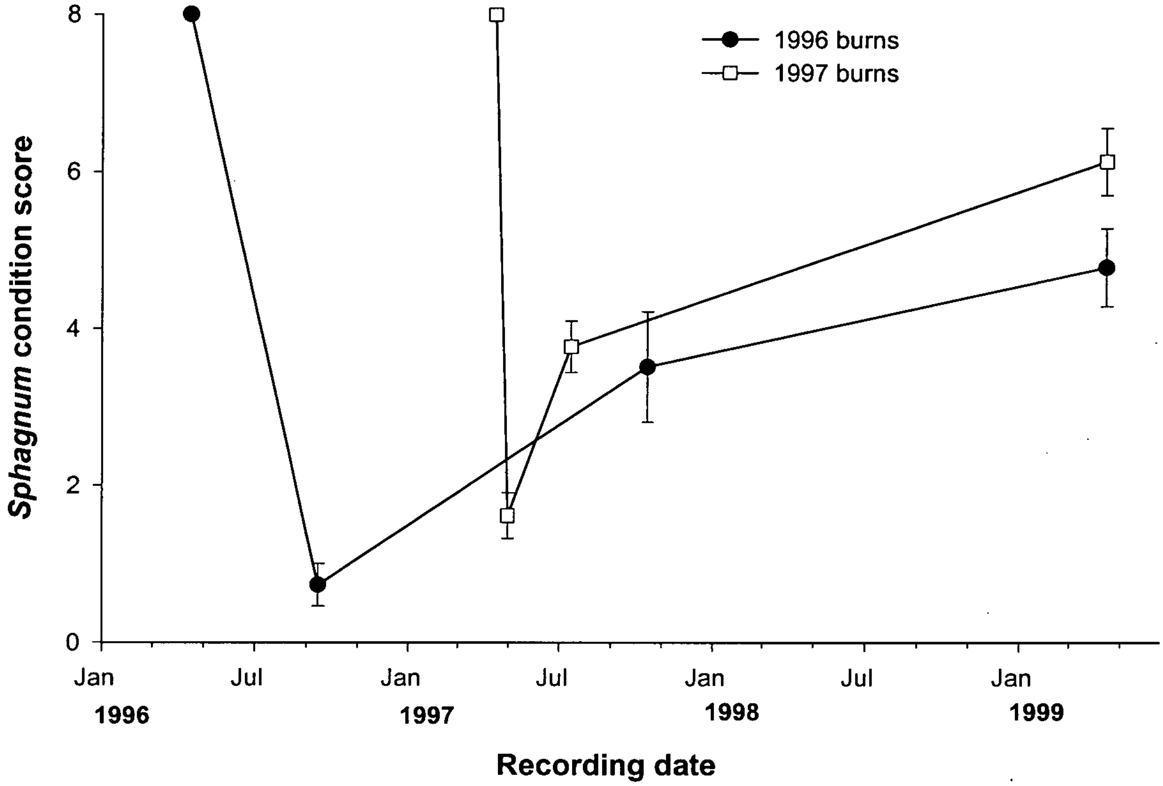

Figure 5.7. ***Sphagnum*** **condition recovery curves for pooled 1996 and 1997 burn data, mean and standard errors shown.**

5.4 Discussion

The results from all sites show the large variation in the effects of fire on *Sphagnum* condition between sites. This is illustrated by the two 1997 burns having significantly different condition scores, and the variability seen between the 1998 burn sites (Figure 5.2A). The better condition score on site B (1998 burns) may be because this site was observed to be slightly wetter than the others, and therefore had better growing or recovery conditions for *Sphagnum*. Perhaps the best illustration of differences between sites is Figure 5.4, which shows the recovery over time of the 1996 burns. This shows that not only can sites recover at different rates, but in some cases recovery can even reverse. Possible explanations for this reversal of recovery are the effects of grazing animals attracted onto the site and trampling the *Sphagnum* (although the effects of grazing was found to be non-significant, a larger study may reveal a significant effect), or a drought effect on some sites, or a physiologically delayed response to the effects of the fire (either direct effects of the fire on the *Sphagnum*, or a delayed effect though the fire changing the environment in some manner).

Figure 5.2B shows the highly significant effect of the amount of pre-fire *Calluna* on the post-fire condition score on the 1998 sites, and the effect of *Calluna* is emphasised by the significant (but weak) relationship between condition score and *Calluna* height (Table 5.3). The reason for this result may not simply be the increase in fuel available, since much of this 'extra' *Calluna* fuel is not actually consumed, as discussed in Chapter 4. One or a combination of the following factors may be responsible:

- increased fuel load;
- different fuel arrangement (including dried *Molinia* litter caught in the *Calluna*, and the shrub itself providing a 'path' for the fire into the moss layer;
- topography (*Calluna* on bogs is often associated with a hummock, resulting in drier fuel, drier *Sphagnum*, and therefore *Sphagnum* being more susceptible to fire damage and less able to recover if water is limiting in the summer).

It is unlikely that fuel load alone is responsible for the differences in condition scores observed in the 1998 sites, because no significant changes in *Sphagnum* conditions score resulted from adding extra fuel (although this may be due to the sample size, or incorrect fuel type and/or arrangement). The effects of *Calluna* on condition score is therefore likely to be due to a combination of the reasons listed above, with the arrangement of fuel and the slightly drier *Sphagnum* on the hummock all contributing.

The plots burnt in 1998, from which the fire characteristic and condition score data (Table 5.3) were taken, were designed primarily to quantify fire and fuel characteristics. Nonetheless, the weak (but highly significant) relationships between the condition scores and fire temperature characteristics suggest that these are important factors in determining the damage caused to the *Sphagnum* layer by fire. It is notable that if the average condition score is taken for site C plots 6 –10 (those first to be burnt, with less intense fires and flame length compared to other plots, see Chapter 4), then their average score (6) is greater than that for site B overall.

Further work is required to determine the effects of different temperature regimes on the different aspects of the *Sphagnum* layer, including the depth to which *Sphagnum* is killed, and methods of recovery. Observations of *Sphagnum* on the sites used in this study suggested two different ways in which bleached *Sphagnum* (the commonest category after a fire) recovered. The first was by a gradual 're-colouring' of the *Sphagnum*, implying recovery of the original plants. The second involved very small, new *Sphagnum* shoots appearing amongst the bleached *Sphagnum*, and gradually growing. These innovations arise from the outer cortex of the buried *Sphagnum* stems. Clymo & Duckett (1986) found that such innovations could be produced from *Sphagnum* stems buried up to 30 cm deep. However, this was done by slicing and exposing *Sphagnum* cores, and it is not known from what depth innovations can grow upwards to penetrate an *in situ* layer of dead *Sphagnum*.

The relationships between *Sphagnum* condition scores and the fire intensity measures (I_B and H_A) reinforce the results from the previous chapter. I_B does not appear to be a good fire characteristic to measure if information about the impact of fire on the *Sphagnum* layer is required. A more relevant measure appears to be H_A, however this will suffer from the 'averaging out' effect discussed in Chapter 4, in that plot scale measurements may not reflect the small-scale heterogeneity in the observed *Sphagnum* response. In future work of this kind, the scale of the processes and phenomena under study will have to be reconciled with the scale of the measurement of the vegetation and fuel characteristics.

The effects of grazing were found to be non-significant on both the 1996 and 1997 burn sites, but the interaction plots from the 1997 burns showed that grazed plots had consistently (but not significantly) lower condition scores than the ungrazed plots. The major effect of the presence of grazing animals, from observations made on all sites, appears to be the poaching caused by the animals hooves. It was noted in a few plots that *Sphagnum* compressed by a hoof-print often did not recover, but entered the decaying condition. In other situations, *Sphagnum* plants were apparently kicked out of the ground. These effects, although apparent over the whole area of all burn sites, were especially noticeable in accessible or favoured parts of the sites. Although all the reasons for some areas being favoured are unknown, sheep and deer appeared to be attracted to the burn sites. Size of burn is therefore of importance, as smaller burns may concentrate grazing animals more, resulting in more severe poaching. The poaching effects of grazing animals may have contributed to the decline in condition seen on two 1996 burn sites, between 18 and 36 months after the fires (Figure 5.4).

There is little information to indicate the time taken for *Sphagnum* to recover after a fire. Barkman (1992) noted that *S. molle* and *S. compactum* recovered completely 1 year after a fire on a Dutch bog, but that *S. papillosum* and *S. tenellum* were 'still absent'. This indicates different recovery rates for different species, although individual species recovery rates can be confounded by the suitability of the post-fire environment for *Sphagnum* recovery, and differences between actual fire events. The implied total loss of *S. papillosum* suggests that Barkman may be discussing a more severe fire than this study. The time taken for overall recovery has not been established by this study, as a longer observation period is required (all site and plots used in this study are being maintained indefinitely, with co-operation of all land-owners and crofters involved).

Figures 5.5 and 5.6 indicate the observed recovery rates, however the condition score starting point is required to establish the 'target' score for a recovering site. No observations of the 1996 burns were made till after the fires. Although condition scores were recorded before burning for all plots on the 1997 and 1998 burn sites, the vegetation and time constraints made detailed recording (as was done after burning) impossible. It is likely that the pre-fire condition scores are below the assigned score of 8 to some extent, with several possible reasons for this. Poaching will occur on all areas and, although *Sphagnum* undamaged by fire is likely to recover better than damaged *Sphagnum*, some damage due to poaching is inevitable. It has also been observed that in summer, particularly after dry weather, some *Sphagnum* appears to be bleached, although such patches appear to recover later in the year. Although most of the *Sphagnum* recording in this study was done in the spring, autumn or winter to avoid this effect, it may contribute to a slight over-estimate of the pre-fire *Sphagnum* condition scores. Finally, the *Sphagnum* layer may still be recovering from a previous fire event.

5.4.1 Can fire encourage *Sphagnum*?

The discussion in this chapter has focused on the negative effects of fire on *Sphagnum*, however observations of the study sites suggested that fire may aid *Sphagnum* growth in some situations. In addition, observations made by A. MacDonald on Creag a' Mhadaidh suggest that *S. fuscum* was more abundant on burnt than unburnt areas, which is counter to the common opinion that burning reduces the amount of *S. fuscum*.

When the high fuel study sites that were burnt in 1998 were first surveyed, it was noted that the *Sphagnum* layer, although extensive, was almost completely covered by *Molinia* litter from previous years. This litter layer was not only extensive, but in places was up to 15 cm deep. Clymo & Hayward (1982) note that *Sphagnum* growth is reduced if the amount of photosynthetically active radiation reaching the plants is reduced by 50 %. The amount of light cut out by a layer of litter is unknown, but the removal of this litter layer by burning may have a 'rejuvenating' effect on the growth of the *Sphagnum*. This theory has also been suggested by Chapman & Rose (1991) who suggest that a lack of management on Northumberland mires has led to a decline in *Sphagnum*.

Another means by which fire may aid *Sphagnum* growth was suggested by the observations of caged plots, in areas where a strip of netting was pegged horizontally across the moss. It was noted that the moss in these situations grew very quickly and luxuriantly (up to 5 cm vertical growth a year), with the netting apparently providing a 'climbing frame' for the *Sphagnum*. An additional observation was that the recovery of *Calluna* after fire (on a bog) is apparently vegetative, with many small plants originating from the stems of *Calluna* buried (and protected) by the *Sphagnum*. A fire therefore results in the removal of one or a few large *Calluna* stems, to be replaced by many small *Calluna* plants. Although self-thinning will eventually result in one or a few *Calluna* plants dominating in that area again, for several years at least there will be a high density of stems protruding from the *Sphagnum*. These stems may again provide a 'climbing frame' for *Sphagnum* growth, and this idea has also been proposed by Malmer *et al.* (1994), who refer to the vascular plants providing a 'matrix' to reinforce the *Sphagnum*.

5.4.2 Fire regime and *Sphagnum* recovery

All of the above results are based on single fire events, with no consideration given to the effects of previous fire events, or in other words, no consideration of the fire regime. This is common in many fire studies, with the difficulties in considering events and processes over the time of several fires very impractical for short-term studies. The crucial question in the context of fire in blanket bog is whether the *Sphagnum* component of the bog recovers before the next fire event. As noted in Chapter 1, there are difficulties in even determining the fire regime of the extensive grazing areas in north-west Scotland, far less determining the effects of the fire regime on the vegetation. In one of the few available studies on fire frequency and *Sphagnum*, Kuhry (1994) found an average fire interval of 1 150 years for peat fires over last 2 500 years in Labrador, Canada. Although the types of fire being discussed appear to be ones that enter the peat itself, the vegetation recovers over a few decades after the fire, and it is concluded that '*Sphagnum*-dominated boreal peatlands are clearly well adapted to fire disturbance.' Although indicating that such habitats can recover from fire over decades, this does not imply an ability to recover from less severe, but perhaps more frequent, management fires.

5.4.3 Conclusions

The results presented in this chapter, in agreement with the previous two chapters, suggest that fires cannot be perceived as uniform events, as differences between different fire events are evident. Also, the effects of an individual fire on the *Sphagnum* layer vary spatially and over time. The initial selection of study plots based on an assumption of increased damage to the *Sphagnum* layer beside *Calluna* is justified, with increased damage evident with increasing amounts of *Calluna*. The perception that fire always has an extremely bad effect on the *Sphagnum* layer on a bog is not supported in this study, as the results indicate that a sizable proportion of the *Sphagnum* recovers in the first two years after a fire, perhaps best illustrated by the images in Figure 5.1. However, the effects of the overall fire regime, and therefore the effects of successive fires on *Sphagnum* cover, growth and species composition remain unknown.

Chapter 6 *CALLUNA* AND *MOLINIA* REGROWTH

6.1 Introduction

The reason for burning in north-west Scotland is to improve the grazing for sheep, and to a lesser extent, deer. This may come about through increased amount of forage, improved quality of forage, easier access to forage, or even by growth starting earlier on burnt sites, as suggested by Daubenmire 1968 (cited Currall, 1981).

Previous studies have indicated that herbivores are attracted to recently burnt vegetation. For example Miles (1971) studied the reaction of red deer on the island of Rum to burning, and found that one month after burning grazing intensity was six to eighteen times that on unburnt areas, although by the following year the intensity had dropped to only double. Similarly, Lance (1983) observed that sheep preferred burnt areas to unburnt, and that the sheep performed better (in terms of lamb birth weight) on burnt areas. Grant *et al.* (1987) showed that plant species selection varied between sheep and cattle and also with season, however selection the selection of vegetation patches from within a site is also important (Hester & Baillie, 1998). This may be especially relevant on burn sites in the north-west as the fire effects are very heterogeneous. Lance (1983) also showed that *Calluna* regenerating on burnt blanket-bog had higher nutrient content than unburnt *Calluna*, which contributes to explaining the improvement in sheep performance on the burnt areas.

The aim of this chapter is to address the following broad questions regarding the recovery of vascular species on blanket bog after fire:

1. Is there more forage available on burnt sites versus unburnt, and what are the growth increments after fire?
2. Are herbivores attracted to burnt areas?
3. How does post-fire vegetation recovery vary from site to site?

The above questions will be addressed using regrowth and biomass data for *Calluna* and *Molinia*. These species were selected for study because they are important for grazing, contribute to the distinctive vegetation structure, and are important fuel types (Chapter 3).

6.2 Methods

6.2.1 Biomass harvesting

Three sites were selected for harvesting in October 1997. These were Loch Poll (burnt in the spring 1996), Creag na Braiste and Blar Garvie (both burnt in the spring of 1997). There was therefore one site 18 months after burning, and two sites 6 months after burning. These sites are described in Chapter 2.

At each site, areas where the boundary of the burn passed through blanket-bog vegetation were identified. In all cases, the boundary area selected was of apparently uniform vegetation, with no obvious community and/or topographic differences between the areas 2 to 5 m either side of the boundary. Plots to be harvested were identified, using random numbers to determine:

1. distance along the boundary;
2. distance either side of that boundary, between 2 and 5 m from the boundary.

Five such paired sets of plot locations were randomly loctated on each burn site, and at each location a 25 cm x 25 cm quadrat was marked out covering an area incorporating a shrub/*Sphagnum* interface as described in Chapter 2. All of the above ground (or above moss) vascular plant material was removed from within each quadrat by clipping. All material was sorted into the different species present, and all *Calluna* plants were separated into potential forage material (material less than 2 years old, referred to as young *Calluna*) and older (woody) material. The length of each individual *Molinia* leaf, and whether it was grazed or ungrazed, was also recorded.

All biomass was then dried at 80 °C for two days (Mackey *et al.*, 1993) and the dry weight recorded, with each *Molinia* leaf being dried individually.

The numbers of grazed and ungrazed *Molinia* leaves per plot was recorded, and from them the ratio of the number of grazed to ungrazed (referred to as the G:UG ratio) calculated. This was expressed as a fraction, so a value greater than 1 indicates more grazed *Molinia* leaves than ungrazed, and a value less than less 1 indicates fewer grazed than ungrazed leaves. Where necessary, data were transformed using $\log_{10}(x + 1)$ to meet analysis requirements, and the results back-transformed.

6.2.2 Growth rates

The ten plots on each of the four 1996 burn sites (Chapter 2) were used to determine growth increment of certain vascular species. Within each 25 cm x 25 cm plot, up to five individuals of *Calluna* and *Molinia* were selected and tagged for monitoring. Individual plants to be tagged were randomly selected during June 1996, although often there were fewer than five individuals of each species actually available in each plot. Each plant was tagged using electrical cable markers (RS Components) on a small piece of plastic coated wire, which was then twisted around the stem at ground/moss level. On each visit to the sites, attributes that were considered representative of growth were measured for each individual (Table 6.1).

Table 6.1. Measurements made on *Calluna* and *Molinia*. All length measurements were made in mm.

Plant species	Attributes recorded
Calluna	• length of plant (from tag/ground level); • whether grazed or ungrazed; • if main stem has been grazed, the length of longest ungrazed branch as well.
Molinia	• total number of leaves; • length of each leaf; • for each leaf, whether grazed or ungrazed.

It was originally intended to visit each site monthly or bi-monthly, but the time taken to re-locate and carry out measurements on all plants made this impossible. The dates that recording actually occurred in each site are shown in Table 6.2.

Table 6.2. Monitoring dates for the four 1996 burn sites. Plants were tagged before the first recording date, and more plants tagged prior to the first recording date in 1997 on each site.

	Recording dates							
	1996			1997				
Badagyle	9-7	20-8	17-9		28-5		5-9	15-10
Loch Poll	9-7		13-9	28-4		26-6	7-9	17-10
Loch a' Chaoruinn	8-7	19-8	15-9		26-5	24-6		13-10
Mast	8-7	19-8	16-9	24-4		25-6		11-10

The actual number of plants recorded dropped between successive recording dates, because of losses due to plants dying, being ripped up by grazing animals, or just going missing. The latter was the commonest reason for individual plants not to be recorded, and the main reason is thought to be the vertical growth of *Sphagnum* moss obscuring the plant tags. Additional plants were therefore randomly selected, tagged and recorded during 1997.

Molinia – data manipulation

For the growth increment data, the lengths of individual leaves were summed for each plot on each recording date, and divided by the number of leaves to obtain a mean leaf length. This was done for grazed and ungrazed leaves separately. This resulted in one measure of mean ungrazed leaf length for each plot, and one measure of mean grazed length for each grazed plot.

6.3 Results - Calluna

6.3.1 Plant length

For each recording date, analysis was carried out to determine whether there were any consistent site – site differences. It was found that for every recording date upon which data was collected from the Badagyle site, the length of ungrazed *Calluna* was significantly greater than on the other recorded sites (*P* values ranging from <0.001 to 0.013). The data from all sites was then pooled to establish trends in *Calluna* length with time since burning (which occurred in April 1996). The data for all sites, for grazed and ungrazed plants, are shown in Figure 6.1. ANOVA carried out on these data showed that the only date upon which the ungrazed plant length was not significantly greater than the grazed length was in May 1997 – however these results must be treated with caution as the sample sizes vary greatly between sites, dates, and treatments. Figure 6.1 also indicates that, at least for the first 18 months after a fire, the *Calluna* is grazed to a relatively consistent height (typically between 2 cm and 5 cm). This consistency is presumably because the whole plant is still young and palatible/nutritious. As the plant ages and the lower stem thickens and becomes more woody, the lower parts will be less desirable to the grazing animals.

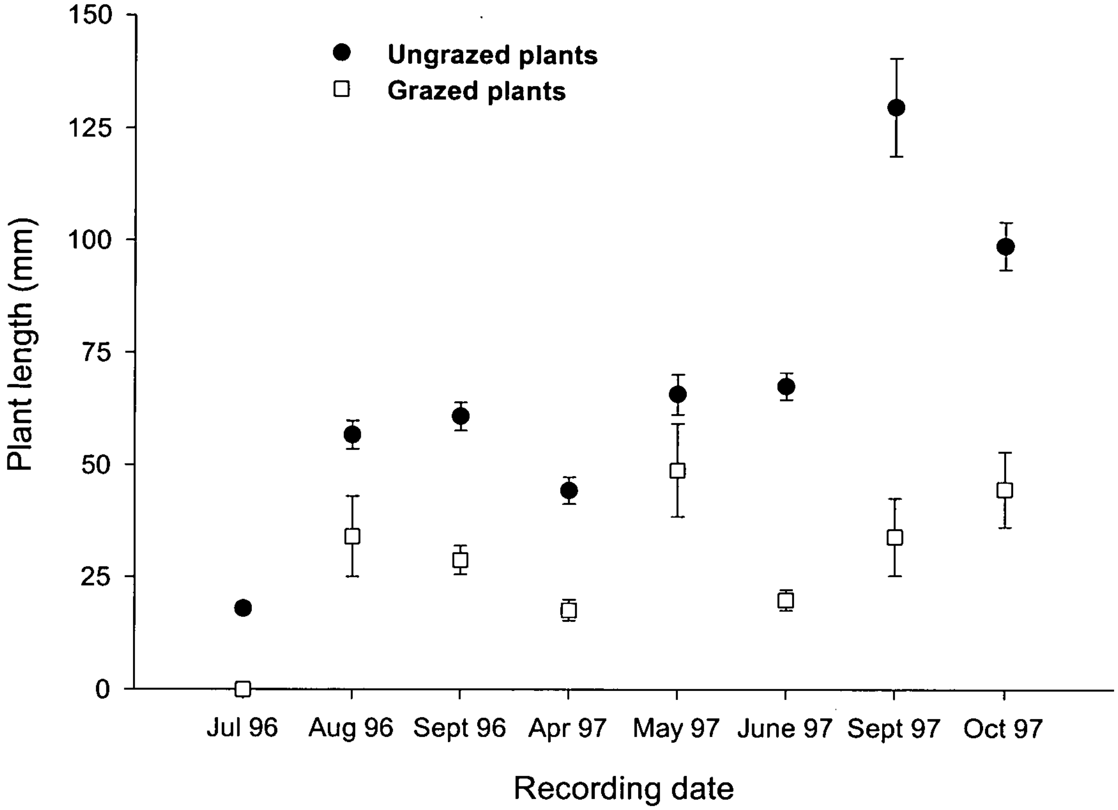

Figure 6.1. ***Calluna*** **length (mean and standard error) for all sites on all recording dates, divided into grazed and ungrazed plants.**

The data from ungrazed plants only are shown in Figure 6.2, which shows mean and standard error of length of ungrazed *Calluna* plants for each recording date (note that not all sites are represented at all dates, refer to Table 6.2). The difference in plant length between August and September 1996 was less than the difference between July and August, and this is expected as growth slows into the autumn. However the drop in plant length from the end of 1996 to April 1997 was observed in many individual plants, where a slight reduction in height was only noticed when comparing the data. The large jump in plant size between July and August in 1996 is also reflected in the data from 1997, where the equivalent period is covered in the June to September 1997 data points. There is again a drop in length, this time between September and October in 1997.

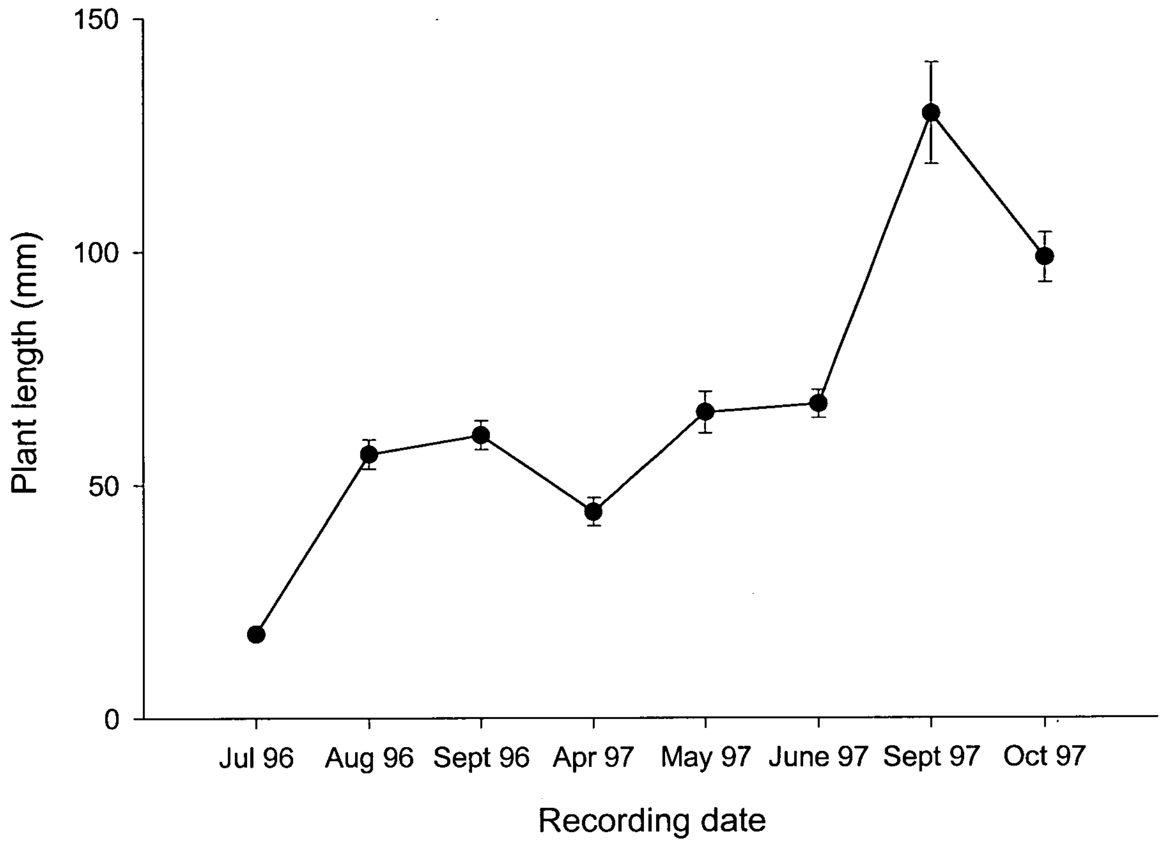

Figure 6.2. Plant length (mean and standard errors) of ungrazed *Calluna* plants. Data from all sites pooled.

6.3.2 Biomass

The biomass of young *Calluna* from the burnt and unburnt areas of each site was analysed, after transformation, using a GLM with site and burn treatment as factors, and including the interaction term. The results (Figure 6.3) show that both site ($F_{2,24} = 6.14$, $P < 0.01$) and burn treatment ($F_{1,24} = 57.81$, $P < 0.001$) were significant, with the interaction non-significant. The significant difference in young *Calluna* available between the burnt and unburnt areas is to be expected, with more *Calluna* on the unburnt areas. The significant site result is due to Creag na Braiste having lower values than the other two sites, under both burn treatments. The site result thus does not differentiate between the 1996 burn site (Loch Poll) and the two 1997 burn sites. However, although the Loch Poll unburnt area mean lies between the means of the two 1997 sites, the Loch Poll burnt area mean biomass is greater than the two 1997 sites (though not significantly so).

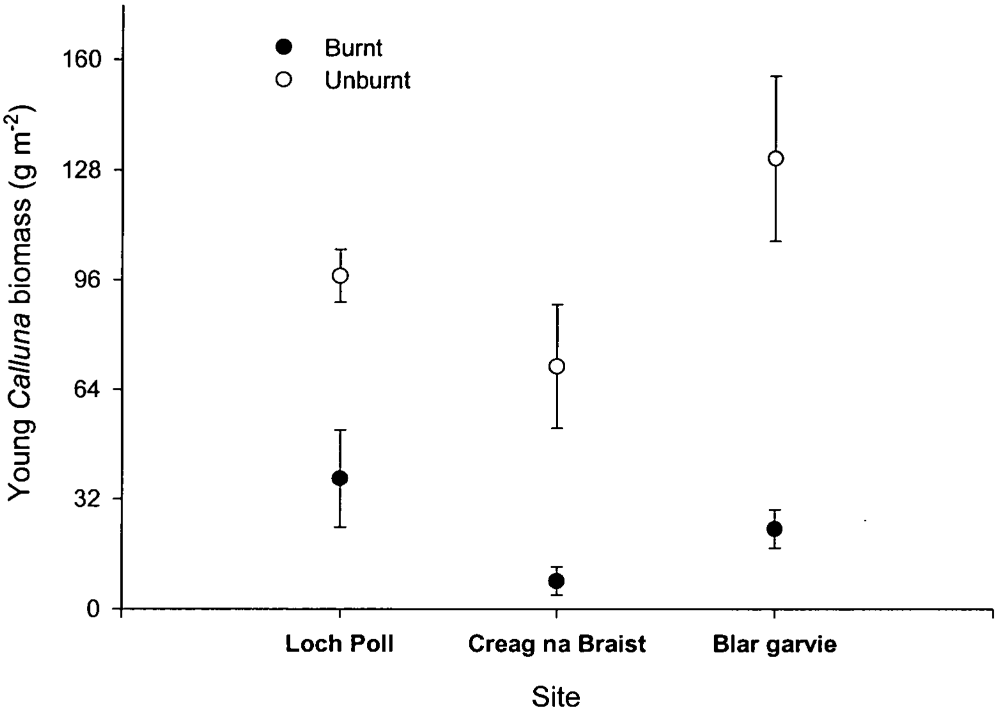

Figure 6.3. The biomass of young *Calluna* on the burnt and unburnt areas, over the three sites. Loch Poll data is 18 months post-fire, the other two sites 6 months post-fire.

6.4 Results - Molinia

6.4.1 Leaf length

The mean lengths of ungrazed *Molinia* leaves from both grazed and ungrazed plots were analysed for each recording date using site and grazing treatment as factors, and including the interaction term. The results (Table 6.3) show that there was only a significant difference between sites on the first two recording dates, when Badagyle mean ungrazed leaf length was significantly greater than from the Mast site. At all other dates where Badagyle was recorded, although it had a greater mean ungrazed leaf length than all other sites, the difference was not significant. There were four recording dates with significant grazing factor results, in each case with ungrazed plots having a greater mean ungrazed leaf length than the grazed plots. This trend is seen at all other recording dates (Figure 6.4), where the grazed plot mean is greater than the ungrazed plot mean (but not significantly so).

Table 6.3. Summary of GLM results from analysis of ungrazed leaf lengths. The grazing factor refers to grazed and ungrazed plots, the sites recorded on each recording date are denoted: B = Badagyle, M = Mast, LC = Loch a' Chaoruinn, LP = Loch Poll. Significant results are highlighted.

		Factor		
Date	**Sites**	**Site**	**Grazing**	**Interaction**
July 1996	B, M, LC, LP	**$F_{3,31} = 3.51$** **$P < 0.05$**	$F_{1,31} = 2.85$ $P = 0.102$	$F_{3,31} = 1.6$ $P = 0.209$
Aug 1996	B, M, LC	**$F_{2,22} = 3.67$** **$P < 0.05$**	**$F_{1,22} = 4.37$** **$P < 0.05$**	**$F_{2,22} = 4.14$** **$P < 0.05$**
Sept 1996	B, M, LC, LP	$F_{3,28} = 1.39$ $P = 0.266$	$F_{1,28} = 2.97$ $P = 0.096$	$F_{3,28} = 1.82$ $P = 0.166$
Apr 1997	M, LP	$F_{1,14} = 3.5$ $P = 0.082$	$F_{1,14} = 3.11$ $P = 0.099$	$F_{1,14} = 1.83$ $P = 0.197$
May 1997	B, LC	$F_{1,15} = 2.98$ $P = 0.105$	$F_{1,15} = 3.13$ $P = 0.097$	$F_{1,15} = 0.63$ $P = 0.438$
June 1997	M, LC, LP	$F_{2,23} = 0.62$ $P = 0.546$	**$F_{1,23} = 8.03$** **$P < 0.01$**	$F_{2,23} = 1.82$ $P = 0.184$
Sept 1996	B, M, LP	$F_{2,18} = 1.94$ $P = 0.172$	**$F_{1,18} = 13.59$** **$P < 0.01$**	$F_{2,18} = 0.46$ $P = 0.638$
Oct 1996	B, LC, LP	$F_{2,21} = 2.06$ $P = 0.152$	**$F_{1,21} = 15.90$** **$P = 0.001$**	**$F_{2,21} = 4.57$** **$P < 0.05$**

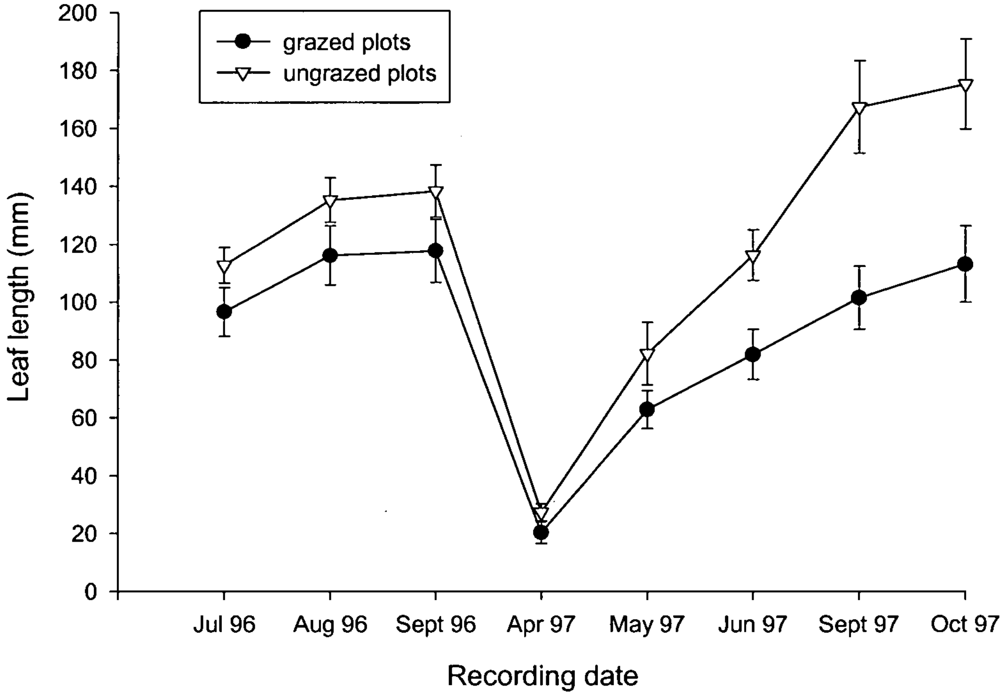

Figure 6.4. Mean and standard error of ungrazed leaf length, on grazed and ungrazed plots, for all recording dates, and using data pooled from all sites. See Table 6.3 for statistical analysis results.

6.4.2 Biomass

Number of leaves

The harvested data were analysed to determine any differences in the number of *Molinia* leaves between sites or between treatments. This was not possible using the previous (growth) data, as only randomly selected plants in each plot were measured. A GLM using site and treatment as factors showed that both burnt and unburnt areas on Creag na Braiste had significantly greater numbers of leaves than the other two sites ($F_{2,24} = 6.12$, $P < 0.01$). In addition, the burnt areas had a significantly greater number of *Molinia* leaves than the unburnt areas ($F_{2,24} = 5.34$, $P < 0.05$). The interaction was not significant. The data are shown in Figure 6.5.

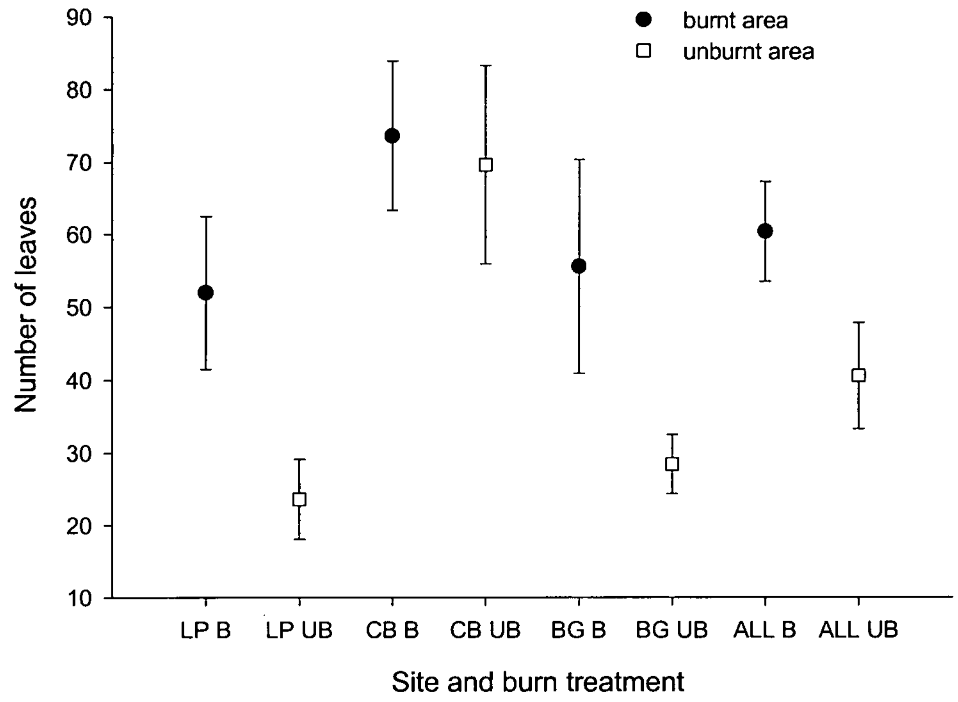

Figure 6.5. Total numbers of *Molinia* leaves on the burnt (B) and unburnt (UB) areas of the three sites, and for all sites pooled. LP = Loch Poll; BG = Blar Garvie; CB = Creag na Braiste; All = all sites pooled.

Leaf length

The *Molinia* leaf length data from each site was analysed separately, using burn treatment and grazing status of each leaf (grazed or ungrazed) as factors, and including the interaction. The results from all sites showed that grazed leaves are significantly shorter than ungrazed leaves, which is to be expected. The results also showed that unburnt area leaves were significantly longer on two sites (Loch Poll and Creag na Braiste) than on the burnt areas. These results are illustrated in Figure 6.6, where the first three graphs show the interaction plots from the analysis. On each of these interaction plots, the grazed leaf length can be seen to be shorter than the ungrazed length. In addition, the longer leaves on the unburnt areas on Loch Poll and Creag na Braiste are clearly seen. This trend is also seen for ungrazed leaves on Blar Garvie, but the opposite trend is seen for grazed leaves (although the difference is not significant).

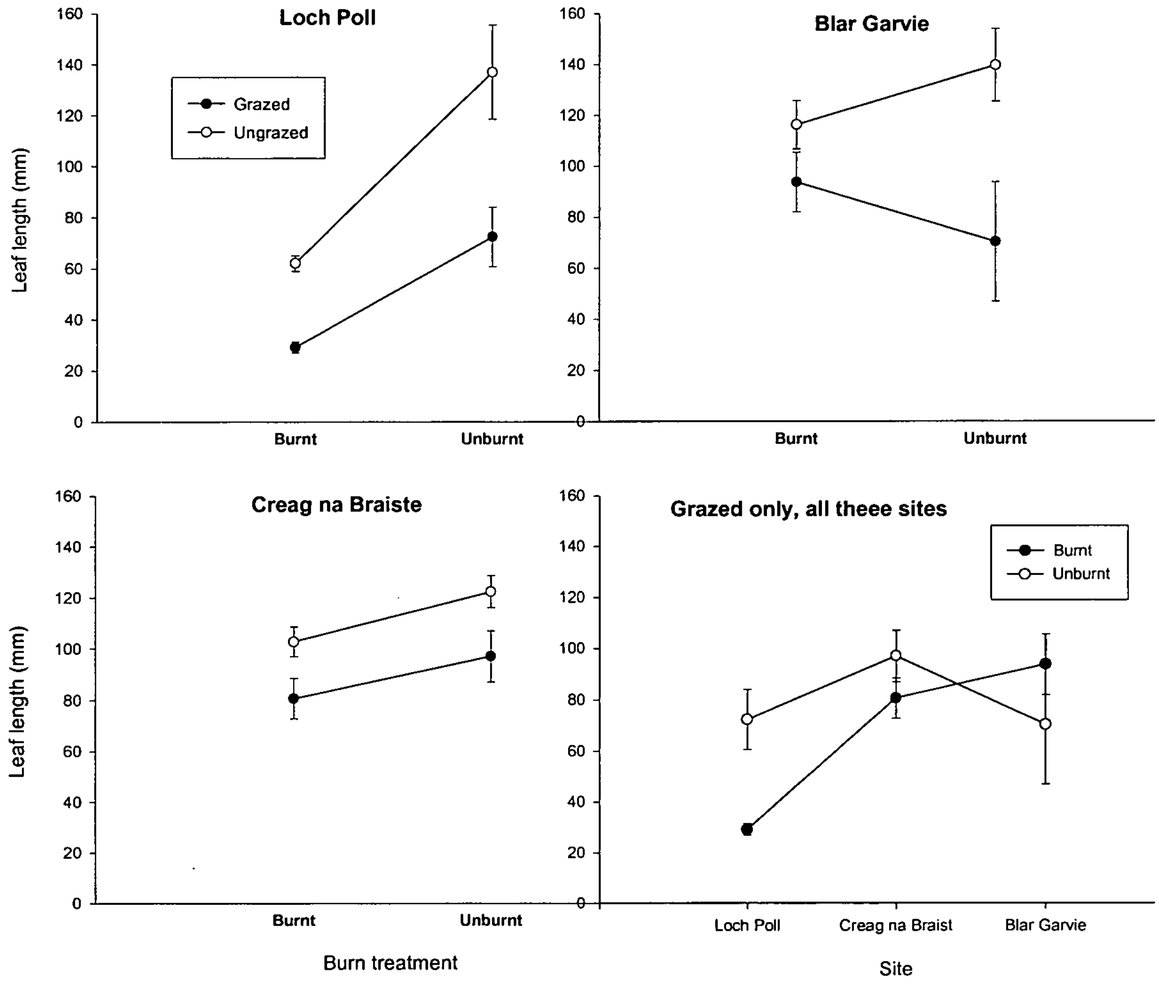

Figure 6.6. Leaf length (mean and standard error) shown on interaction plots (grazing and burning treatments), for the three study sites. The fourth graph shows the results for grazed leaves only from all three sites, and the effects of burning.

The lengths of grazed leaves only for all sites and both burn treatments are shown on the fourth graph in Figure 6.6. The very short length that the burnt area Loch Poll leaves were grazed to is very noticeable, with Creag na Braiste showing the same trend (shorter grazing on the burnt area), but Blar Garvie showing the opposite, with leaves grazed shorter on the unburnt area.

Grazed:ungrazed ratio

The ratio of grazed to ungrazed leaves for every plot was then calculated, and the data transformed using $\log_{10}(x+1)$. Using a GLM with site and burn treatment as factors, both site ($F_{2,24} = 43.24$, $P < 0.001$), burn treatment ($F_{1,24} = 34.23$, $P < 0.001$) and the interaction were highly significant ($F_{2,24} = 20.03$, $P < 0.001$). The data (untransformed) are shown in Figure 6.7. The grazed:ungrazed ratio was greater on Loch Poll. This figure also shows that although the grazed:ungrazed ratio was higher on all burnt areas compared to unburnt (indicating more of the available *Molinia* is grazed on the burnt areas), but only the differences between the burnt and unburnt areas on Loch Poll and Creag na Braiste are significant.

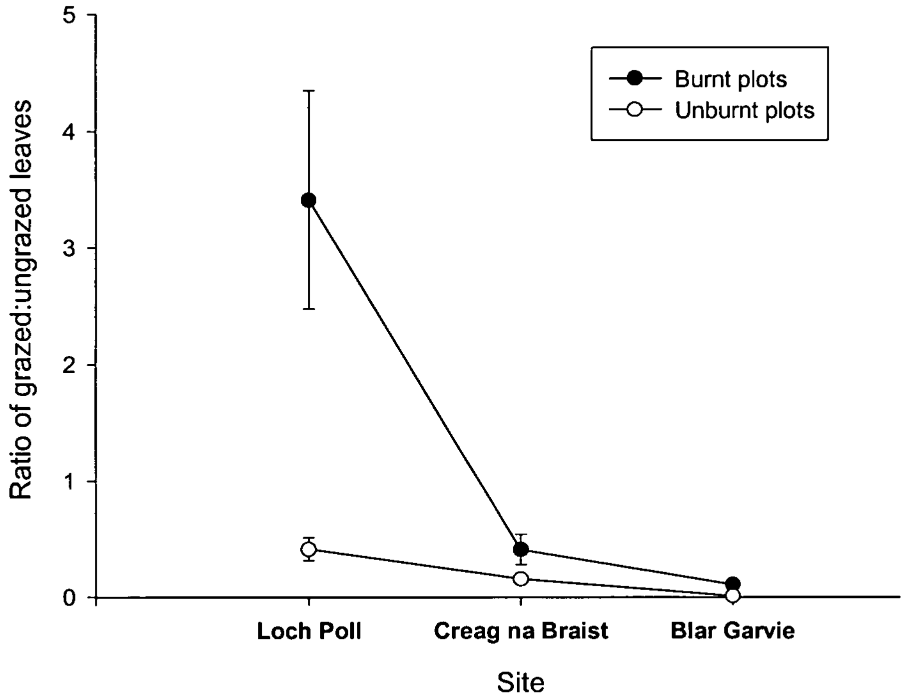

Figure 6.7. Ratio of grazed to ungrazed *Molinia* leaves from the burnt and unburnt plots (mean and standard errors shown).

6.5 Discussion

6.5.1 Molinia

Molinia is thought to be favoured by burning, for several reasons:

- during the burning period, *Molinia* reserves are stored below the surface of the peat or moss, and are protected from the fire;
- removal of the litter layer allows the photosynthetically active basal internodes to photosynthesise before the leaves are produced;
- as nutrients (NPK) are increased, *Molinia* is better able to out-compete *Calluna* and *E. tetralix*, although the reverse is true at low nutrient levels (Aerts *et al.*, 1990). The flush of nutrients after a fire resulting from ash deposition may enable *Molinia* to increase in competitiveness for some time afterwards, although this point is debatable (Currall, 1981)

There are several possible reasons for the relatively consistent trend found in this study, of the ungrazed leaves being longer in ungrazed plots than grazed plots:

1. there is a better environment in the cages, with the netting providing a favourable micro-climate;
2. similarly, protection is obtained from the surrounding undisturbed vegetation;
3. although ungrazed leaves are measured in the grazed plots, they may be on plants that were previously grazed, and therefore have been growing for less time, or have less reserves available for growth.

Although no quantitative micro-climate data are available regarding the first explanation, all cages were observed at all seasons for a build-up in snow or litter caused by the netting. This was not observed, and it is concluded that the netting had a minimal effect of the cage interior micro-climate. Likewise, the data provide no evidence either way for the third explanation. However, if the second explanation applied, the effect would be expected to increase with time since burning as the vegetation increases in height and density. This is indeed observed, with the three greatest effects being seen at the end of the recording period.

Differences between the sites in the *Molinia* biomass results are to some extent explained by observations made on each site on various visits. The Blar Garvie was the site furthest from any road, and therefore far from where winter feeding occurred. Although the sheep wandered over extensive areas in the summer (when not being fed), they still tended to concentrate along the roads. This means that the grazing pressure may have been less on the Blar Garvie site compared to others, and sheep were not often observed on this site. In contrast, heavy grazing was apparent at all times on the Loch Poll site. This site was close to the access point into a large area, and sheep were often observed on the site, as well as signs of heavy grazing being obvious. As a result, the difference the ratio of G:UG plants is high on the Loch Poll burnt area, but much lower on Blar Garvie. The difference between the burnt and unburnt areas may also be a result of the differences in grazing pressure, with a large difference on Loch Poll, but a very small difference on Blar Garvie. The higher grazing pressure on Loch Poll shows as heavier selection of the burnt area, but the fewer numbers on Blar Garvie may result in less selection of the burnt area. Only on the Loch Poll burnt area was the mean G:UG ratio positive, the result of more grazed than ungrazed leaves. On the unburnt area, and on both areas and both of the other sites, the mean G:UG ratio is negative.

6.5.2 Calluna

The reduction in *Calluna* length between 1996 and 1997 may be due to the growth of the *Sphagnum* over the autumn/winter/spring months. Although measurements were made from the tag, it was necessary to leave the tag loose on plants this small, and the tag may therefore have been moved upwards. The large September mean and variance are probably due in part to the small sample size that month (only 18 plants recorded). Amalgamating the September and October data gives a set of data point for 1997 very similar in distribution to the 1996 data points, although showing increased overall plant length.

The site results also indicate that the amount of *Calluna* available after a fire is closely related to the amount available before burning, with the amount of *Calluna* on a burnt site closely paralleling the amount on the adjacent unburnt areas.

The significant site difference is due to Creag na Braiste having an overall greater biomass of young *Calluna*. However, looking at the burnt data only (Figure 6.3), the amount of young *Calluna* is greatest on Loch Poll (though not significantly so), which will be due to the extra year of growth. The non-significance of this result backs up observations of heavy grazing on the Loch Poll burnt areas.

6.5.3 Community recovery

The results presented here show that site to site variation can have a large effect on the availability of forage after a fire. Both *Calluna* and *Molinia* grow significantly better on Badagyle compared to the other three 1996 burn sites. This may be because Badagyle was noted to have uniform shallow peat, just over 0.5 m, and the environment may therefore be better for plant growth. The pre-fire vegetation on blanket bog is therefore likely to be an important determinant on the development of the vegetation post fire, and as the 1996 burn sites were selected after burning, there may have been a noticeable difference on the Badagyle site compared to the others. From the biomass data, Creag na Braiste stands out in having significantly less young *Calluna* biomass, but a significantly greater density of *Molinia* leaves. These differences apply to both the burnt and unburnt areas, showing that pre-fire vegetation does indeed affect the post-fire vegetation, which is expected given that the plants are recovering vegetatively after the fires.

On the burnt areas, it was found that:

- there is less young *Calluna* (but it may be either more accessible, and/or more nutritious);
- there is a greater density of *Molinia* leaves;
- more *Molinia* leaves are grazed (on two sites out of three);
- *Molinia* leaves are grazed shorter (on two sites out of three);

Previous studies have shown that post-fire *Calluna* has a greater concentration of nutrients (Lance, 1983), and that it is preferentially selected by sheep. The *Molinia* results indicate that fire may encourage *Molinia*, which has been proposed as a reason for its spread in the uplands. Aerts *et al.* (1990) found that although *Calluna* and *E. tetralix* could out-compete *Molinia* at low nutrient (NPK) levels, as nutrients are added the ability of *Molinia* to out-compete the other two species increases. The results from this study are consistent with *Molinia* reacting to the flush of nutrients following a fire. Whether this is by extra individuals, or through increased leaf production from existing plants is unknown. Given that the system would be expected to return to a nutrient-poor status in the years following a fire, it may be expected that increased leaf production would be the favoured option, but the spread of *Molinia* would suggest otherwise.

6.5.4 Conclusions

Although burning and grazing together have the potential to be a powerful management tool on blanket bog, the observation noted by Lance (1983) still applies, that '...there remains a need to determine the combinations of stocking density and burning regime at which heather can maintain its dominance and productivity'. To that can be added the requirement that the seasonality of grazing (either stock removal or shepherding) needs to be introduced as another factor requiring study.

The results from this chapter show that *Molinia* and *Calluna* recover very quickly following a fire. Although the available young *Calluna* decreases compared to unburnt areas, the *Molinia* regrowth, accessibility of the forage, and probable increased nutrient content of the recovering vegetation attracts the grazing animals. This is reflected in the increased grazing on the *Molinia*, and the shorter length to which the *Molinia* is grazed.

Chapter 7 DISCUSSION AND CONCLUSIONS

7.1 Introduction

This chapter summarises the general conclusions from this study, and suggests changes in the use of fire in the north-west of Scotland. The distinction between severe fires, which can occur at any time of the year, and management fires, which take place primarily in spring, must be emphasised. Many possible problems can arise as a consequence of severe fire, but as these are not the remit of this study, this chapter deals with the consequences of management fires, with the characteristics and under the conditions described in Chapters 3 and 4. Judging the success or otherwise of management fires (or any management option) depends on the stated objectives, and the criteria set for judging the outcome. It is therefore assumed that the primary aim of management fire is to provide increased or better quality grazing for herbivores, whilst at the same time maintaining the species present in the bog habitat, in particular the *Sphagnum* layer.

The overall objectives of this study are the characterisation of fire and its effects on blanket bog, the production of guidelines for management burning on blanket bog, and recommendations for future fire research. The latter two objectives are dealt with later in this chapter, but with regard to the specific aims regarding fire and its effects (described in section 1.7), the main conclusions are that:

- the spatial distribution of fuel across the bog habitat is very heterogeneous;
- the different fuel types are of varying importance in contributing to management fires;
- the range of temperatures recorded in such fires is comparable with dry heathland fires, but with a greater proportion of low values;
- there are definite patterns in temperatures recorded, with maximum temperatures being found in the middle of the vegetation, but greater total energy output often found at the surface;
- different measures of fire intensity convey different information about a fire, and should be used and interpreted with care;
- the *Sphagnum* layer, although apparently severely damaged in the year following a fire mainly due to bleaching, can recover very quickly;

- *Calluna* and *Molinia* regrowth results in very fast recovery in the years following a fire, and animals preferentially graze burnt areas;
- the question of whether to use fire as a management tool on blanket bog must not be addressed by considering the consequences of a single fire event only, but must take into account other impacts (such as grazing and trampling) and the effect of the overall fire regime.

7.2 Possible disadvantages of management fire

The recommendations against burning on blanket bog (Table 1.2) are based upon a perception that the effects of fire result in habitat degradation to some extent. The possible reasons for fire being inappropriate for use on a blanket bog are that:

- management fires, for reasons of environment or lack of control, can become severe;
- fire damages *Sphagnum* to the extent that it does not recover before the next fire event (either in terms of cover, height growth, or species diversity);
- fires may cause an eventual degradation of both *Sphagnum* and vascular plant cover leading to bare peat, and possible erosion;
- the cumulative effects of burning cause losses in species abundance and/or the number of species, or stops certain species from colonising the bog habitat (e.g. *Betula nana*);
- the attraction of too many animals (from what are large unfenced areas) may result in overgrazing, and perhaps more importantly localised but severe poaching damage.

Fires may become uncontrollable for several reasons. Either the people conducting the fire may be very inexperienced, or there may be insufficient people attending the fire (a common problem in the north-west of Scotland), or wind conditions may change unexpectedly. A better understanding of fire behaviour under the conditions we experience in this country would result in clearer and more explicit guidelines being available to land managers. This would not stop people ignoring the guidelines, but at least better information would be available than is currently the case.

The damage to the *Sphagnum* layer, from the results in this study, does not appear to be as bad or as long-lasting as has been thought previously. Although the data presented here do not show the *Sphagnum* recovering to full health, the rate of recovery shown in Chapter 5 indicates that the effects of fire may be difficult to detect after a decade of recovery. However, as emphasised earlier, the question of fire regime, in particular the time until the next fire event, is critical. The results here broadly support the view that 'fire is one of the least drastic disturbances in living bogs' (Barkman, 1992), but the caveat should be added that this statement is only true if conditions for favourable recovery are maintained for a long enough period of time. This applies equally to both the vascular plants and the *Sphagnum* species.

The question of whether a bog is 'healthy' or not is sometimes addressed by way of describing the bog as healthy if it is 'active', or actually depositing peat. Leaving aside the debatable assertion of whether 'health' equates to peat deposition, it was found by Kuhry (1994) that for boreal bogs in Canada, peat accumulation rate and carbon sequestration were negatively correlated with fire frequency. With individual nations now responsible for their carbon balance, the effects of fire on both carbon content and carbon accumulation (or loss) on peatlands must be addressed. The use of fire in a certain way (most probably with respect to the overall fire regime, in particular fire frequency) may be responsible for tipping the whole ecosystem from one state (carbon accumulation) to another (carbon loss).

7.3 Possible advantages of management fire

The following are the possible advantages of management fire use on blanket bog:

- it makes forage more accessible to grazing animals, or promotes more and /or better quality forage;
- it promotes *Sphagnum* growth by removing the litter layer and improving the light regime, or encourages a relatively dense flush of vascular plant growth (in particular shrubs) which can act as a climbing frame for the *Sphagnum*;
- it creates firebreaks that may stop (or least provide places to attack) future uncontrolled and/or severe fires;
- it promotes the regeneration of *Calluna*.

The results from this and other studies indicate that grazing animals do indeed select recently burnt areas over unburnt areas, but whether this is due to forage amount, accessibility, or quality is unclear. The idea that fire may actually encourage *Sphagnum* growth may be controversial, but observations indicate that this may be the case under some conditions. However, growth of one or two common *Sphagnum* species may be promoted at the expense of other species. Even if it can be confirmed that *Sphagnum* growth can be encouraged in certain species, there still remains a question over whether other species are lost because of fire. To date, all such evidence has been observational and conjectural. The effectiveness of management fire in creating firebreaks may be more applicable to wet and dry heath than blanket bog, but it is undoubtedly true that management fires do reduce fuel loads, and therefore lessen the potential severity of future fires.

7.4 Changing fire use

7.4.1 Fire in context

The different land-use priorities were discussed (Chapter 1), in particular the conflicts between agricultural and conservation objectives, although the actual difference between these objectives may be narrowing. The management of much of the uplands, not just the north-west of Scotland, is currently somewhat uncertain with sheep prices being extremely low and the subsidy system being subject to possible change. Large areas may therefore see significant changes in management priorities, and it is conceivable that the maintenance of sheep grazing may in places become purely conservation-driven. This makes the use and role of fire more difficult to ascertain, but also makes research to understand fire ecology even more important, if the use of fire is to be adapted to these changing objectives.

The social and cultural aspect of fire was also discussed, and must be appreciated in making management fire recommendations. In a study involving farmers in Brazil, Mistry (1998) looked at the decision-making process farmers use in deciding whether to use fire as a management tool, and the main conclusions were that:

1. financial and time constraints prevent farmers from opting for alternatives to fire;
2. perceptions of fire are equally as important as alternative choices available;
3. traditional beliefs are dominant in determining how and when fire is used;

4. community relationships strongly determine fire use;
5. laws and regulations play a negligible role in decision-making.

The results from that study emphasised that farmers perceptions of fire (such as that fire is 'good') are just as important, if not more so, than more objective economic considerations. There are obvious parallels with the use of fire in the north-west of Scotland, where the culture of fire has been very much under-appreciated to date. It may be that fire will continue to be a part of the landscape no matter what the precise recommendations of any study. In such a situation, the way forward for advisory and conservation bodies may be to work within this culture of fire, and promote the best practice for management fire from within this culture.

A possible example for the way forward is found in the French Pyrenees (Metailie *et al.*, 1995). In this area, it was noted that there was a loss of local and indigenous knowledge about burning, and an increasing number of uncontrolled fires. A 'committee of prescribed burning' was formed, involving all relevant parties (land managers, conservation bodies, local government, foresters, fire control agencies), using the existing 'traditional rural structures' (which may be similar to the present crofting Grazings Committees). As well as planning burning and fire control, provision was built-in to allow relevant research to be done. After three years, the result has been an increase in the number of planned fires, fewer unplanned fires, and perhaps equally importantly, better relationships between the involved bodies. A similar structure could be tried in the north-west of Scotland, based on the croft Grazings Committee structure. These could be expanded to include all land managers in an area (not just the crofters), and plans drawn up that included burning intentions for the coming season and fire control guidelines. Where possible, manpower and equipment could be pooled, resulting in safer prescribed burning and a much better response to uncontrolled fires. The importance of having the ability to act quickly and in accordance with pre-defined plans was evident very recently, when an uncontrolled fire in the area of this study resulted in 1 km^2 of blanket bog, wet heath and native woodland being burnt.

7.4.2 Suggestions for burning guidelines

The results of this study with respect to specific quantifiable objectives are discussed in section 7.1. However, equally important objectives are the recommendations based not only upon the results, but the integration of the results with experience gained in practical management of blanket bog within the environment (ecological, economic and social) of the north-west of

Scotland. Before making these recommendations, it is important to emphasise that in many areas, blanket bog is part of a mosaic of habitats, together making up extensive grazing units. It is therefore difficult to manage small areas of bog independently to the rest of the area. The obvious exception to this is the Flow Country, where there are extensive areas of unbroken blanket bog. The following suggestions are based on the results of this study, but also the observation of management fires and their effects elsewhere in north-west Scotland on wet heath and blanket-bog habitats.

1. CO-OPERATION AND PLANNING. More contact between interested parties, as recommended above, is required in order to ensure greater understanding of different objectives, and increased co-ordination of burning and fire control efforts.
2. RECORDS. Records of all fires (management and otherwise) should be kept, including at least outlines of the burnt area sketched onto a map, with appropriate target notes.
3. FREQUENCY. Do not burn sooner than roughly once every 20 years, however this recommendation may have to be altered on a site to site basis. Some areas, such as very wet bog areas, or areas that have apparently never been burnt, may not require any burning.
4. WHEN TO BURN. Spring burning is recommended as the *Sphagnum* may be more susceptible to fire damage in the autumn, due to natural bleaching having occurred, the water table on the bog being low, and the *Sphagnum* itself drier. Burning should also be started as soon as possible after rain, but should not continue after the litter layer on the top of the *Sphagnum* has dried out. In practice, this may mean stopping burning after 3- 4 days of dry and suitable weather.
5. HOW TO BURN. Fires in the north-west are naturally very heterogeneous, and this should be retained. Unburnt areas should not be re-lit, and there is no need to obtain a 'clean burn'.
6. SIZE OF FIRES. Due to the possible poaching and grazing damage on small areas, and the difficulty in burning many small areas, large burns (10-15 ha) are recommended. This will spread herbivore pressure, and it must be remembered that the within-fire heterogeneity will ensure that burnt areas are not homogeneous.
7. FIRE CONTROL. More appreciation of fire behaviour, especially with respect to wind and topography, is required. There is also a need to plan where fires will be controlled (linked to point 1 above), in particular using roads, or 'natural' firebreaks such as bog areas themselves or lochs. This requires sufficient people being available and co-operative planning.

8. INTEGRATED MANAGEMENT. Fire should be used in conjunction with grazing to achieve desired aims. For example, burning followed by heavy spring grazing for some years after a burn may help control the spread of *Molinia* provided that grazing pressure is decreased at other times of the year. This assumes a much greater shepherding role for land managers, but if the maintenance of sheep in the north-west becomes conservation driven, this may be possible.

The above recommendations are in places contrary to the current Muirburn guidelines, however they are based on what is thought to be relatively easily achievable within the north-west Scotland context. Changes such as those recommended do place more responsibility on land managers, conservationists, and statutory bodies, but the outcome of increased co-operation should be sustainable management of these areas whilst meeting differing objectives.

7.5 Further research priorities

7.5.1 Fire and fuel characteristics

Ward *et al.* (1995) consider that the north-west of Scotland suffers from overburning, but they go on to say that fire itself may not be the problem but rather our lack of understanding of its effects. Much of the fire research to date has examined the effect, without looking at the original cause, with fire treated very much as a uniform phenomenon. We therefore need to study fuel and fire characteristics in order to understand the *range* of fire behaviour and subsequent effects we can expect from a typical management fire. Such information can also be used in predicting fire behaviour for fire control and hazard prediction purposes.

A first step in conducting further research is to define the objectives for such research. The results in Chapter 4 revealed that different ways of measuring fire intensity can result in conflicting estimates. A full review of the different fuel and fire techniques used overseas should be undertaken with particular regard to our own specific requirements. Relevant techniques will need to be tested under controlled burning conditions, and parameterised for our fuel and environment. As well as increasing our understanding of fire ecology, this process should also result in the development of a standard set of guidelines and techniques with which further research should conform if possible. This will enable the results from different studies to be legitimately compared, and therefore ensure that studies do not remain 'one-off' events, where the results are very site and technique-specific.

7.5.2 Species and community response

There has been much work in the UK on the response of certain species to fire, in particular the response of *Calluna* in dry heathland. However, given that *Calluna* recovers via different pathways on dry heathland and blanket bog, there is clearly a need for research into vegetative recovery after fire. The same may be true for all vascular and bryophyte species, and there is a need for many autecology studies to determine how plant recovery varies with fire and site characteristics. In particular, work on the effects of fire on *Sphagnum* is required, with the most obvious questions being;

- are certain species able to recover better after fire than others?
- to what depth is *Sphagnum* killed by heat, and from what depth can it recover?
- what heat input (temperature and duration) is required to kill *Sphagnum*?

On the community scale, the question of how quickly the vegetation recovers is unknown, bearing in mind that different species / groups may be recovering at different rates. This information is needed in order to determine fire frequencies for achieving different aims. Community recovery from a fuel build-up viewpoint is also important, in that it is almost certainly true that enough fuel for another fire builds up much quicker than the bog community recovers. With there being an attitude of 'if you can light it, it's ready to burn' in some areas, there may be a large mismatch between the minimum fire return time required for community recovery, and what is actually occurring. There are also aspects of community recovery that have yet to be addressed, for example (Jonsson *et al.*, 1999) found that low intensity fires in Swedish boreal forest do not affect ectomycorrhizal diversity, but more severe fires reduce diversity. The effects of fire on blanket-bog ectomycorrhizas are unknown.

7.5.3 Defining a fire regime

Perhaps the most important question to be addressed, but one outwith the scope of this thesis, is what the overall management regime should be. Hobbs (1984) demonstrated the importance in length of burning rotation, finding that shorter rotation (10 year) reduced *Calluna* cover compared to a longer (20 year) rotation. Definition of a fire regime depends upon the management objectives in the short term (e.g. increasing forage availability for a few years) as well as objectives over much longer timescales. The latter are not often considered when determining the use of fire on blanket bog, but should be. Such considerations include carbon balance issues, maintenance (or expansion) of the *Sphagnum* layer, and vascular community composition. As this thesis has emphasised, there are wider issues that must also be taken into account when the management of such an important habitat is being discussed. These include maintaining the rural communities in the area, either though agriculture, conservation or tourism income. The main areas of conservation / agricultural conflict are thus production of better grazing for animals, and the maintenance of the blanket-bog habitat, which can probably be best defined as the maintenance of the *Sphagnum* cover. Although the results presented suggest that *Sphagnum* can recover from fire, there is insufficient information to determine whether *Sphagnum* cover (and species composition) can be maintained in the long term, whilst meeting agricultural objectives.

Unfortunately, in the north-west of Scotland, the overall fire regime is perhaps the one aspect of fire ecology that we know the least about. However, in identifying the desired fire regime, there are some recommendations that can be made. In order to define a fire regime, we should not be trying to define what may or may not be a 'natural' regime. We should start by defining our objectives (conservation and agricultural) for the blanket-bog habitat as a whole. Once objectives are defined, the role of fire within the overall management regime can be determined, bearing in mind that the complete exclusion of fire is an option. If fire is to be used, then fire prescriptions will be based on our knowledge of the characteristics of different fire regimes and the effect they have on the habitat. However, such prescriptions must be the result not only of ecological considerations, but also economic and cultural ones. Pyne *et al.* (1996) state that 'a fire regime is thus a cultural as well as a biological system. Neither fire nor fire regimes are wholly natural or wholly anthropogenic'.

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