A modelling approach to farm management and vegetation degradation in pre-modern Iceland

By

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Statement of originality

I hereby confirm that this is an original study conducted independently by the undersigned and the work contained herein has not been submitted for any other degree. All research material has been duly acknowledged and cited.

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ABSTRACT

Grazing by domestic livestock is one of the primary ways by which humans have modified landscapes. At low stocking rates livestock grazing can modify vegetation community composition, but at high stocking rates grazing can also reduce vegetation productivity and initiate soil erosion, leading to land degradation. The country of Iceland has undergone severe land degradation over the past 1100 years, with over half of the former vegetation cover being lost, and the remainder having depleted productivity. This work focuses upon the role that grazing by domestic livestock played in this degradation, and how the interactions between farm management, vegetation cover and climate affected grazing patterns in space and time.

The aims of the research were achieved by constructing an environmental simulation model, called Búmodel, which allowed a cross-disciplinary approach that integrated landscape ecology, environmental archaeology and historical analysis. Búmodel was loosely coupled with GIS so that spatially based model inputs and outputs could be displayed and analysed in map form. The purpose of Búmodel was to predict spatial and temporal patterns of vegetation biomass production and utilisation (through grazing and hay-making) with a view to commenting on vegetation degradation in the pre-modern period (pre-1900 AD). The model was parameterised using contemporary and historical Icelandic agricultural data. Model validation was undertaken using sensitivity tests and comparison with data from an independent grazing experiment in the north of Iceland. Búmodel was then applied to two contrasting study areas: Vestur-Eyjafjallahreppur, a farming community on the south coast of Iceland, and Hofstaðir, a farm estate in the north east of the country, situated inland by Lake Mývatn. These applications demonstrated the importance of farm management in avoiding land degradation and in ameliorating the impact of climate. They also established the usefulness of Búmodel as a tool for the investigation of human and environmental interactions in Iceland.

Glossary of abbreviations and Icelandic terms

á	river
afréttur (sing., plural: *afréttir*)	Communal grazing areas, also refers to other communal resources
bú	Farm estate or farming enterprise
hreppur (sing., plural: *hreppar*)	Local communal units. Responsible for controlling communal resources, organising communal labour and providing local 'social insurance' in cases of hardship.
jökull	glacier
Landnám	'Land-taking'. The period when Iceland was first fully settled, c. 870-930 AD.
RALA	Agricultural Research Institute of Iceland
rofabard	Erosion escarpment
tephrochronology	Method of dating using volcanic ash layers
thúfur	Vegetation covered soil hummocks formed by frost heave
tún	The enclosed and fertilised hayfield of the farm
vatn	lake

Icelandic letters have been used in the text. The symbols ð and þ both represent *th*-sounds: ð is the symbol for the *th*-sound in 'the', and þ is the symbol for the *th*-sound in 'think'.

Chapter 1: Introduction and Aims: Landscape Modification by Grazing

1.1 Introduction

Grazing is one of the primary means by which humans have modified landscapes in the past. Even in the present day, some 47% of the world's land surface (principally mountain and sub-arctic areas) is suitable only for extensive pastoralism, giving an indication of the potential environmental impact of grazing (Simmons 1996). Grazing livestock can affect a pristine environment even at light stocking pressures by modifying the species composition of the dominant vegetation communities. At low stocking rates, this will shift the botanical composition towards grasslands, which are most productive for grazing. If stocking rates are too high, then over-grazing reduces vegetation productivity and creates bare patches, increasing the risk of soil erosion.

Over-grazing is one of the main causes of land degradation (Blaikie and Brookfield 1987), a global issue that affects over 40% of the world's vegetated land surface (Brady and Weil 1999). The term 'land degradation' encompasses a reduction in the quality of land resources (soil, water, vegetation, rocks, and climate), resulting in an 'irreversible decline in the capacity of the land to produce' (Biot 1993). From a human subsistence viewpoint, this degradation can be extremely serious, resulting in:

> 'Reduced animal productivity, soil erosion, reduced water catchment efficiency, elimination of productive palatable pasture plants and increase in the abundance of toxic herbs and browse-resistant, unpalatable woody plants.'(Crawley 1997): 444.

Loss of vegetation productivity and change in botanical composition means that fewer livestock and humans can be supported, and the remaining vegetation is more sensitive to climatic shocks and other environmental impacts, such as volcanic ashfall. Degraded vegetation is also less resilient (i.e. less able to return to its former state following change).

1.2 The human role in over-grazing

> ‘Human-induced degradation occurs when land is poorly managed, or where natural forces are so powerful that there is no means of management that can check its progress.’ (Blaikie and Brookfield 1987): 3.

Management decisions play a crucial role in human-environment interactions in any landscape, but particularly ones in which environmental conditions for human subsistence are marginal. Even within a simple pastoral agricultural system a wide range of management decisions are possible. Farmers can control the composition of their herds and their distribution in space and time across the farm landscape. The production of hay, winter feeding regimes and improvement strategies such as fertilisation and drainage are all areas within the farmers’ control. These decisions can initiate, exacerbate or ameliorate vegetation degradation by affecting two key elements: the amount of grazeable vegetation that is available, and the amount that is consumed by domestic livestock.

The proportion of annual vegetation production that is removed by grazing livestock (the cumulative utilisation) can be used as a proxy measure of vulnerability to over-grazing (discussed in Chapter 4). The cumulative utilisation is responsive to the distribution of livestock in time and space:

> ‘The rhythm of pasturing is the key to good management. In general, overgrazing is basically the result of a poor seasonal or weekly distribution of livestock rather than an average excess of the number of animals.’ (Forman and Godron 1986): 279.

Although human decisions may be the immediate, or proximate, cause of over-grazing (and/or land degradation) consideration should be given to the intermediate and ultimate causes as well. Intermediate causes are the reasons why the farmer chooses a management strategy that leads to degradation, and ultimate causes ‘are firmly rooted in the socio-economic, political and cultural environment in which land users operate’ (Stocking and Murnaghan 2001).

1.3 Iceland: a landscape modified by grazing

Iceland is an example of a place whose contemporary landscape has been extensively remodelled by grazing. The country has experienced land degradation on a catastrophic scale over the past 1100 years, and has been called ‘the most eroded land in Europe, if not the world’ (Bjarnarson 1978): 241 and ‘perhaps the biggest ecological catastrophe in northern latitudes’ (Forbes and Jeffries 1999): 20. Since the ninth century there has been an estimated reduction in vegetation cover from 65% to 25% and a similar substantial reduction in the quantity of topsoil (Friðriksson 1972; Bjarnarson 1978; Thorsteinsson 1978). Much of the remaining vegetated area is suffering from ongoing erosion and depleted productivity (it is estimated to have degraded to less than 20% of its potential (Thorsteinsson 1986)). A review of the physical environment and pre-modern agricultural system of Iceland will provide context for the discussion of this degradation.

1.3.1 Physical environment of Iceland

Iceland is an island of 103,000 km^2, located in the North Atlantic Ocean between 13º and 24ºW and 63º and 66ºN, just south of the Arctic Circle. Greenland is 300 kilometres to the west, Norway 1000 kilometres to the east and mainland Scotland is 830 kilometres to the southwest (Figure 1-1 and Figure 1-2).

Iceland is predominantly mountainous, with lowland (defined as less than 300m) accounting for less than 35% of the land area (Figure 1-3). Glaciers, rivers and lakes cover around 20 % of the land area, 58 % is barren or sparsely vegetated desert, and 2 % is cultivated. Only one quarter of Iceland's surface area is vegetated, of which the majority lies below 200m elevation.

1.3.1.1 The climate of Iceland

Iceland lies at a point where warm air and the Irminger Current (a branch of the North Atlantic Drift) meet cold air and the East Greenland Polar Current from the arctic regions (Ogilvie 1984; Lamb 1995) (Figure 1-1). Consequently Iceland has an oceanic climatic regime, which is highly variable but relatively warm when compared to other areas at similar latitudes. The climate of southern Iceland is cool and maritime, while the north of the country and the interior highlands can be defined as having a low arctic climate (Einarsson 1976), and are cooler and dryer. The warmest month of the year is July, with mean temperatures in the range of 8-11 ºC across most of the country (Figure 1-4). The coldest month of the year is January, and mean temperatures in this month can vary widely, from 1-2 ºC on the southern coast to -6 or -7 ºC in the interior highlands (Icelandic Meteorological Office 2001). Annual precipitation also varies across the country, from <400 mm immediately to the north of the Vatnajökull icecap to >4,000 mm in the southern coastal mountains (Figure 1-4). Precipitation is highest in the winter months, when much of the precipitation falls as snow.

The earliest reliable long-term instrumental records of the Icelandic climate date from 1837 at Stykkishólmur on the western coast (shown on Figure 1-2). The climate of Iceland earlier in the historic period can be described on a decadal scale using evidence from ice cores (Dansgaard *et al*. 1975), marine sediment cores (Jennings and Weiner 1996; Jennings *et al*. 2001) and glaciology (Gudmundsson 1997; Mackintosh *et al*. 2002). Astrid Ogilvie has developed detailed annual and sub-annual climate data-sets for Iceland using rigorous documentary analysis (Ogilvie 1986; Ogilvie 1990; Ogilvie 1992).

The spatial and temporal coverage of this historical climatic information is uneven. It is apparent that the Icelandic climate has always been highly variable: there are reports of sea ice, severe winters, and dearth years in all centuries, although their frequency in the earlier period is unknown. Circumstantial evidence points to a relatively mild climate during the ninth to the twelfth century (Ogilvie *et al*. 2000). From that point to the sixteenth century, short periods of harsh climate occurred periodically, when ‘mean annual temperatures may have fallen to 1 ºC or 2 ºC below typical twentieth century Icelandic temperatures’ (Ogilvie 1990). From 1500 to 1900 there was ‘profound variability in climate on an annual and decadal time scale’, with a general cooling of the climate (Bergþórsson 1969; Ogilvie 1992) (Figure 1-5). Glacial advances also took place during this cooler period (Dugmore 1989; Mackintosh *et al*. 2002), similar to those in Europe during the ‘Little Ice Age’ in the seventeenth and eighteenth centuries (Grove 1988).

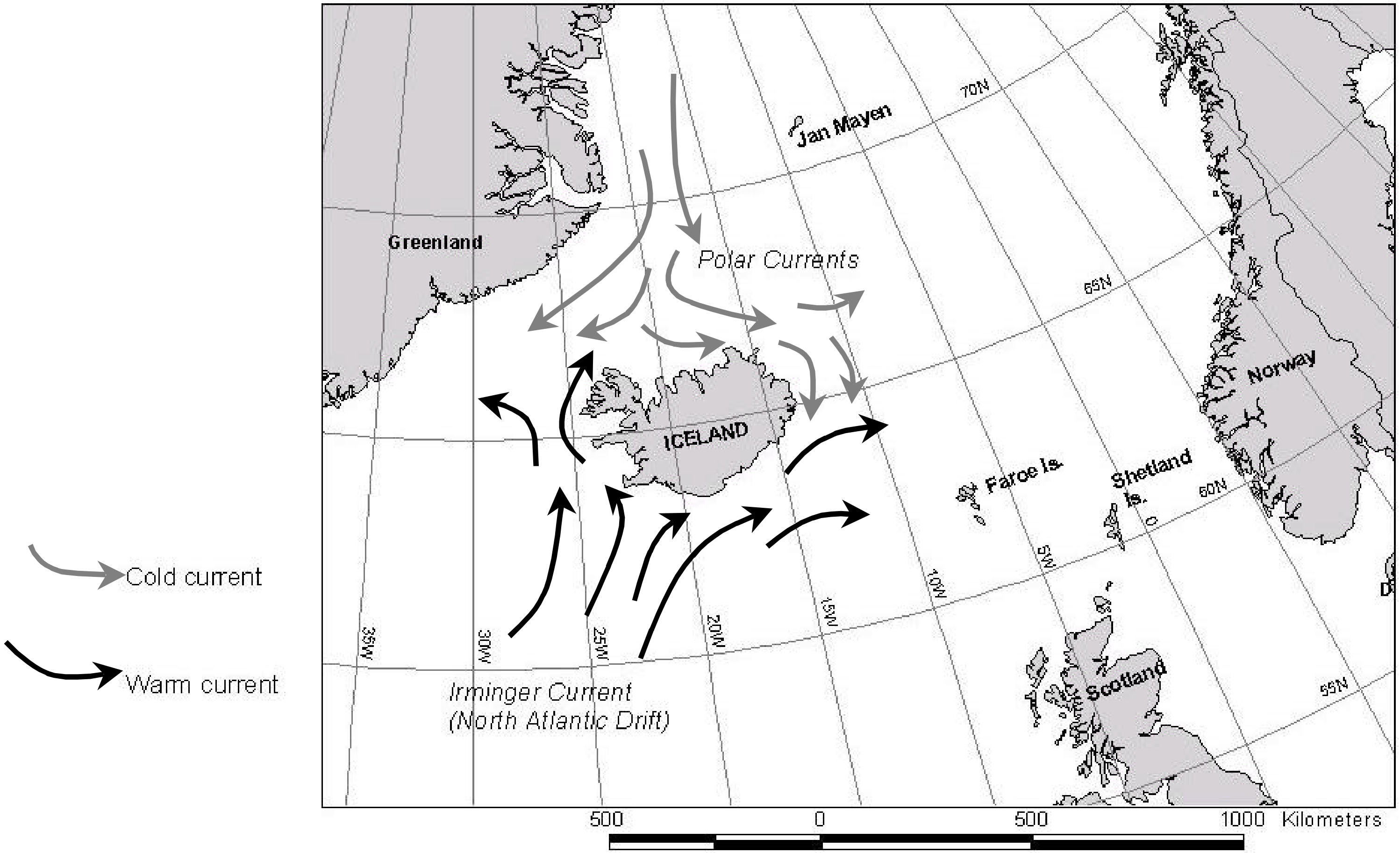


Figure 1-1: Regional map of the North Atlantic Ocean, showing islands and ocean currents around Iceland

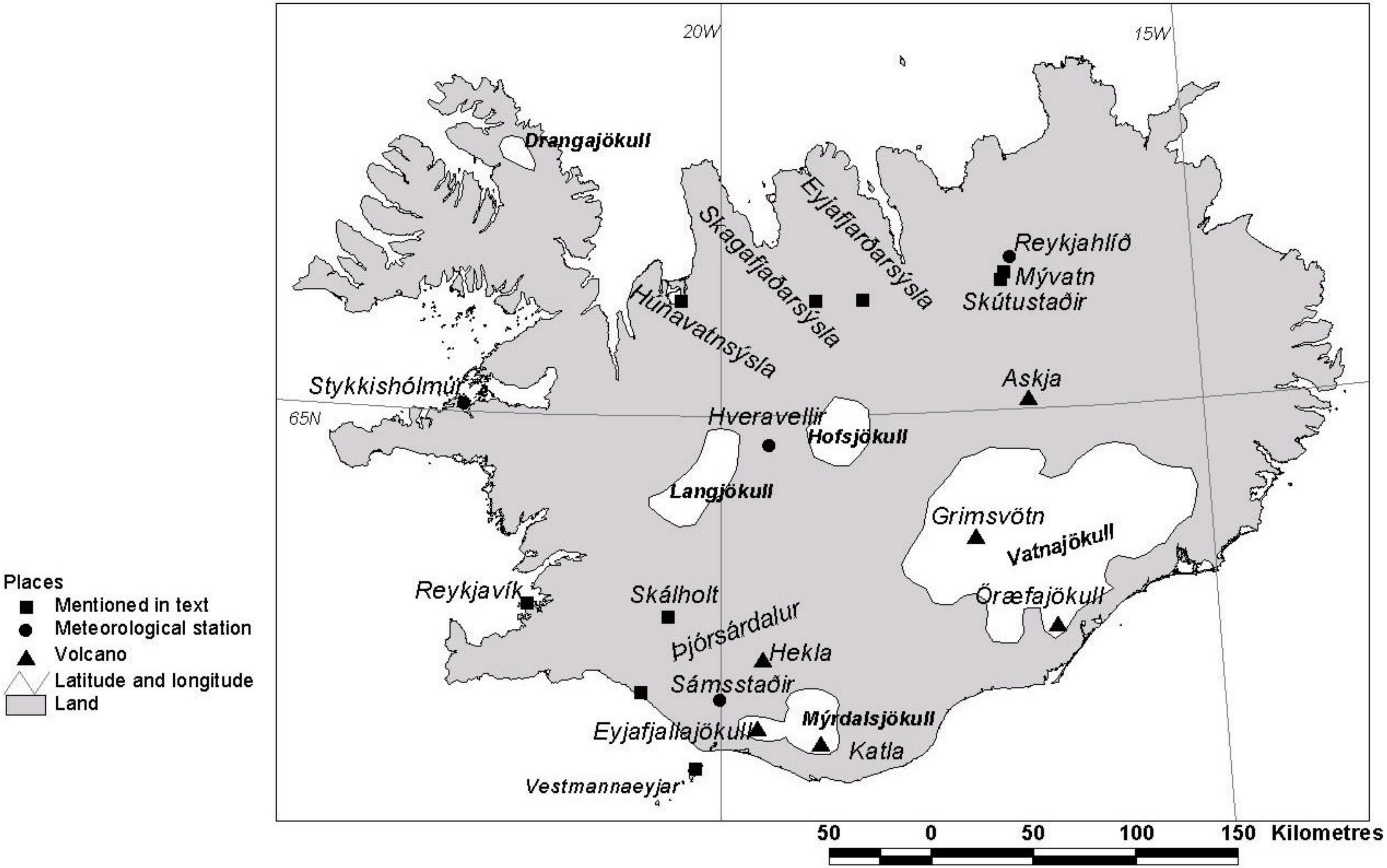


Figure 1-2: Locational map of Iceland, showing places mentioned in the text

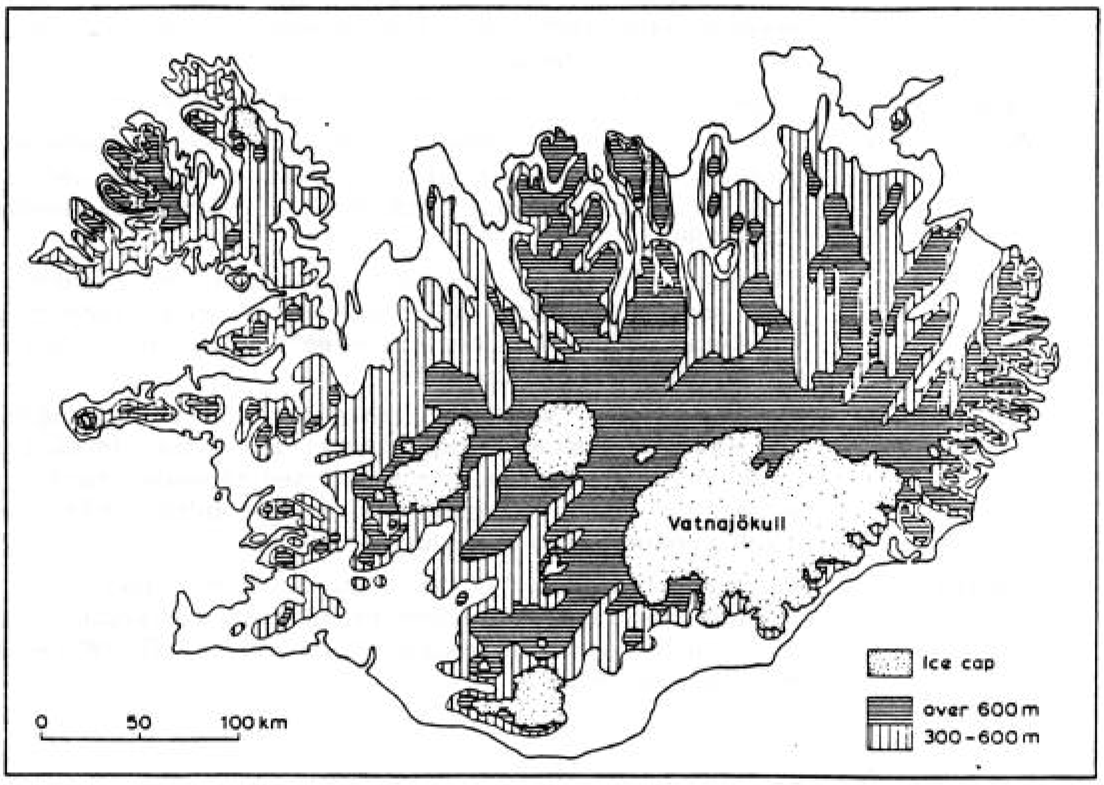


Figure 1-3: The topography of Iceland, showing lowland areas (<300m) and highland areas (>300m) (from (Bergþórsson *et al*. 1987))

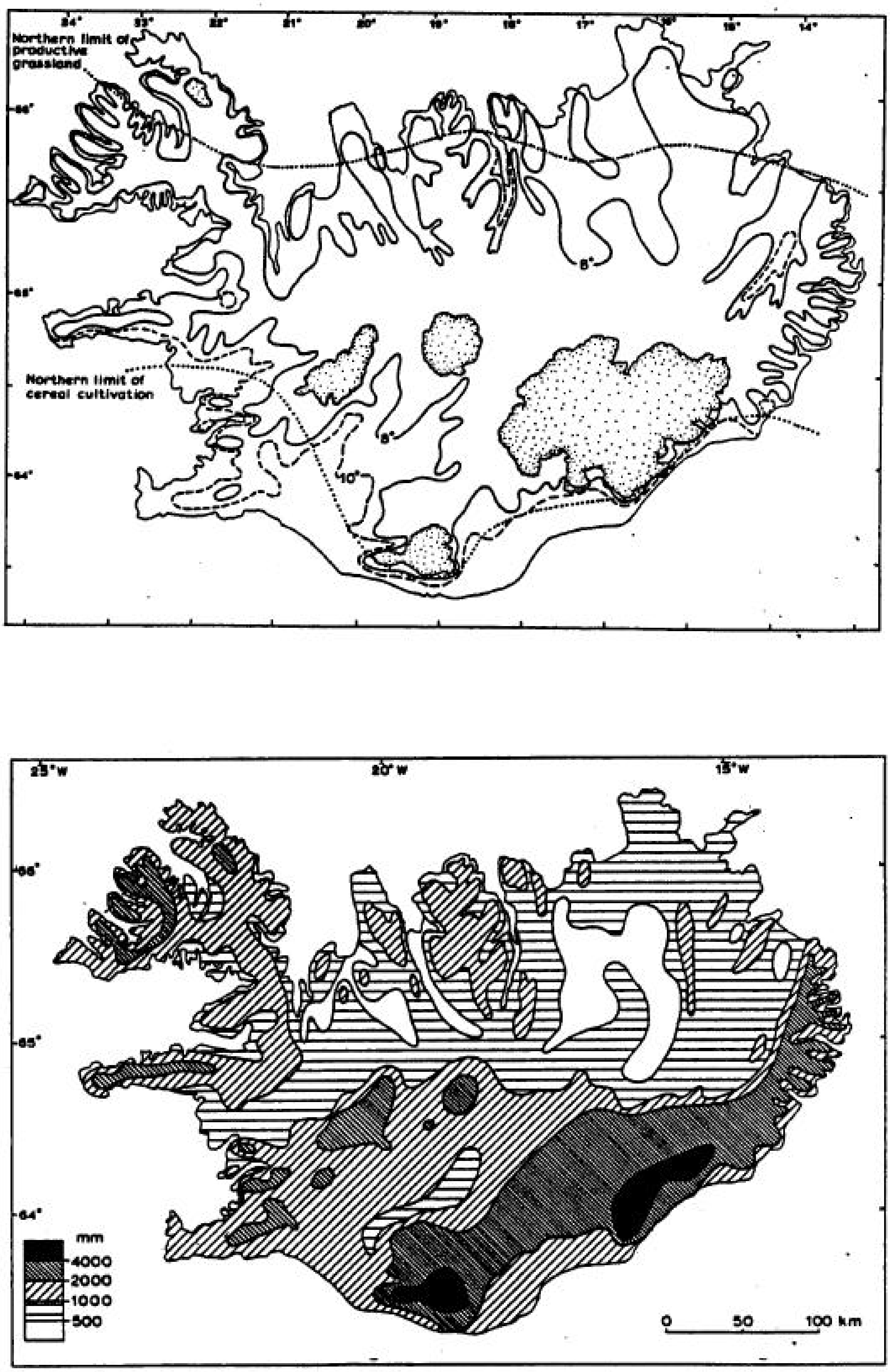


Figure 1-4: Map of mean July temperature (1951-1980) (ºC) and mean precipitation 1931-1960 (mm) in Iceland (from Bergþórsson *et al.* 1987)

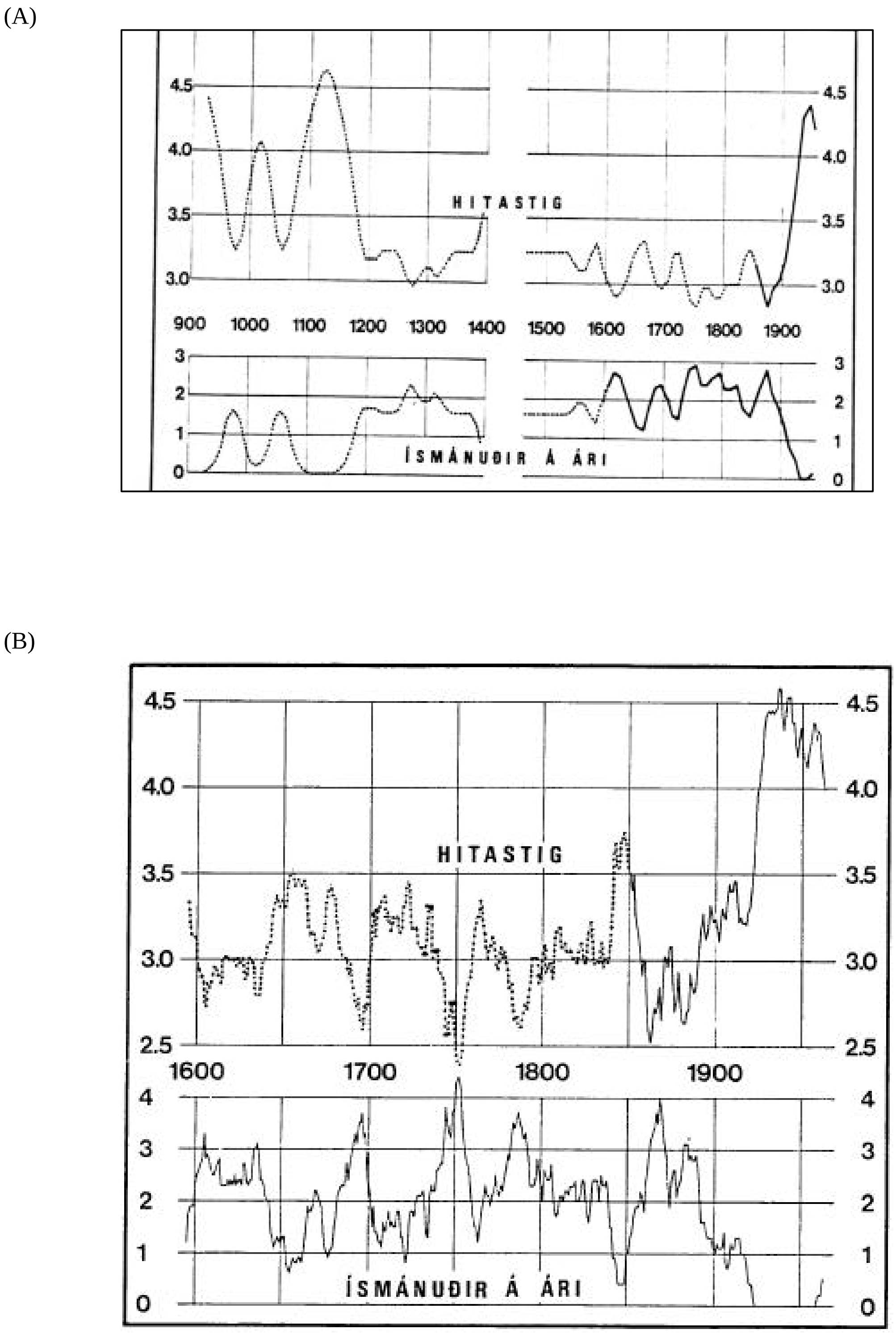


Figure 1-5: Estimated running means of temperature and sea ice incidence off the coast of Iceland in months per year, (a) 30 year running means 900-1950 AD, (b) decadal running means 1600-1950 (from (Bergþórsson 1969))

Hitastig: Mean annual temperature for lowland Iceland, °C; Ísmánuðir á ári: sea ice incidence in months per year

1.3.1.2 The geology and soils of Iceland

In terms of geology, Iceland is a very young country: the oldest rocks to be found are only 20 million years old (Fridriksson 1975). It is situated on the North Atlantic Ridge, the divergent boundary between the North American and Eurasian continental plates, which runs from the southwest to the northeast of the country. All bedrock is of volcanic origin, being either basaltic lava, eruptive volcanic material or deposits that have been eroded and reworked by glacial, fluvial and/or aeolian processes. There have been high levels of volcanic activity, and associated lava flows, earthquakes and floods throughout Icelandic history, continuing to the present day. Around 200 eruptions have taken place during the historic period, which sometimes had a catastrophic effect upon the human population (Þorarinsson 1979c). For example, at least thirty farms were destroyed in Litla Hérad, in southern Iceland, by tephra fall and flooding from the eruption of Öræfajökull in the 14th century (Einarsson *et al.* 1980), and the prosperous area of Þjórsárdalur was permanently abandoned following the eruption of Hekla in 1104 (Þorarinsson 1961b). The large amounts of tephra (volcanic ejecta) produced by many of these eruptions, is incorporated into the soil as a layer of material, providing precise chronological markers, which have proved useful in palaeo-environmental research (Figure 1-6).

Glaciers and rivers have also shaped the surface of the Icelandic landscape. During the last Ice Age the country was completely covered by ice, which retreated between fifteen and ten thousand years ago, revealing features such as deep U-shaped valleys and moraines. Around 10% of the country is still permanently covered by ice, including the largest ice cap in Europe, Vatnajökull (marked on Figure 1-2). The glaciers produce

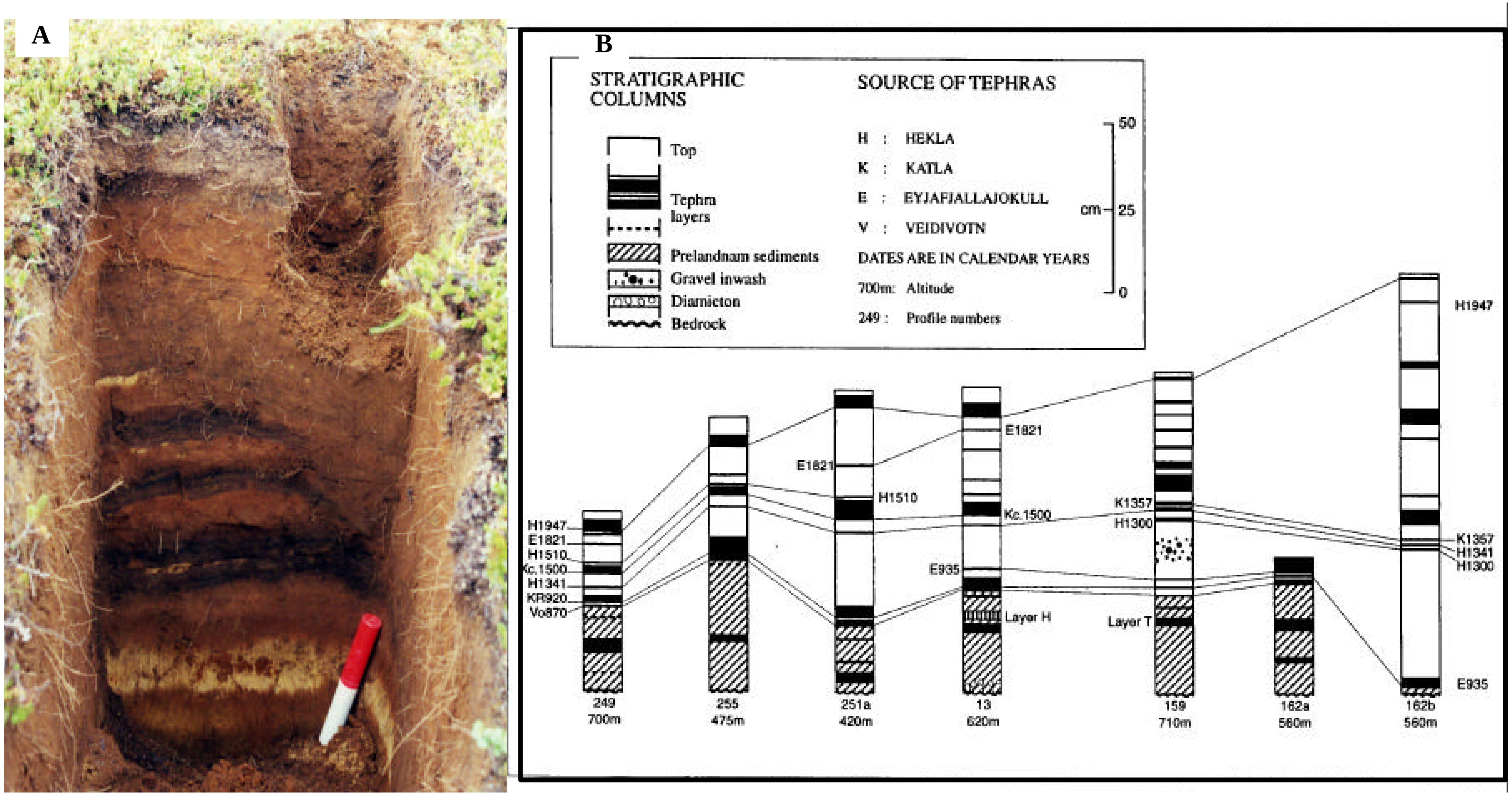


Figure 1-6: The use of tephrachronology to provide precise chronological markers for palaeo-environmental research: (a) example of soil profile with dark and light tephra layers, (b) example of linked tephra stratigraphy demonstrating changing rates of soil accumulation (from Dugmore and Simpson, in press)

vast quantities of sediments, which are removed by rivers. Occasionally there are tremendous floods, jökullhlaups, caused by the bursting of ice-dammed lakes, or by sub-glacial volcanic eruptions. The total volume of these floods can be 6-7 cubic kilometres, sufficient to carry icebergs and cause extensive erosion (Þorarinsson 1979c). The material carried by these floods has formed extensive depositional plains, or sandar, along the southern coast of Iceland, which extend up to ten kilometres beyond the original coastline of basaltic sea cliffs.

Well-developed Icelandic soils consist mainly of volcanic andosols and histosols (peats) (World Reference Base (1998); Parfitt and Clayden (1991)), which cover 55 % of the available surface area. Andosols (equivalent to Andisols in Soil Taxonomy (Soil Survey Staff 1998)) are young soils formed on volcanic deposits (ash, tuff, pumice and other ejecta). They are characterised by high organic matter content (giving a typically dark colour), low bulk density, high phosphate retention and significant quantities of special clay minerals such as allophane and imogolite (Arnalds 1990). They also have a high water holding capacity (which intensifies freezing processes), high hydraulic conductivity and very little cohesion once the liquid limit is reached (Maeda *et al.* 1977). Histosols are organic soils that form by the accumulation of partially decomposed organic material in anaerobic environments. Other soils in Iceland are usually classified as Vitrisols or Leptosols (Soil Map of Iceland 2001). They are shallow with little horizon differentiation or distinct morphological features or properties; these soils represent the initial phases of soil formation or are the product of severe erosion.

1.3.1.3 Vegetation cover and history

Given its size and climatic regime Iceland has a paucity of higher plant species, due to its isolation (its nearest neighbour is Greenland, 330 km away) and the short time since the end of the last glaciation. There has been debate over whether some of the endemic species survived in refugia whilst Iceland was covered by ice, or whether the country was a *tabla rasa* following the end of the ice age (Steindórsson 1962; Löve and Löve 1963; Buckland and Dugmore 1991; Rundgren and Ingólfsson 1999). Today there are approximately 440 species of flowering plants and ferns growing wild in Iceland (Kristinsson 1998) if microspecies of *Hieracium* sp. (hawkweed) and *Taraxacum* sp. (dandelion) (the only endemic Icelandic species) are excluded. The Icelandic flora has a northern European and Arctic bias, although Western Atlantic species are also represented. Humans have introduced approximately 100 plant species (mostly cultivated and ruderal species) in the last eleven centuries, both accidentally and deliberately (Steindórsson 1962). Plant nomenclature in this thesis follows Kristinsson (1998).

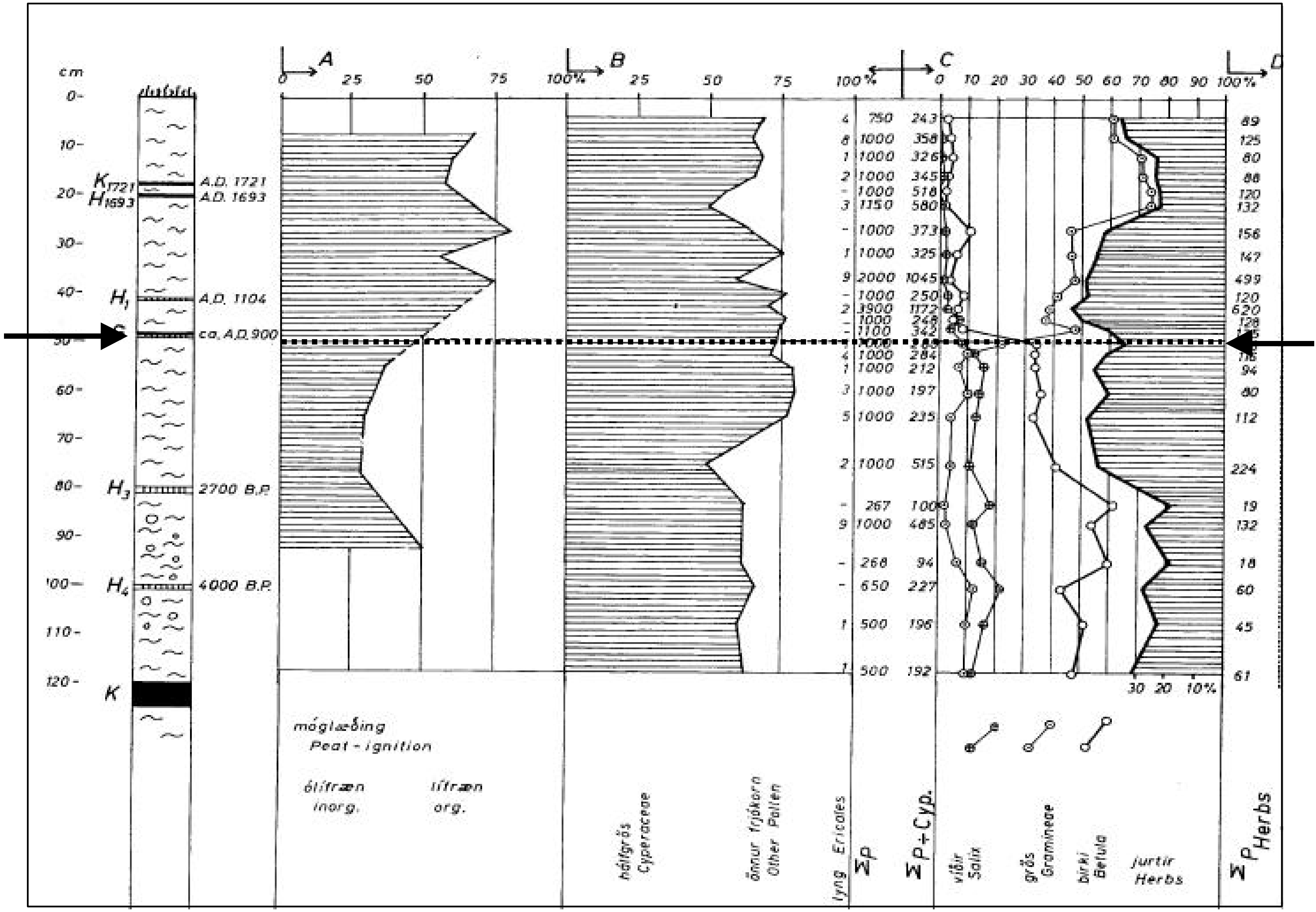
The main vegetation boundaries are between the highlands and lowlands, and between dryland and wetland vegetation types. The present day distribution and inter-relationship of species is mainly determined by grazing pressure (present and past), and only partly by growth conditions (Thorsteinsson and Arnalds 1992). Palynological research has established the pre- and post-Settlement history of the Icelandic vegetation. It is estimated that 65 – 70 % of the total land area had a continuous vegetation cover before Settlement (Thorsteinsson *et al*. 1971). Before the ninth century the prevailing dryland vegetation community up to 300 - 400m was birch woodland (*Betula pubescens*) with a lush understorey of herbs, grasses and dwarf shrubs (Thorsteinsson and Arnalds 1992). The precise extent of this forest has been much debated (see for example Eysteinsson and Blöndal (2000) and Ólafsdóttir *et al*. (2001)), possibly due to differences in the definition of 'forest' (some authors include birch scrub as forest, whereas others define forest as consisting of trees over two metres in height). *Betula pubescens* declined at higher elevations and was replaced by *Betula nana* and *Salix* scrub. Various types of heath were common at higher elevations, such as dwarf shrub heath (characterised by *Betula, Salix lanata, S. herbacea, S. phylicifolium, Empetrum nigrum, Calluna vulgaris, Vaccinium myrtillus* and *V. uliginosum*), rush and sedge heaths and grasslands (characterised by species of *Festuca, Agrostis, Poa* and *Deschampsia caespitosa* and *D. flexuosa*). Moss heath (*Racomitrium* spp. with *Carex bigelowii* and *Kobresia myosuriodes*) was dominant at the upper limits of continuous plant cover (around 600 – 700m); this community is also the pioneering vegetation type on post-glacial lava fields and eroded land. Above 700m climate limits plant growth to lichens and mosses with scattered hardy arctic-alpine vascular plants.

Wetland habitats consisted of a combination of rushes, sedges, cottongrass and scattered willows. Typical species include *Equisetum palustre, Juncus articus, Eriophorum angustifolium, Trichophorum caespitosum* and *Carex* (*C. rostrata, C. chordorrhiza, C. rariflora* and *C. lyngbyei*). These vegetation communities remained relatively stable from the time of Settlement until the twentieth century, when drainage has become increasingly common (Thorsteinsson and Arnalds 1992).

The post-settlement period saw a change in the dominant lowland vegetation from birch woodland to a more open grass-dominated landscape. This change in the vegetation cover is indicated by a decline in birch pollen and a substantial increase in grass and sedge pollen (Figure 1-7) and the appearance of plants and insects associated with a human presence in the landscape (Steindórsson 1962; Buckland *et al*. 1991; Zutter 1992; Sadler and Dugmore 1995; Sadler and Skidmore 1995). This grassland community was maintained by grazing, but overgrazing, combined with livestock preferences for certain plant species over others, caused degeneration to dwarf shrubland with increased levels of the less palatable sedges and rushes (Thorsteinsson 1986; Thorhallsdóttir 1997). Eventually over-grazed land degenerated into moss heath, with increasing areas of bare ground and increasing vulnerability to soil erosion (Thorsteinsson and Arnalds 1992). An estimated 60% of the total vegetated area in the country has been lost since settlement, so that the largest areas of vegetation cover exist below 200m and continuous vegetation cover is uncommon above 500-600m (Thorsteinsson 1986).

1.3.2 Resource management and the pre-modern agricultural system

A detailed national picture of farming in the pre-modern period can be constructed from three important historical sources. The first is the national farm census (Jarðabók) (Magnússon and Vídalín 1913-1990), undertaken between 1706 and 1714 on behalf of the Danish colonial government. This census provides information on farm values, ownership, the numbers and types of livestock, and any additional farm resources and their condition (such as fishing rights). This census can be cross-referenced with the 1703 land registry (Vésteinsson, *pers. comm.*). The medieval law code Grágás (Dennis *et al*. 2000), which was used as the legal framework for many aspects of rural life into the 20th century, provides insight into the structure of Icelandic agriculture and the operation of communal institutions and resources.



LANDNÁM TEPHRA LAYER

LANDNÁM TEPHRA LAYER

Figure 1-7: Pollen diagram showing change in the pre- and post-Landnám vegetation composition (example from Skálholt, south Iceland from Einarsson (1963))

The pre-modern Icelandic economic system was almost wholly dependent upon livestock farming, as fishing did not develop into an intensive economic activity until the early nineteenth century (hampered by social and political factors (Eggertsson 1996) and a lack of construction materials). Although cattle were the main livestock kept in the early centuries of settlement (Amorosi 1992), the focus shifted to sheep from the thirteenth century onwards, possibly because they require less winter hay feeding (Sveinbjarnardóttir 1992) (hay production became more difficult as the climate started to deteriorate). Cattle, mainly dairy with some beef, were still kept, as were horses for transport, and some goats. Pigs seem to disappear from the zooarchaeological record early in Icelandic history (McGovern *et al.* 1988). The wool and homespun cloth produced from sheep were the main cash product (Byock 2001), but dairy production was also a vital part of the economy, both for subsistence and for the payment of rents and tithes. Even in the eighteenth century, at least a proportion of the rent on the majority of tenant farms was being paid in butter (Magnússon and Vídalín 1913-1990).

Icelandic pastoral agriculture was based upon lowland farms, which consisted of the farm buildings and homefield (called tún, töðuvöllr or ‘manured field’ in Grágás) and meadowland, or outfield grassland, which was used for hay and limited grazing. Although there might be several households with separate livestock within the same farm (as is evident from pre-modern farm surveys), each farm estate was discrete. In addition to the homefields and outfields, there was extensive pastureland, or rangeland, which was used for summer grazing. Rangeland could be privately or communally owned, in which case grazing was closely regulated. Regulations on usage also applied to other communal resources such as woodland, fishing, driftwood and bird nesting areas.

The following information is taken from Aðalsteinsson (1990). The Icelandic agricultural system is similar to that of other Norse-settled areas of the North Atlantic (Borchgrevnik 1977; Amorosi *et al*. 1997). The agricultural year split into two main seasons, summer and winter. Lambing occurred in May, and the lambs were usually separated from their mothers in June and driven to the highland pastures with the wethers, yearlings and barren ewes. These sheep were left to freely graze during the summer, before being rounded up and brought back to the lowlands in mid-September.

The lowland pastures and meadows were used for milk cows and ewes, which produced milk and other dairy produce (which was used both for farm subsistence and as a measure of exchange). These livestock were either kept close to the farmstead or taken to shielings where there were particularly good pastures. The use of shielings or *sels* seems to have varied considerably between districts and over time (Sveinbjarnardóttir 1990). Little is mentioned about the management of horses and non-dairy cattle in the summer, but it seems likely that the cattle and at least those horses required for transport would have remained on the lowlands close to the farmsteads.

Hay production in summer was one of the most important times in the agricultural cycle. Hay was essential to the ongoing survival of the agricultural livestock, and hence to the survival of the farm household, as it ensured that the cattle survived in milking condition throughout the winter months. The hayfield, or tún, was the only area of the farm that was regularly fertilised, and produced hay of relatively high quality that was used for feeding the cattle over the winter. The first hay harvest usually took place late in the period of rapid grass growth, which equates to early July in typical circumstances. If conditions were favourable a second hay cutting was sometimes possible in August. Hay of poorer quality would be harvested from suitable areas in the outfield on a two to three year cycle (Aðalsteinsson 1990). The labour involved in this harvest was considerable:

> ‘In northern Iceland, in the steep valleys of inland Skagafjörður, strings of ponies would be taken up onto the high plateaux to bring back hay harvested from any available wild stands... In the south of Iceland, in Öræfi, lush growths of *Carex lyngbyei* were harvested by men wading waist-deep in water’ Amorosi *et al*. (1998): 46.

The autumn roundup of stock on the highland pastures took place at the end of September, and was a collaborative effort between the farmers in the district. It could take up to a week or ten days to round up all the livestock from the rangeland, depending upon the size of the common grazing area. This roundup was followed by the autumn slaughter: undertaken to provide the household with meat during the cold months and to ensure a balance between the available fodder and the numbers of animals that were to be kept through the winter. This balance had to be carefully calculated to ensure the survival of the remaining livestock and of the farming enterprise to the following spring.

> ‘Farmers had to balance the winter fodder needs of currently mature stock, immature animals needed for replacement and herd expansion, human meat requirements and dairy provisioning needs, pasture productivity of the previous

> summer growing season, and the estimated, but still unknown duration of the winter feeding season.' (Amorosi *et al*. 1998).

The dairy cattle were housed in winter and fed hay until spring. The sheep generally grazed the outfield and were provided with shelter at night. Any remaining fodder was mainly kept for the replacement lambs, and sometimes the ewes. The wethers generally required little in the way of extra feeding except in very poor weather. Winter shepherding was used in some areas (Dýrmundsson, *pers. comm.*) to drive the sheep to areas with little snow cover for grazing. Farms with beach access could also feed their stock on seaweed, saving their hay supplies (Hallson 1964). It was possible to stockpile hay for use in cold years to ensure the survival of the livestock, but due to a tradition of communal support, there is evidence that farmers deliberately avoided such a strategy, and trusted to luck and winter grazing to carry them through a bad winter (Eggertsson 1998).

Arable cultivation did not last beyond the 14th century in Iceland, and even before then was confined to the southern part of the country (Sveinbjarnardóttir 1992; Byock 1993; Smith 1995). Thereafter, all grain and flour had to be imported. Edible lichen (Iceland moss, *fjallagrös*) was sometimes used in place of ground meal, as were the seeds of lyme-grass (*Leymus arenarius*) (Guðmundsson 1996). Wild resources (marine and fresh-water fish, birds, eggs, berries and plants such as *Angelica*) were also widely used for subsistence (Amorosi *et al*. 1997; Lucas 1999).

1.3.3 Indications of land degradation in Iceland

Soil and pollen records indicate that environmental conditions in Iceland were generally stable through most of the Holocene, the ecosystem having developed without the impact of large herbivores (Einarsson 1963; Thorsteinsson 1986; Hallsdóttir 1987;

Thorsteinsson and Arnalds 1992). The vegetation must have been resilient and well able to cope with climatic change and periodic volcanic eruptions, as erosion rates were low at all elevations (less than 0.5 mm/year at the centennial scale) (Dugmore and Buckland 1991). However, even during periods when the climate was most favourable and environmental conditions were stable it is unlikely that more than 65% of the country was vegetated. Areas at high elevations and/or near the glacial margins have naturally sparse vegetation cover, due to freely drained soils and a short growing season (Þorarinsson 1979b; Forbes and Jeffries 1999). The proximity of the active volcanic areas also adversely affects vegetation growth, either through the direct deposition of tephra or lava, or by eruption-induced landslides or flooding.

Vegetation degradation in Iceland has been more complex than a simple reduction in area. The overall biomass production also decreased as grasses, sedges and rushes replaced tree species and herbs. In general the botanical productivity and condition of much of the vegetation today is poorer than its climatic potential (Thorsteinsson 1986). Regeneration of the vegetation after erosion is hampered because, in addition to the removal of vegetation cover, the nutrient status of the soil is degraded, with ‘a marked decline in the soil surface layer of organic matter, nitrogen content, exchangeable cations K, Na, Ca, Mg and of cation exchange capacity’ (Thorsteinsson and Arnalds 1992): 112).

Evidence for this degradation may be gathered from a variety of sources. Qualitative sources, such as the 1706-1714 farm census (Magnússon and Vídalín 1913-1990) include records of pasture and even entire farms being lost to erosive processes, such as in the Markarfljót river area of southern Iceland (Sveinbjarnardóttir 1992). There is also archaeological and place name evidence for farms and vegetation in areas that are now almost entirely barren (Sveinbjarnardóttir 1992; Kristinsson 1995), such as the abandoned farmsteads of Sveigakot and Hrísheimur (*hrís* being one of the names for dwarf birch) in Mývatn hreppur. Quantitative evidence is supplied by pollen analysis and tephrochronology (chronological correlation of sediment deposition using volcanic ash layers). Tephrochronological analysis indicates substantial increases in the rate of deposition of aeolian-andic materials over the past thousand years from less than 0.5 mm/year before Landnám to 2.2 – 5 mm/year or more post-Landnám (Þorarinsson 1961a; Guðbergsson 1975; Haraldsson 1981; Dugmore and Buckland 1991; Dugmore and Erskine 1994; Ólafsdóttir and Guðmundsson 2002). Micromorphological analysis of sediment accumulations can distinguish between local and regional sediment inputs, identifying changes in rates and processes of sediment deposition in the past (see for example Simpson *et al*. (in press)). Pollen analysis indicates vegetation change to less productive communities (for example from woodland to grassland) and an increase in species associated with disturbed landscapes (e.g. *Rumex* sp.) (Einarsson 1963; Hallsdóttir 1987).

Much of this degradation has been blamed upon direct and indirect human impacts, principally over-grazing and deforestation, upon a highly sensitive landscape, coupled with an agriculturally marginal climate and frequent volcanic events. Research has elucidated the physical processes behind land degradation in Iceland (discussed in section 1.4), but despite discussion of the nature of anthropogenic impacts (section 1.6) few attempts have been made to quantify their contribution (Simpson *et al*. 2001).

Iceland stands as an extreme example of human-induced land degradation but is also a highly suitable study area for its further investigation. The country is relatively simple and homogenous in terms of culture, agricultural system and environmental influences. It is possible to unravel the human component of the land degradation over a long, but bounded, time-scale, since human settlement only happened comparatively recently (c. 874 AD). Excellent historical documentation and a well-developed archaeological record provide information on the socio-economic environment and management practices in the past. Detailed multi-disciplinary environmental data sets, which can be correlated using tephrochronology, allow environmental reconstruction in both the historic and pre-historic period.

Research in this area will also contribute to the regional synthesis of human-environmental interactions in the North Atlantic. Since the 1970s Iceland has been one of the foci of multi-disciplinary investigations into the impact of the Norse settlers as they spread across the North Atlantic between the 7th and 11th centuries AD. The Norse dispersed from western Scandinavia to the western and northern isles of Scotland, the Faroes, Iceland, Greenland, and eventually (and briefly) to the western seaboard of Canada. It is now possible to compare the Norse impact upon the landscape both within and between countries, and to examine ideas of historical contingency and the interaction between landscape sensitivity and human interference (McGovern *et al.* 1988; Amorosi *et al.* 1997; Vésteinsson *et al.* 2002).

1.4 The immediate causes and process of degradation

Land degradation includes deterioration in the condition of the vegetation and the soil as well as its removal. In Iceland livestock grazing has been implicated in this deterioration because vegetation that has been overgrazed is less resilient and less able to cope with adverse climatic fluctuations and other shocks (Arnalds 1984). Grazing of vegetation affects biomass production in the short term because it removes nutrients and energy, altering normal plant growth and development, although most plants can withstand a certain amount of grazing without ill effects. In the long term grazing can alter the species composition of the vegetation community as grazed plants are out-competed by those that have remained ungrazed. Overgrazing reduces plant vigour above- and below-ground, initiating a feedback by creating favourable conditions for increased cryoturbation and solifluction processes (Morgan 1985; Evans 1998). Weakened root systems are less able to bind the soil, and the reduction in organic matter input to the soil alters the soil structure and water retaining capacity. Repeated grazing of young and/or palatable plants can cause a shift in the vegetation community composition and an increase in the area of bare ground. The new vegetation community is likely to be less productive for grazing, and more susceptible to further degradation. Once the vegetation cover has been breached a relatively low intensity of grazing can maintain exposure, and climatic factors may play a more important part in the propagation of erosion (Dugmore and Simpson, in press).

Most of the Icelandic erosion forms begin their existence as isolated bare spots (<1m in diameter) in otherwise fully vegetated areas (Table 1-1). They may be induced by many processes but frost action, livestock trampling and solifluction are most common. Erosion spots can form in a relatively short space of time, but take a long time to heal. They can form on flat or sloping ground, but the consequences are more serious if spots develop on hillsides as running water can then remove the exposed soil (Arnalds *et al.* 2001). On flat ground the development of erosion spots is associated with the presence of thúfur, or vegetation covered soil hummocks formed by frost heave (Webb 1972).

The tops of thúfur are sensitive to erosion because they are comparatively drier, and more exposed than the hollows. In winter the thúfur tops may emerge above the snow cover, and so are vulnerable to winter grazing, frost action and abrasive winds (Ólafsdóttir and Guðmundsson 2002). The formation of erosion spots is most unlikely where there is a dense cover of healthy vegetation, and they are rarely found in marshy or wooded areas (Arnalds *et al*. 2001).

Table 1-1: Model of the escarpment erosion process in Iceland (Arnalds 1990)

Stage of erosion	Description
1. Healthy vegetation	Soil surface is protected from erosion by healthy vegetation cover (Figure 1-8)
2. Isolated spots	Vegetation disturbance exposes isolated spots of bare soil (Figure 1-9)
3. Escarpments and isolated spots	Spots enlarge and/or increase in density until they coalesce to the initial stages of erosion escarpments (rofabard) (Figure 1-10)
4. Escarpments	Rates of erosion increase as the length of exposed perimeter increases (Figure 1-11)
5. Vegetation remnants	Area of barren ground exceeds area of vegetation remnants and the rate of erosion declines (Figure 1-12)
6. Barren surface	Eventually only the unvegetated barren surface remains (Figure 1-13)

Once the soil is exposed wind, water and frost action may all operate to enlarge the area of bare ground. Rills can form as the erosion spots grow, which may then develop into gullies (Figure 1-8) and/or erosion escarpments (rofabards). If sufficient soil surface becomes exposed, wind erosion can remove the finer soil fraction (silt, fine sand and organic material), leaving the coarser sands behind. Over time the productivity and

Figure 1-8: Escarpment erosion stage 1: Healthy vegetation cover (note the gully erosion to the right of the picture, which develops through a different process)

Figure 1-9: Escarpment erosion stage 2: Erosion spots developing in vegetation cover

Figure 1-10: Escarpment erosion stage 3: Initial stages of erosion escarpment (rofabard) development as isolated bare spots coalesce

Figure 1-11: Escarpment erosion stage 4: Erosion escarpments

Figure 1-12: Escarpment erosion stage 5: Isolated patches of vegetation remain as the rate of erosion slows

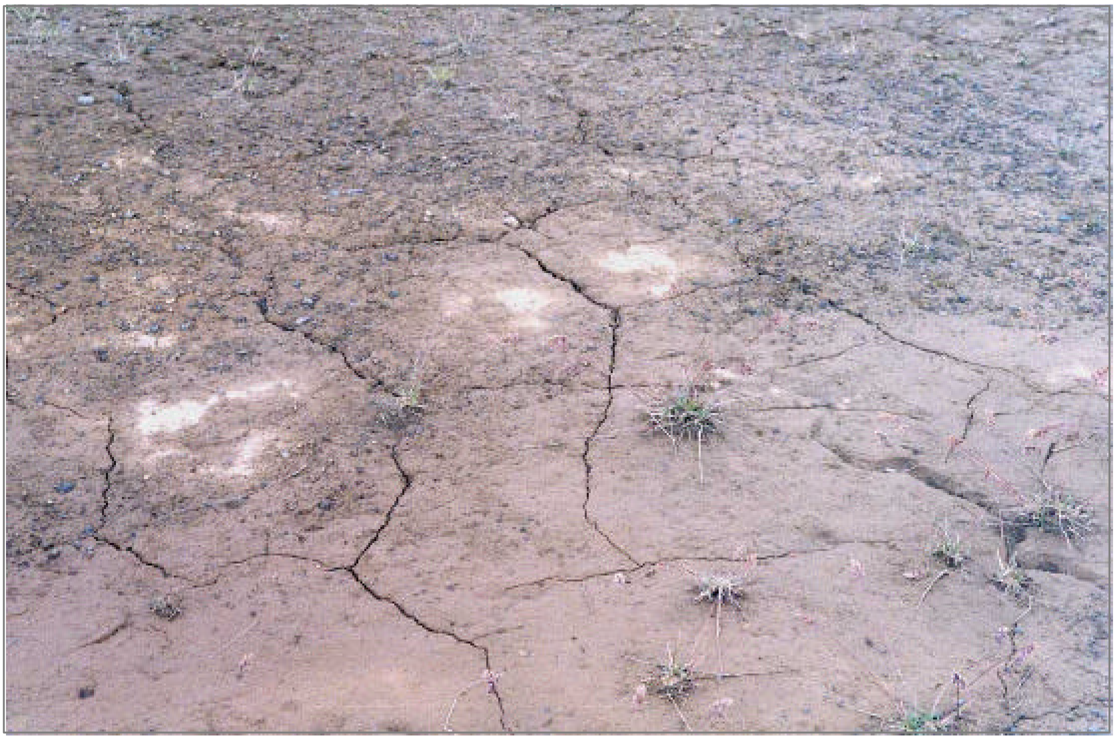


Figure 1-13: Escarpment erosion stage 6: A virtually barren surface remains

water retentiveness of the soil declines and plant growth is minimised, increasing vulnerability to further erosion. In extreme situations the remaining coarse sand begins to drift, forming advancing sand fronts, which encroach on and smother 'healthy' vegetated areas. In severe cases of erosion the entire profile may be removed, leaving only a bare gravel or lava surface (the landscape in Figure 2-12 is an example of this). The most severe erosion losses have occurred in the highlands in the active volcanic regions, where there is an ample supply of loose material that can be used in wind erosion (Arnalds 1990). [For further information and photographic examples refer to the Soil Conservation Service website at www.rala.is/.]

Other processes of land degradation may be significant at a more local scale. Erosion may be initiated by landslides and the mass movement of rock and/or scree, which open up vegetated areas to the erosive action of wind and water. Such occurrences are frequent, and are often recorded in historical documents: 'The hayfield is eroded by wind, sand, and scree brought down by the melting of the snow.' (1703 land register) and 'All the mountain slopes greatly spoiled by landslides and rockfalls from the mountain' (1730 land register) (examples taken from Friðriksson 1972). Glacier movement can destroy vegetation: either directly, by glacier expansion and increased meltwater flow, or indirectly by local cooling of the microclimate. The removal of vegetation cover and increased sediment load can precipitate river channel alteration, increasing channel erosion, the formation of barren gravel flats and flooding, as has occurred with the Markarfljót in southern Iceland (Haraldsson 1981). Coastal areas in the south are susceptible to sand dune encroachment (Runolfsson 1978) and coastal erosion, and farms have been lost to such processes (such as Stóraborg (Sveinbjarnardóttir 1992)). Degradation associated with volcanic activity, through the actions of lava flows, tephra falls, gases, earthquakes, mudflows and water-floods (including jökulhlaups) (Þorarinsson 1979c) can have a significant impact on local areas in the south and centre of Iceland. Between 30 and 40 volcanoes have been active in Iceland since the Norse Settlement (Þorarinsson 1979a). There are historical records of eruptions, and their associated tephra falls, being responsible for farm abandonment (see section 1.3.1.2 for examples). Damage caused by tephra can be effected directly, through abrasion and burial of vegetation, and indirectly through the transportation of noxious volcanic gases and compounds, which can wither vegetation and kill livestock. Tephra falls can also initiate large-scale erosion, by providing material for advancing erosion fronts; by choking streams and rivers, thereby causing bank erosion and the formation of new channels; and by overloading steep slopes, causing mass movement (Sheets and Grayson 1979). Tephra can also have a positive impact, as it contributes nutrients, such as phosphate, to the soil, and the coarse tephra grains assist soil drainage.

Erosive processes may operate simultaneously and vary in importance according to the season and soil properties, and frequently the processes that initiate erosion are not the same ones that maintain and continue it. The Soil Conservation Service of Iceland classifies erosion by its form in the landscape (Table 1-2), rather than by erosive process, of which several may be active (Arnalds *et al*. 2001).

1.5 Alternative explanations of land degradation in Iceland

Tephrochronological evidence indicates that accelerated soil erosion at higher elevations set in soon after 900AD (Þorarinsson 1944; Þorarinsson 1961a; Dugmore and Buckland 1991; Guðbergsson 1996), which corresponds with the accepted period of human colonisation (Landnám) in Iceland. Evidence from southern Iceland indicates

Table 1-2: Erosion scale used by the Soil Conservation Service to classify erosion forms in Iceland, showing the size of affected areas (from Arnalds *et al*. 2001))

Erosion form	Severity [*]	Area affected (km^2)
Rofabards	1 - 5	8,800
Encroaching sand	5	100
Erosion spots	1 - 2	28,200
Erosion spots on slopes / Solifluction	2 - 3	17,700
Gullies	1 - 3	4,700
Landslides	1 - 2	700
Melur (gravel-till)	3	25,000
Sand and pumice	5	4,800
Scree	4 - 5	5,000
Lava	1	2,000
Sandy *melur*	4	13,700
Sandy lava	3 - 5	4,900
Brown soil remnants	4 - 5	1,000

[*] **Severity scale:- 1: Little erosion; 2: Slight erosion; 3: Considerable erosion; 4: Severe erosion; 5: Extremely severe erosion.**

that accelerated erosion rates first took hold at higher elevations, and although forest clearance led to increased soil mobility early on in the settlement period, lowland areas remained relatively stable well into the medieval period (Dugmore and Buckland 1991; Dugmore and Erskine 1994). The onset of severe soil erosion in most of Iceland post-dates the medieval period (delineated by a Hekla tephra layer in 1510 AD), and soil accumulation rates in areas of deposition have accelerated into the modern period, inferring accelerating erosion.

Volcanic activity and the deterioration of the climate during the Middle Ages and Early Modern period have been blamed for the extensive losses of vegetation and soil, but this has been increasingly disputed over the past few decades. As Þorarinsson (1961a) was the first to point out, further substantiated by work by Dugmore and Buckland (1991), the Icelandic landscape was also subject to volcanic eruptions and extremes of climate before settlement, yet there is no evidence of extensive erosion prior to the arrival of the Norse settlers in the ninth century. Recently Ólafsdóttir and Guðmundsson (2002) have reintroduced the idea of climate being the primary factor in degradation; however, there have been greater losses of vegetation and soil cover in the historic period than can be explained by climatic impact alone (Ólafsdóttir *et al*. 2001).

Initially anthropogenic explanations of land degradation described the pre-human landscape as a highly dynamic but stable system, almost a sub-arctic Eden, which was unbalanced by the introduction of agriculture and livestock (Friðriksson 1978). Þorarinsson (1944; 1961a) was the first to identify the increase in the soil accumulation rate after the arrival of the Norse settlers, and to attribute this increase (with an equivalent inferred increase in erosion) to human impact. Climatic deterioration during the period 1500-1900 AD may have intensified erosion but did not instigate it. The changes in post-Landnám vegetation composition (section 1.3.1.3) bolster this 'human impact' argument.

A more complex picture of landscape change and degradation emerged with subsequent research. The development of detailed, long-term sediment, tephrochronological and pollen data sets enabled researchers to examine the impact of human settlement more effectively and compare historic and pre-historic records (for example: Haraldsson 1981; Hallsdóttir 1987; Dugmore *et al*. 2000; Ólafsdóttir *et al*. 2001). Instances of substantial degradation phases were discovered in the pre-historic sediment record

(Ólafsdóttir and Guðmundsson 2002), with climatic deterioration and extreme volcanic events implicated as triggering factors. None of these Holocene soil erosion phases operated on the same catastrophic scale as that found in the historic period. An investigation in north east Iceland by Ólafsdóttir *et al.* (2001) concluded that anthropogenic impacts reinforced climatically-induced erosion and landscape change, and that these impacts pushed the ecosystem beyond its 'threshold of natural recovery' (Ólafsdóttir and Guðmundsson 2002). This conclusion is not always supported by the evidence from other areas: for example, on the Hofstaðir estate within the same region, after a period of post-Landnám accelerated sediment accumulation, rates of accumulation declined in comparison to the regional average, despite climatic deterioration (Simpson *et al.*, in press), and there are similar histories elsewhere in northern Iceland (Guðbergsson 1996).

In terms of the spatial pattern of soil erosion, topography is a significant influence. A simple altitudinal model of landscape instability, developed by Dugmore and Buckland (1991) describes a 'wave of erosion' (Buckland *et al.* 1991) moving from the uplands to the lowlands during the medieval period. The earliest human impact triggered episodes of acute soil erosion on the thin soils in the marginal upland areas. Over time there was an intensification and concentration of this impact, with instability spreading downhill into less marginal areas. By 1500 AD, extensive upland areas were eroded, increasing grazing pressure on the lowland vegetation. The climate had also deteriorated, reducing the length of the growing season, and diminishing the productivity of the remaining vegetation. Breaching of the vegetation cover in the lowlands allowed the development of major sediment sources on the deeper lowland soils. This is reflected in the acceleration of sediment accumulation rates and, by inference, erosion into modern times (Dugmore and Erskine 1994; Ólafsdóttir and Guðmundsson 2002).

Simpson *et al.* (2001) refined this altitudinal model and highlighted the difference between factors that trigger erosion and factors that maintain and propagate erosion (Figure 1-14). The triggering of erosion depends upon the opening up of the vegetation cover. This may be accomplished by catastrophic events (storms, flooding, volcanic activity) or by human impact (grazing, burning). Factors that maintain erosion prevent the breaches from healing via vegetation regrowth. These include continued grazing; low temperatures; cryoturbation; abrasion by wind blown sand; desiccation of the surface layer; the lack of a seed bank or seed source; low biological activity in the soil; low nutrient status within the root zone; and leaching of nutrients (Arnalds *et al.*, 1987). The sensitivity of the landscape to trigger factors is affected by its previous history: for example, bad management practices or a short growing season in previous years will lower vegetation productivity and increase sensitivity to overgrazing. Dugmore and Simpson (in press) stressed the importance of human interference in historic soil erosion:

> ‘We would see land management, through both its long term impacts and response to short term environmental change, as playing the crucial role in determining the timing and location of vegetation cover disruption, and the triggering of soil erosion. But, crucially, sensitivity to this critical threshold may be altered by both long and short-term climatic changes.’(Dugmore and Simpson, in press)

Several investigators (Gerrard 1991; Amorosi et al. 1997; Simpson et al. 2001) have discussed this idea of a critical threshold, which was breached by the introduction of people and their livestock. The ecologically marginal position of Iceland leaves the country sensitive to minor shifts in climate, but it seems to have been the arrival of the Norse settlers that finally pushed the system beyond the point of no return.

In conclusion, land degradation in Iceland is highly dynamic, both before and after the arrival of human settlers. Although the factors contributing to degradation are well known, their impact in different localities can vary. While different researchers have put different emphasis on the various factors, all seem to agree that the soil erosion and vegetation degradation of the historic period is unmatched in magnitude and spatial extent in Icelandic prehistory. The catastrophic nature of this degradation is primarily due to human impact, whether it instigated degradation or pushed it beyond a threshold of recovery. There have been three strands of research into anthropogenic impacts on the Icelandic landscape. The first attributes the majority of the devastation to overgrazing, implicitly assuming a ‘tragedy of the commons’ scenario of overstocking (Hardin 1968). The second strand is concerned with the impact of the first settlers and the idea of ‘thresholds’ in the landscape. The third strand is one of ‘historical ecology’ (Crumley 1994), and concentrates on the more indirect human impacts, particularly the role of the socio-economic situation in perpetuating bad practices and worsening the situation.

1.6 Research into the anthropogenic influence on land degradation in Iceland

The anthropogenic influence upon the Icelandic landscape dates from the arrival of the first settlers in c. 874 AD. The main period of settlement in Iceland took place in the late ninth and early tenth centuries. After an initial period of exploration, permanent settlers arrived from the western coast of Norway and the Western and Northern Isles of

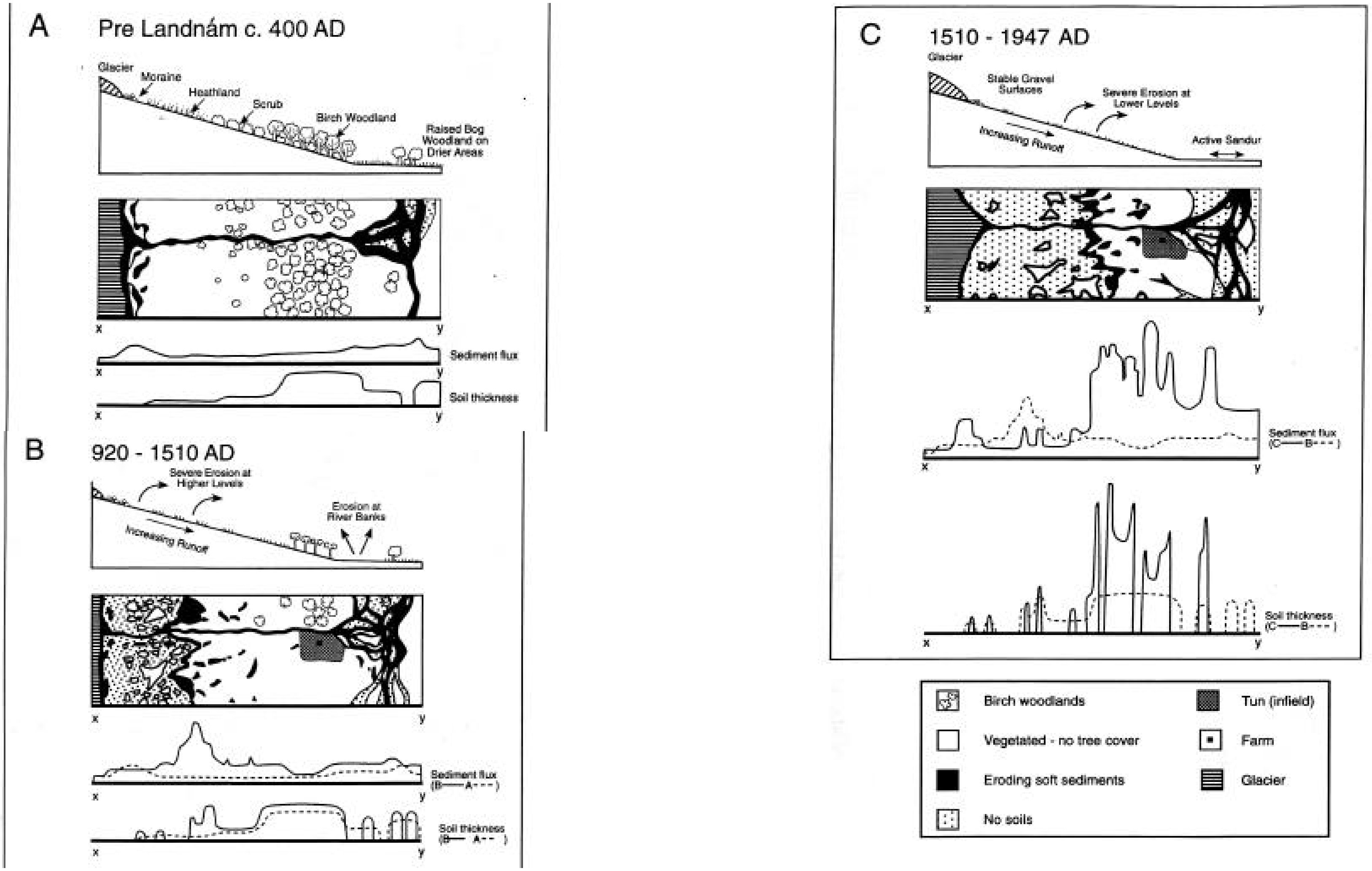


Figure 1-14: Altitudinal model of land degradation (Dugmore and Simpson, in press)

Scotland. The beginning of this settlement period, or Landnám (land-taking) can be dated using the 871 ± 2 AD tephra layer (Grövold *et al*. 1995), as the earliest signs of human occupation are found immediately above this tephra layer (Vésteinsson 1998).

1.6.1 The 'Tragedy of the Commons'

The 'tragedy of the commons' (Hardin 1968) has been implicitly used as the template for explanations of land degradation in Iceland, as a result of domestic livestock overgrazing of the summer mountain pastures (Þorarinsson 1961b; Thorsteinsson *et al*. 1971; Friðriksson 1972; Arnalds *et al*. 1987). These mountain pastures functioned as common grazing areas, known as *afréttir*, used by the farmers in a single agricultural community, or *hreppur*. It was economically logical for farmers to share a common grazing area, rather than keep individual summer pastures, because of the sparse and scattered nature of the upland vegetation and the high transactional costs of managing extensive pastures (Eggertsson 1992).

Although the Icelandic landscape has been described as 'ovigenic' (created by sheep) (Dugmore and Buckland 1991) there is strong evidence that the 'tragedy of the commons' does not provide an adequate explanation in the case of Iceland. Ostrom (1990) proposed eight conditions that are fulfilled by long-enduring common-resource systems (Table 1-3). These conditions seem to have been met in the Icelandic common grazing system, according to the legal code Grágás (Eggertsson 1992; Dennis *et al*. 2000). Access to the afréttur (*sing*.) was strictly controlled, with a system of fines for misuse. Grazing was only allowed on the high pastures from the eighth week of summer (June 4-10) to mid-September (12th-18th), although communities were subsequently allowed to establish the exact dates on the basis of local circumstances. There were also controls on the number of sheep that could be grazed, which may indicate an awareness of the problems of overgrazing in the Icelanders. The calculation of livestock quotas aimed at a fine balance between maximising livestock capacity and minimising grazing damage:

> ‘they are to calculate quotas of such a size that the animals, as they think, will not get fatter even if there are fewer of them on that communal pasture, but they think it is fully stocked all the same’ (Dennis *et al.* 2000: 133).

Similar controls on common grazing in the medieval period can be found elsewhere, for example in the Faroe Islands (West 1972), in northern England (Winchester 2000), in the Atlas mountains of Morocco (Ilahaine 1999), and in Switzerland (Netting 1996), where such systems were successful in ensuring sustainable use of the common resource.

Eggertsson’s analysis of the Icelandic afréttir system concludes that the afréttir were relatively efficient, with the capacity to satisfactorily resolve the commons ‘tragedy’. Recent research by Simpson *et al.* (2001) has also concluded that the ‘tragedy of the commons’ is an inadequate explanation for Icelandic land degradation. Their use of a grazing model to explore different management scenarios raised the possibility that timing of grazing played a crucial role, rather than absolute numbers of sheep. Failure to harvest sufficient hay to feed livestock in the event of a hard winter would have resulted in large numbers of deaths from starvation but also an incentive to start grazing stock before the grass had fully recovered from the winter. The model suggests that there was in fact sufficient biomass available to produce hay to feed livestock throughout the winter, but farmers did not follow this strategy. This was possibly due to labour and storage difficulties but there is also evidence that the Icelanders deliberately followed a high-risk strategy with regards to the stockpiling of hay to tide them over a bad winter, as hay surpluses could be annexed by other farmers in the hreppur to support their own livestock (Eggertsson 1998).

Table 1-3: Elements of long-enduring common-pool resource (CPR) systems (from Ostrom(1990)).

1. Clearly defined boundaries
   The boundaries and the users of the CPR are clearly defined.
2. Compatibility between usage rules, user-obligations and local conditions
   Rules restricting the use of the CPR are related to local conditions and to user obligations requiring labour, material and/or money.
3. Collective-choice arrangements
   Most individuals affected by the rules governing the CPR can participate in modifying these rules
4. Monitoring
   Monitors, who actively audit CPR conditions and user behaviour, are accountable to the users or are the users.
5. Graduated sanctions
   Users who violate CPR rules are given graduated sanctions (depending on the seriousness and context of the offence) by other users, by officials accountable to these users, or both
6. Conflict-resolution mechanisms
   Conflicts are resolved rapidly and in the local area
7. Minimal external interference
   Users are allowed to control the CPR without interference from external governmental authorities

1.6.2 The impact of the first settlers

According to the second anthropogenic explanation of land degradation in Iceland the first settlers altered the Icelandic landscape in such a way that thresholds of recovery were breached and the onset of degradation was inevitable. The Norse settlers of the ninth century were the first permanent human inhabitants of Iceland, barring a few Irish anchorites. Zooarchaeological data from the Settlement period demonstrates that the first Norse settlers brought a mixture of herbivorous species with them: cattle, sheep, goats, horses and pigs (Amorosi et al. 1997). It is thought that the joint presence and different grazing and browsing habits of these species had a rapid and comprehensive impact on the landscape: shifting the ground cover towards grass-sedge communities which produce the most useful pasture for grazing, effectively raising the agricultural productivity of the landscape from the settlers’ perspective (McGovern *et al.* 1988).

The removal of the birch forests is the largest environmental impact attributed to the settlers. The greater part of this removal took place in the centuries immediately following Landnám (Eysteinsson and Blöndal 2000). The reduction and prevention of regeneration of woodland by grazing was most significant but deliberate clearance, to make way for farmsteads and hayfields, also took place. The woodlands also provided a source of fuel, construction materials and the means to manufacture charcoal, necessary for the production of bog iron. It is possible that woods were cleared by burning, either deliberately or accidentally: this is thought to have occurred during the Norse settlement of Greenland (McGovern *et al.* 1988). What would not have been appreciated by the settlers is the role of the woodland as a stabiliser and protector of the fragile soil. The birch woodland promoted an even snow cover, which protected the ground vegetation from frost and abrasive winds during the winter (Thorsteinsson and Arnalds 1992). The open vegetation that replaced the birch woodland allowed greater overland flow of water, creating the opportunities for gullies to develop. Wind-borne sediment and tephra could also travel greater distances in an open landscape, contributing to vegetation damage and soil erosion.

Some researchers (Eggertsson 1992) are of the opinion that catastrophic erosion and land degradation in Iceland was unavoidable once deforestation had taken place, and that deforestation was ‘an unavoidable consequence of the only type of agriculture that was practicable in the country at that time’ (Eggertsson 1992): 437. However, the location and timing of the onset of soil erosion refute this rather fatalistic viewpoint. Work by Dugmore *et al.* (2000) established that five responses to settlement are visible in the sedimentary record, so the impact of the first settlers was not a uniform one. What is certain is that the changes wrought in the landscape set the scene for future degradation. As stated by Amorosi *et al.* (1997) in reference to Cronon: “Unknown to themselves, the first few generations were drawing down an ‘environmental capital’… that would not be available to later settlers.” (p 509)

Another North Atlantic island that was also settled by the Norse in the 7th-10th centuries and suffered extensive land degradation in consequence was Greenland (McGovern *et al.* 1988). The situation in Greenland is particularly analogous to the Icelandic situation, and gives further evidence of the role of the settlers in instigating erosion. The Norse colony in Southern Greenland existed from the late tenth century AD to the fifteenth century. Prior to settlement there had been a period of several thousand years where soil conditions were stable, with minimal erosion rates and well-established vegetation cover. Some time soon after settlement, erosion rates started to accelerate, and the associated land degradation may have contributed to the collapse of the Norse colony. Following the extinction of the Norse settlement (Barlow *et al.* 1997) erosion rates decreased and the vegetation started a period of recovery and stabilisation (Jacobsen 1987). This period is interrupted at the beginning of the twentieth century, when southern Greenland was resettled and grazing animals were re-introduced (Fredskild 1992). A combination of climatic, topographic and grazing interactions have been held responsible for historic soil erosion in Greenland (Jacobsen 1987), but, as in Iceland, it is apparent that the explanation is more complicated than simply too many sheep (Keller 1990).

1.6.3 An historical ecology perspective

Historical ecology is ‘the study of past ecosystems by charting the changes in landscapes over time’, where landscapes are the ‘material manifestation of the relation between humans and the environment’ (Crumley 1994): 6. An historical ecological approach integrates knowledge of social and economic change with that of physical environmental change to give an holistic perspective on land degradation over time. Of relevance are issues of land ownership, settlement patterns, population change, technological innovation and human perceptions of farming and the landscape.

After a rapid period of settlement (c. 870 – 930 AD), a pattern emerged of large and medium-sized independent farms, with good access to terrestrial and marine resources, interspersed with smaller, dependent farmsteads in less favourable locations (Vésteinsson 1998). The pattern of landownership started to shift at the end of the 12th century with the breakdown of the Icelandic Free State and submission to Norwegian (in c. 1280 AD), and later Danish, rule (from 1380 AD to complete independence in 1943 AD). Ownership of land was concentrated into the hands of a smaller and smaller group and the numbers of freeholders declined (as indicated by falling numbers of land-owning farmers who were eligible to participate in the legislative process (Miller 1990)). Rates of tenancy increased, to the extent that by 1695 the majority of farmers were tenants (95%) (Lárusson 1967), on land that was owned by private individuals, the church or the Crown (Jónsson 1993) (respectively 52%, 31% and 16% of farms).

A large proportion of the surplus production of the farm was expended upon land rents, which were typically 4-5% of the farm's tax value. In addition to this, tenants were normally required to pay *leigukúgildi* (rented livestock to the value of one cow), as land was usually rented with livestock (Vésteinsson, *pers. comm.*). Tenants might also owe various obligations to their landlord, typically *dagslátta* (cutting of hay) and *mannslán* or *skipsáróðrarkröð* (serving on the landlord's fishing boat for part of the year). Contracts were fixed-rent, placing any risk of income failure with the tenant rather than the landowner, and inviting 'excessive use of unpriced inputs by the cultivator, particularly of valuable qualities of the soil' (Eggertsson 1998):13. Tenancies were usually short (1-2 years) and there was frequent movement of farmers between holdings, either due to the termination of the lease, or because tenants moved between farms according to personal circumstances. The nature of the tenancies, which placed the burden of farm maintenance and taxes upon the tenant rather than the landlord, encouraged tenants to invest in livestock and improve their economic situation by moving between farms, rather than invest in the agricultural improvement of the current farm (Jónsson 1993).

There was a policy of maximum usage, which is relevant to issues of land utilisation. Tenants were under an obligation to their landowner to fully utilise farm resources, such as hay fields, otherwise they could be punished for breach of contract and the tenancy might not be renewed. This policy was enshrined in law so that any farmers unable to exploit their lands fully were legally compelled to lease them to someone else (Dennis *et al.* 2000). The result of the tenancy system was to promote short-term profits over long-term sustainability, and to encourage over-intensive utilisation of land resources. This was not accompanied by a move towards more intensive production; in fact it seems that farming technology and knowledge actually declined during the medieval period (Hastrup 1990). This stagnation of technology might be due to the relative isolation of the country during the Middle Ages: divided from the rest of Europe by the treacherous seas of the North Atlantic, with outside contact tightly controlled by the colonial rulers. Development was also hampered by a lack of capital and of construction materials. The existing agricultural resources were utilised less effectively as time went on, as noted by several contemporary accounts in the 17th and 18th centuries (Hastrup 1990); for example the use of shielings declined and cattle were allowed to graze the hay meadows, reducing potential yields. With high tenant mobility and farm abandonment (Sveinbjarnardóttir 1992), issues of cultural knowledge come into play. An effect of this high turnover of farm households was the loss of local knowledge of past yields and responses, so that detrimental farming practices were perpetuated.

Several attempts were made by external reformers and administrators to change aspects of the farming system and avoid the regular bouts of agricultural failure and starvation (Jónsson 1993; Eggertsson 1998). The majority of these were unsuccessful, possibly because the reforms did not constitute an optimal strategy for farmers, or because they were not enforced properly or supported by the appropriate institutions.

1.6.4 Summary of anthropogenic impacts

All of these factors may have contributed to Icelandic land degradation. The human element has frequently been kept separate from past considerations of degradation, with the role of humans being to keep too many sheep and to chop down the forests. Little attention has been given to the reasons behind the over-exploitation. In particular the role of the land-owning and governing elite in the degradation of Iceland's environment has been ignored. They directly made, or influenced, many of the decisions to do with the utilisation of the country’s resources and their decisions could have far-reaching consequences. Their influence was by no means entirely negative, and it seems that in the early modern period attempts were made to modify some of the more detrimental farming practices.

In summary, land degradation in Iceland is the result of a number of processes and the effects are diverse, yet inter-related. There is a wide range of evidence from a number of different disciplines that catastrophic land degradation has taken place in Iceland over the last millennium. Environmental and documentary evidence sets the date of onset of this degradation soon after the arrival of the first Norse settlers and the introduction of their farming system and livestock. The anthropogenic impact on Iceland’s marginal landscape was intensified by a ‘thousand natural shocks’ in the form of volcanic activity, glacial and fluvial activity and climatic variation. The most evident form of degradation in Iceland is soil erosion, but loss of vegetation cover and productivity are also important, particularly from the point of view of human subsistence.

Although the ‘tragedy of the commons’ has been frequently used to explain the human causes of the devastation of the Icelandic landscape, a growing body of research indicates that it is more than a simple problem of livestock numbers, and that Hardin’s model does not hold for the Icelandic case. There were legal and social mechanisms in place to prevent the over-exploitation of pasture resources, which should have been effective if properly applied. Theories that the first few generations of settlers set in motion a chain of events that led to the devastation seen today are intriguing and merit more investigation. The evidence from soil profiling and tephrochronology is not wholly supportive, as some of the most significant erosion took place in more recent centuries. Maybe the concept of a landscape threshold that was exceeded by the early Icelanders should be modified to a series of such thresholds, the timing of which is linked with climatic or volcanic events. There is also a need for further research into the social and economic aspects of land degradation in Iceland, and the role of the land-owning elite in controlling access to and usage of land resources: the ‘why’ of land degradation.

1.7 The aims and hypotheses of the research project

The aim of the research is to define the relationship between patterns of vegetation degradation and seasonal resource utilisation by domestic livestock over space and time in Iceland in the pre-modern period. To achieve this aim requires the development of an historical grazing simulation model. The design, construction and testing of this model forms the key objective of the project. Analyses of historic grazing patterns are crucial to understanding the causes of overgrazing and the sensitivity of the landscape. The use of simulation modelling allows a cross-disciplinary approach integrating landscape ecology, environmental archaeology and history, making it possible to combine both spatial and temporal analysis. This approach will assess the characteristics of the pre-modern Icelandic agricultural system that are thought to have given rise to overgrazing and degradation. This will provide temporal depth to a present-day problem, as ‘a[n] historical perspective is indispensable… The mere fact that there are ‘lags’ between causation and consequence establishes the need for historical understanding.’ (Blaikie and Brookfield 1987: xxi.)

In this research project, the pre-modern period is taken to be the period of human settlement in Iceland prior to the introduction of modern farming methods in circa 1900 AD (Jónsson 1993). The earliest period of settlement (before 1000 AD) is excluded from consideration because both the natural and socio-economic environment were undergoing rapid change during that period: therefore it is not necessarily comparable with later periods. A single time span, the early part of the 18th century, has been selected from the pre-modern period for detailed investigation. The main reason for this choice is the availability of particularly rich historical information on farming for this time period (see section 1.3.2 for details). These information sources enable historical reconstruction of both the natural and socio-economic landscapes at a far greater level of detail and accuracy than is possible for other times in the pre-modern period. The chosen period is also on the cusp of a climatic downturn, when the country entered the coldest period of the ‘Little Ice Age’ (Grove 1988). Evidence of increased sediment mobility in the soil record indicates that land degradation increased during the 18th and 19th centuries, so the start of this period is of interest for investigating ideas of historical contingency and landscape sensitivity. The investigation of recent centuries is also most critical for tracing the development of present-day landscapes (Davidson and Simpson 1999).

Two hypotheses can be developed from the research aim, which will be used to demonstrate the application of the historical grazing simulation model. These hypotheses state that:

(1) Natural biomass production during the pre-modern period was sufficient to support the numbers of livestock indicated by historical data; and

(2) Alternative land management strategies could have maintained livestock numbers and vegetation cover, whilst avoiding extensive erosion and landscape degradation.

The methods used to investigate these hypotheses and achieve the research aim are described in Chapter 2.

Chapter 2: Research Design and Methodology

2.1 Introduction

The aim of the research is to explore the pastoral agricultural system and the relationship between patterns of vegetation degradation and seasonal resource utilisation over space and time in Iceland in the pre-modern period. This chapter will describe and discuss the methods that will be used to achieve this aim. Two regions of Iceland will act as study areas for the project; these are described in detail in the second half of the chapter.

The approach taken is based upon the principles of historical landscape ecology, in that ecological relationships and processes are established within a chronological framework (for example Kirch and Hunt, 1996; Dugmore *et al.* 2000; and papers in Butlin and Roberts, 1995). The environmental (in terms of vegetation cover, climate etc.) and human-perceived (in terms of land-use zones) landscape will be reconstructed for specific periods in the past, using all the available lines of evidence. Within these reconstructed landscapes, the range of possible grazing management strategies will be identified and evaluated, enabling testing of the research hypotheses.

The key factors under investigation are the amount and nutritional value of grazeable vegetation available and the numbers (and feed requirements) of the livestock which graze this vegetation. These factors can vary both spatially (across the landscape) and temporally (in different seasons of the year). They also interact, as the quantity of grazeable vegetation constrains the number of livestock that can be supported within a given area, and the level of grazing can affect the growth of vegetation in the future. Grazing management strategies must balance these factors, although the balance depends upon the goals of the grazier, whether they are the maximisation of livestock numbers or income, or the minimisation of land degradation or labour.

2.2 The potential for modelling

The investigation of past human impacts upon the physical environment requires the union of many lines of evidence from different disciplines (see for example Barlow *et al.* (1997)). The environmental processes and relationships involved can be complex: it is difficult to achieve full integration and to evaluate the precise contribution of physical and human factors to the outcome under investigation, in this case, land degradation. Models, whether conceptual or mathematical, are an extremely useful way of representing the linkages and interactions that make up a real-life system, which is generally too complex to mentally grasp as a whole. By representing the quantifiable linkages between the different environmental and socio-economic elements in the human-environmental system, mathematical models improve understanding of the system and the relative influence of each system element. They also stimulate further research by highlighting interesting areas for further investigation, identifying critical data gaps and generating hypotheses that are testable against evidence from archaeology, history and environmental disciplines (McGovern 1995).

The use of models in environmental research is not without hazard, as a model can only ever be a simplification of a real-life system. A good model must include the key system elements and relationships (Bart 1995; Deaton and Winebrake 2000), but it is not always clear what these are at the start of the modelling process. The process is an iterative one, and can thus be extremely consuming in terms of time and resources. There is also a risk of being overly deterministic, particularly when drawing conclusions from the results of modelling: environmental factors may constrain human actions, but they do not necessarily dictate them.

Previous research on environmental impacts on human society in the North Atlantic region has successfully made use of computer-based mathematical models (Simpson *et al.* 2001; Amorosi *et al.* 1998; Barlow *et al.* 1997; McGovern 1995). This region, and Iceland in particular, is an ideal location for the development of such integrative models as there are excellent environmental, archaeological and documentary data sets available, which can be cross-referenced against each other.

A research project on grazing management and landscape sensitivity in southern Iceland (Thomson 1997; Simpson *et al.* 2001) has acted as a pilot for the current project. Using a modified version of the Macaulay Institute's Hill Grazing Management Model (HGMM) (Armstrong *et al.* 1997a, 1997b) it was possible to model vegetation production and its consumption by livestock during the course of a year, and to assess the extent and timing of excessive grazing pressure. The results implicated land and livestock management rather than simple overstocking in the problems of overgrazing and land degradation in southern Iceland.

2.3 The case for a specific Icelandic grazing model

Despite its successful use in previous research the HGMM is not an ideal tool for detailed investigation of pre-modern farm management in its current form. It was designed to simulate hill-grazing systems in the UK, and was limited to ewes and lambs grazing dwarf shrub- and grass-dominated vegetation communities. Although there are visual similarities between upland vegetation communities in the UK and Iceland there are considerable differences in vegetation composition, growing seasons and growth patterns. In addition, neither the livestock nor the climatic regimes are comparable between the two countries. The research problem requires the investigation of the whole farm system, including both upland and lowland land use zones and vegetation types. Calibration of the HGMM for Icelandic conditions is not possible because not all of the data sets required for parameterisation exist in Iceland. Lastly, to fully investigate the impact of farm management, the model would require a spatial dimension, which is not supported by the currently published version of the HGMM.

The practice of grazing livestock on extensive rangeland for part of the year occurs in many areas of the world besides Iceland, and research has generated simulation models of these grazing systems (see for example Pickup (1994); Foy *et al.* (1999); Fernandez-Gimenez and Allen-Diaz (1999); and the Journal of Range Management). In most cases, these models have been developed for southern temperate and semi-arid regions, either for modern agricultural management purposes or for research on rangeland vegetation dynamics. At the present time, none of these models have evolved into a generalised model, in contrast, for example, to the soil agro-ecosystem CENTURY model (Simpson *et al.* 2002). The differences in their aims and the requirement for extensive parameterisation make these grazing models unsuitable for application to the present research problem.

In the absence of a suitable existing model, a specifically Icelandic historical grazing model will be developed. This model is called Búmodel, *bú* being the Icelandic term for a farming enterprise. Búmodel has been designed to run in the Microsoft Excel 97 spreadsheet package on an IBM-compatible computer. It is written in Visual Basic for Applications (VBA) code. As the research problem is spatial by nature Búmodel can be loosely coupled with an ArcView geographic information system (GIS), so that model inputs and outputs can be displayed and analysed in map form. This software environment maximises the model's future applicability, as both MS Excel and ArcView are widely used in academic, research institute and governmental circles and most modern personal computers can support the software required to run Búmodel.

2.4 The development of Búmodel

The development of an environmental simulation model can be described in terms of a flow diagram (Figure 2-1). As regards Búmodel, the different stages of the modelling process are described in the different chapters of this research thesis. The definition of the problem, the bounding of the problem and the selection of complexity are covered in the current chapter. Data requirements are briefly discussed, and an initial conceptual model is proposed. These two stages, together with the development of the mathematical model, are described more fully in Chapters 3 and 4. The verification, sensitivity analysis, calibration and validation of the model are covered in Chapter 5. Chapter 6 is concerned with the application of the functioning model to the research problem, and Chapter 7 discusses the modelling results, the issues raised by the research and the potential for model development.

The problem to be solved by modelling (the research aim) is the prediction of spatial and temporal patterns of vegetation biomass and utilisation with a view to commenting on vegetation degradation and erosion in the pre-modern period. To achieve this aim it is necessary to predict the seasonal changes in standing herbage, the relative nutritional value of the most common grazing vegetation communities and the fodder requirements of livestock at different times of the year.

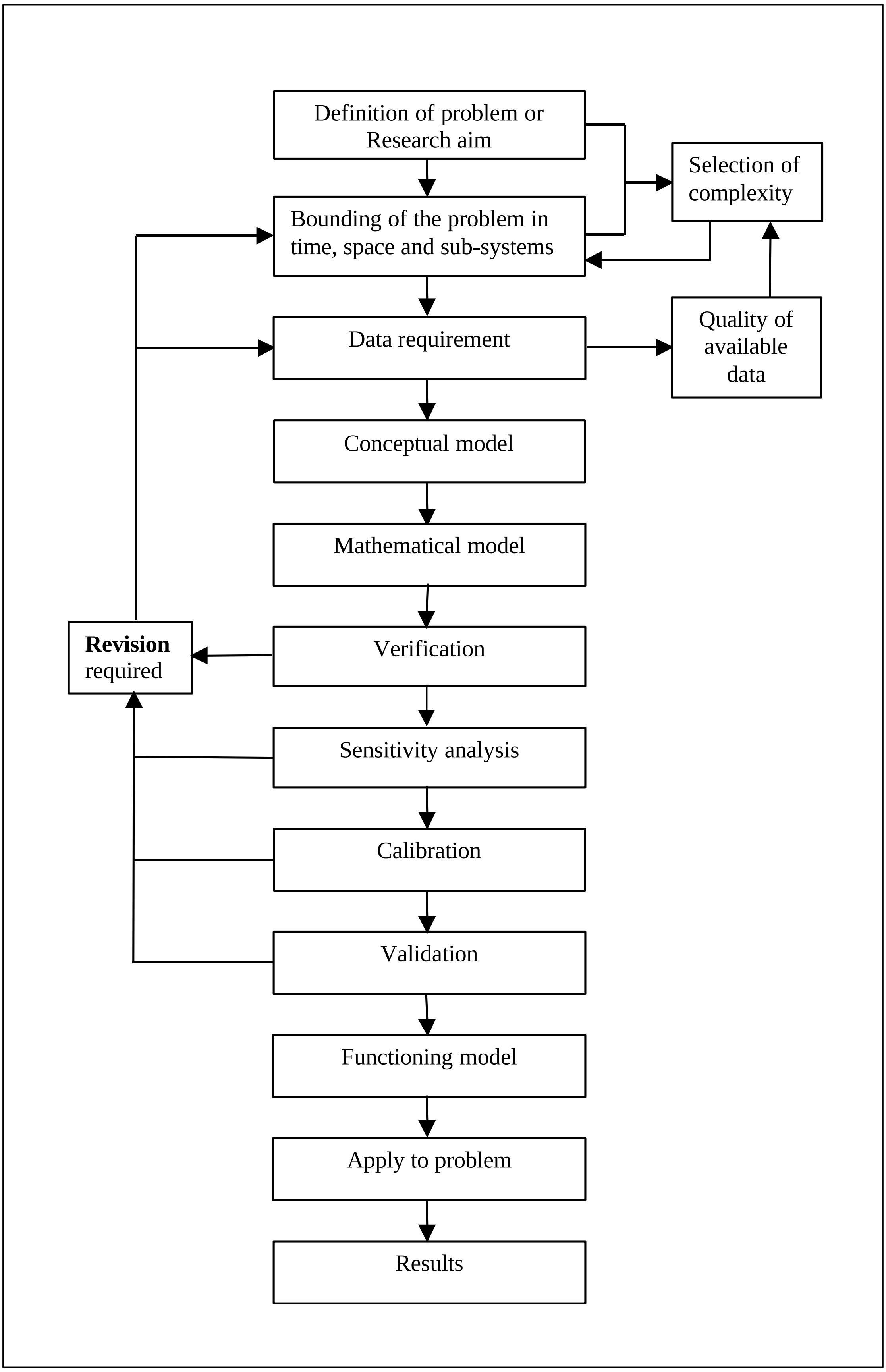


Figure 2-1: The modelling process, adapted from Jørgensen (1986)

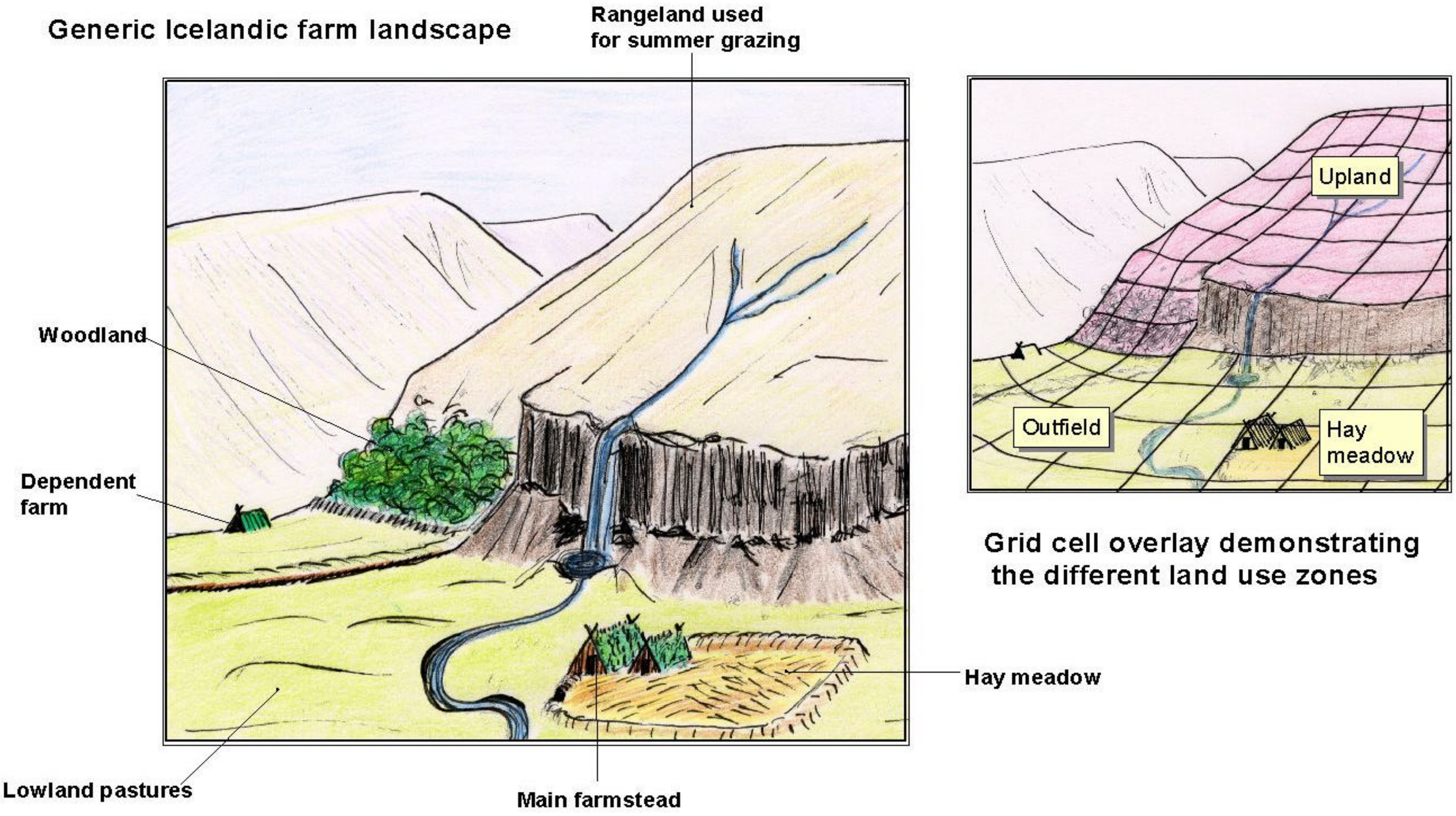


Figure 2-2: An Icelandic farm landscape showing the main land-use elements

The system under investigation is the individual farm, although it would be possible to scale up to the level of the *hreppur*. The farm landscape can be divided into different land use zones (upland rough grazing, lowland pastures, hay meadows) (Figure 2-2), composed of a patchwork of different vegetation communities. Livestock are allocated to these land-use zones according to the time of year, and are assumed to have freedom of movement within the boundaries of the zone. As the vegetation distribution is heterogeneous within each land-use zone, so too is the distribution of livestock. The spatially variable physical landscape can be represented by a grid of cells of equal size (Figure 2-2) in GIS, which can then be used as inputs to the model. The nature of the research problem, the availability of data, and the quality of that data control the selection of the size of these grid cells. The historical nature of the problem makes it necessary to define the set of exogenous variables in such a way that they can be derived for the historic past from archaeological, environmental and documentary sources. For example, it is possible to reconstruct the vegetation cover of a past landscape at a broad vegetation community level (>100m) using palaeoecology, but it is not justifiable to refine this reconstruction to the level of vegetation associations (10-100m). There needs to be a trade-off between representing the spatial variability of the landscape and over-complexity. Too fine a grid scale, when applied to a large area, would be extremely time- and resource consuming to model. A grid-cell size of 500x500m has been chosen as providing a suitable level of detail. This spatial scale is also in the same order of magnitude as the research used to parameterise Búmodel (see Chapters 3 and 4).

The data quality and the aim of modelling seasonal change dictated a monthly time scale. Data on vegetation production and climatic parameters were not available at the level of daily or weekly measurements. This means that both the spatial and temporal dimensions of the model are consistent and operate on a meso-scale. The model runs on a single-year basis, in order to restrict the set of potential management choices to manageable levels, and to avoid the consideration of longer-term environmental processes, such as vegetation community change.

Búmodel has been developed in the same way as the HGMM (section 2.2): a conceptual model was constructed, which was then parameterised using existing data sources. The conceptual model is shown in Figure 2-3. Although Búmodel is designed to investigate a historical problem, it proved necessary to parameterise the model with both historical and contemporary data. Model inputs can be derived either from historical documentary sources or estimated indirectly using evidence from archaeology, palynology, ice core analysis and soil science. The model subsystems have been developed using contemporary agricultural research. Vegetation community composition and biomass production values have been synthesised from the literature and fieldwork by the author. It is possible that pre-modern vegetation communities were dissimilar from those in existence today. Palynological evidence indicates that there were no major plant species extinctions or introductions during the historical period (Hallsdóttir 1987), and that the ecological disruption caused by the introduction of livestock grazing took place in the ninth and tenth centuries, immediately post-Settlement. The Icelandic biota responds quickly to change, as can be seen in areas where grazing has been removed, or in the colonisation of the new volcanic island of Surtsey (Fridriksson 1975). Therefore it can be assumed that any extensive modification of the vegetation occurred in the early centuries of human occupation, and that during most of the historic period the vegetation communities were similar to those found in the modern period. There are obvious exceptions in areas of deliberate cultivation, where the semi-natural vegetation communities have been modified by sowing, chemical fertilisation, the introduction of foreign commercial grass and tree species, and bog drainage. These communities have been omitted from Búmodel.

Where it has been necessary to use contemporary data to parameterise the model, every effort has been made to use Icelandic data in preference to other sources, as there are likely to be more similarities between modern and pre-modern conditions, in sheep grazing preferences for example, than dissimilarities. Collaboration with Icelandic agricultural scientists has ensured that the most appropriate data has been used, and that the model components and structure are reasonable.

As Búmodel is intended to be investigative rather than predictive, and some ecosystem variables, such as vegetation production and community composition are highly variable, these variables were incorporated as stochastic elements. Consequently, the fodder production, consumption and utilisation results can have a range of values. The same set of environmental and management inputs can result in multiple outcomes, due to the inherent variability of the system embodied in the model. This necessitates multiple simulation runs with the same set of input parameters so that the range of possible outcomes can be estimated.

2.5 Model simulation runs

The thorough investigation of the stated research aim would ideally cover all the regions of Iceland at all times in the pre-modern period. Such an investigation would be all consuming, so the focus of the model simulation runs is upon two case studies in contrasting geographical regions at a tightly constrained period in time. The case study

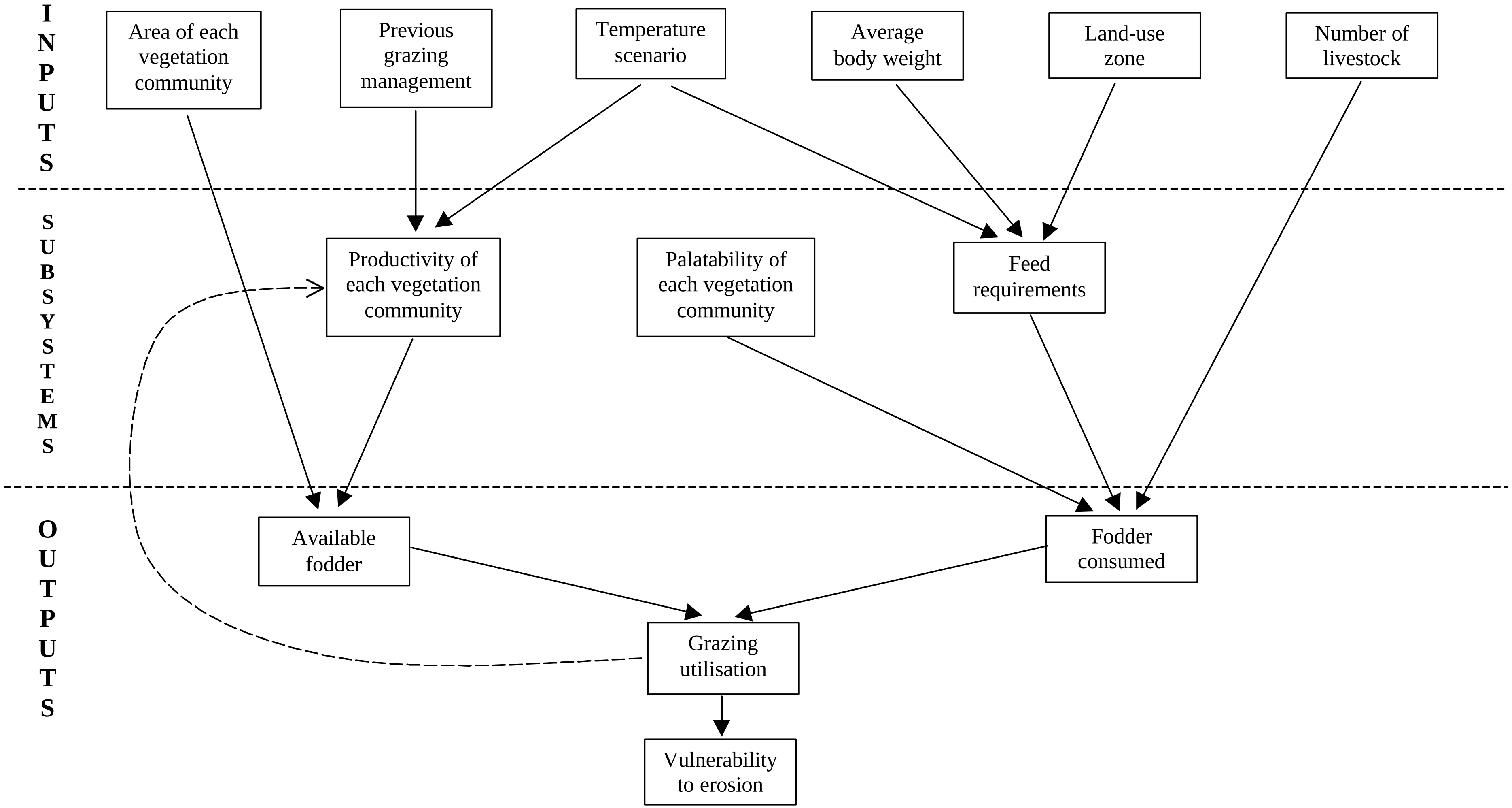


Figure 2-3: Conceptual model of the Icelandic grazing system

regions are two hreppar, described below: Vestur-Eyjafjallahreppur in southern Iceland and Mývatn hreppur in northern Iceland. The selected time period is 1709-1712 AD, when the national farm census (Jarðabók) was undertaken (Magnússon and Vídalín 1913-1990) (see section 1.3.2). This census can be cross-referenced with the 1703 livestock register (Vésteinsson *pers. comm.*). From the two censuses a picture of short-term changes in farm size, ownership and management can be drawn. The detailed nature of these sources is unmatched in the premodern period. Information on hreppur management comes from the medieval law code Grágás (Dennis *et al.* 2000), which was used as the legal framework for common pasture management into the 20th century.

The chosen time period occurs during the cold phases of Iceland's 'Little Ice Age', although the first two decades of the 18th century seem to have been relatively mild, compared to the very cold decades in the 1740s and 1750s (Ogilvie 1986). Nevertheless, some severe seasons occurred, and sea ice was relatively abundant, indicating cooler land temperatures. It was also a time of increasing sediment mobility in the lowland areas, as indicated by higher rates of sediment accumulation in soil profiles (Dugmore and Buckland 1991; Ólafsdóttir and Guðmundsson 2002). The selection of this time period provides an opportunity to examine the resilience of the management system at a time when the landscape would have been sensitive to small climatic shifts.

By running the model with tightly bounded 'real-life' scenarios, for a highly dynamic period of Iceland's environmental history, it is possible to assess the resilience and sustainability of the farm system, and to test the two research hypotheses. The first hypothesis is that there was sufficient vegetation biomass available to support the reported numbers of livestock. The model can test this using livestock numbers from Jarðabók, with realistic management strategies under a range of climatic scenarios.

The second hypothesis is that alternative management could have maintained livestock numbers and vegetation cover, whilst avoiding extensive land degradation and erosion. First it is necessary to test the reaction of the model to strategies that are believed to have caused land degradation, such as early spring grazing or inadequate shepherding (Simpson *et al.* 2001). Then Búmodel can be used to assess whether different management strategies could (a) have supported more livestock without further degradation; or (b) produced less degradation while supporting the same numbers of livestock. The model can also be used to investigate the sensitivity of the farm system to small adjustments in the management strategy, i.e. how easy it would be to produce more extensive degradation from the same environmental and livestock inputs.

The outputs of the Búmodel simulation runs will be compared through statistical analysis. Mapping in GIS will compare the spatial variability in outputs over the course of a year and between different scenarios.

2.6 Case Study region I: Vestur-Eyjafjallahreppur

Eyjafjallasveit is a coastal region in the most southern part of Iceland at 63° 35’ N, 19° 40’ W, bounded by the Markarfljót and Jókulsá rivers to the west and east respectively, and the Eyjafjallajökull glacier to the north (Figure 2-4). The region is referred to simply as Eyjafjallahreppur in Jarðabók, but the farms are divided between an eastern and a western district, with the boundary running through the Holtsós lagoon. This split is still reflected in the present administrative boundaries (DMA 1990: Sheet 1812 III). The total area of the hreppur (excluding glaciers) is 306 km^2.

The region is topographically varied, rising from sea level to 1,651 m at the peak of Eyjafjallajökull. The southern and western part of the hreppur consists of low lying fertile farmland and coastal sand dunes in a strip about 5-8 kilometres wide, with the Vestmannaeyjar (Westman Islands) lying about 8km offshore (Figure 2-5 and Figure 2-6). There are areas of sparsely vegetated gravel flats on either side of the Markarfljót (Figure 2-7). The northern upland area, Eyjafjöll, is rugged, steep rough grazing (Figure 2-8), ranging from 100m to the glacier margin at c800m. The land between the northern edge of the glacier and the Markarfljót is uninhabited, and consists mostly of heathlands and grasslands (Figure 2-9). To the northeast is the inland valley of Þórsmörk; there were farms here in historic times, but these have now been abandoned and the area is a national park (Figure 2-10). Although Þórsmörk lies outside the hreppur area its vegetation provides the closest analogue for the lowland vegetation cover before the impact of extensive grazing and modern farming methods. It also contains the only extensive birch forest in the surrounding region (Figure 2-11).

Volcanic, glacial and fluvial processes have shaped the geology and soils of Eyjafjallahreppur. The region lies in the active volcanic zone of Iceland, with four historically active volcanoes within 50km (Hekla, Katla, Eyjafjallajökull and the Vestmannaeyjar complex). There are at least 78 discrete tephra layers from these eruptions to be found in Eyjafjallahreppur, allowing the establishment of a detailed tephrochronological framework (Þorarinsson 1944, 1967, 1975; Einarsson *et al.* 1980; Haraldsson 1981; Larsen 1981, 1982, 1984; Dugmore 1989; Haflidason *et al.* 1992; Dugmore *et al.* 2000), which has been vital in characterising the environmental and archaeological history of the region. The geology of the upland is a Pleistocene basalt and hyaloclastic formation (Hallsdóttir 1987). The soils on the uplands are predominantly brown Andosols, with some Leptosols and Cambric Vitrosols around the glacier edge and river margins (RALA 2001). The low-lying plain between the upland fells of Eyjafjöll and the coast is an area of "sandur", which are deep glaciofluvial deposits, up to 270m deep in places (Haraldsson 1981). These deposits are overlain by brown and gleyic Andosols, with small areas of arenic Vitrosols on the coast (RALA 2001).

The lowlands are mostly free of erosion, but the uplands and coastal sandur are classed as suffering from considerable to severe erosion, and as being in poor condition in view of this erosion (Arnalds *et al*. 2001) (Figure 2-12 and Figure 2-13). The most common erosion forms are rofabards (erosion escarpments), solifluction and melur (gravels).

The nearest climatological stations to the study area are located at Sámsstaðir, eight kilometres to the northwest (which closed in 1995), and Stórhöfði in Vestmannaeyjar. The climate of southwest Iceland is cool oceanic, and mild compared to the rest of the country (Figure 2-14). The area is relatively wet (Figure 2-15), receiving between 1000 mm to >4000 mm (on Eyjafjallajökull) of precipitation annually; there is a rain shadow effect on the northern side of the glacier. Lying, as southern Iceland does, in the main track of the North Atlantic atmospheric depressions, the weather can be very changeable (particularly in late winter and early spring) and extremely windy at times. The mean length of the frost-free period in the southwest is between 120-150 days, depending on the distance from the coast (Bergþórsson *et al.* 1987).

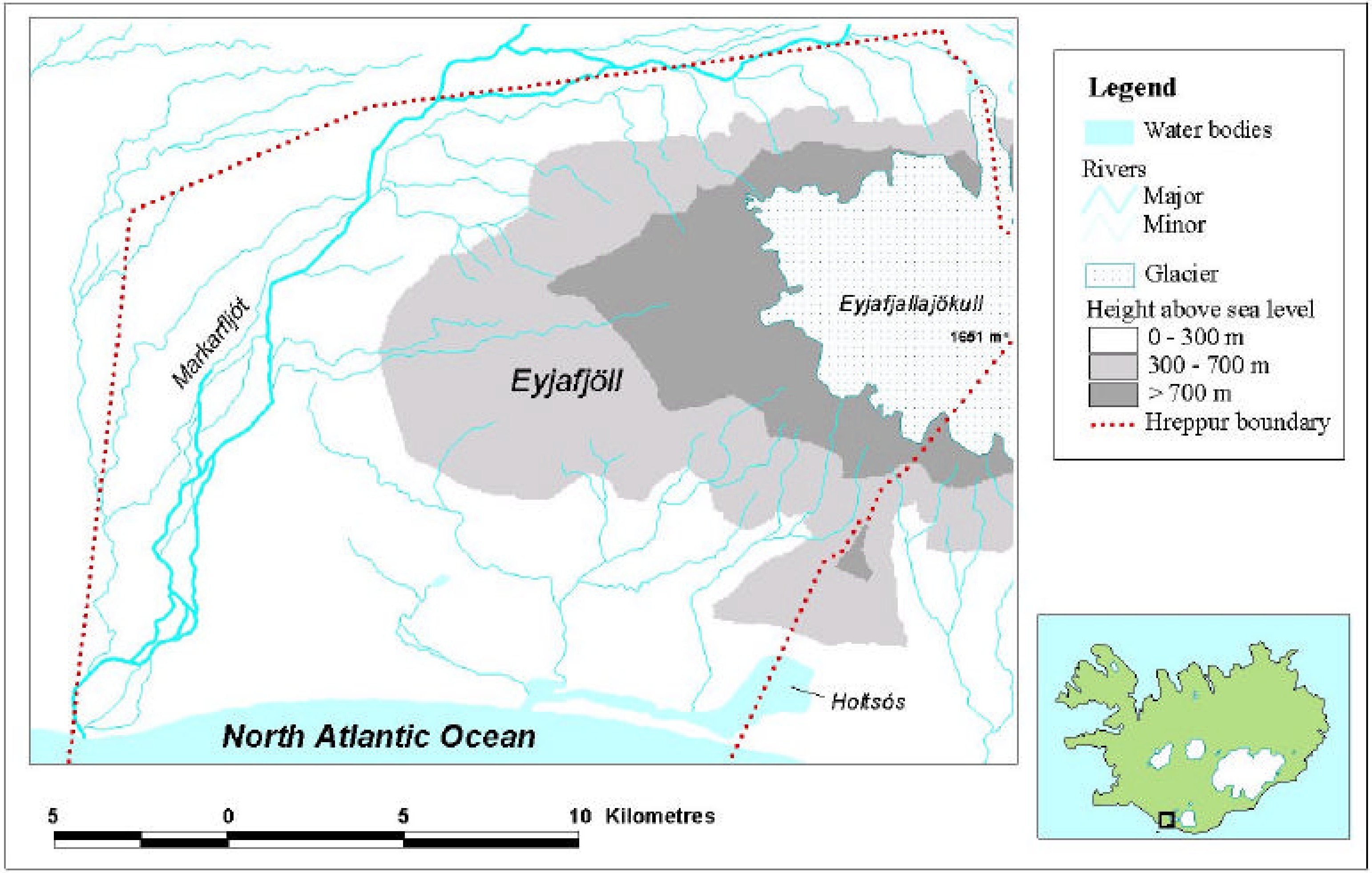


Figure 2-4: The Vestur-Eyjafjallahreppur study area

Figure 2-5: Lowland pastures in Eyjafjallasveit, with Vestmannaeyjar in the distance

Figure 2-6: Lowland farmland, Vestur-Eyjafjallahreppur, with Markarfljót in distance

Figure 2-7: Sparsely vegetated sandur, Vestur-Eyjafjallahreppur

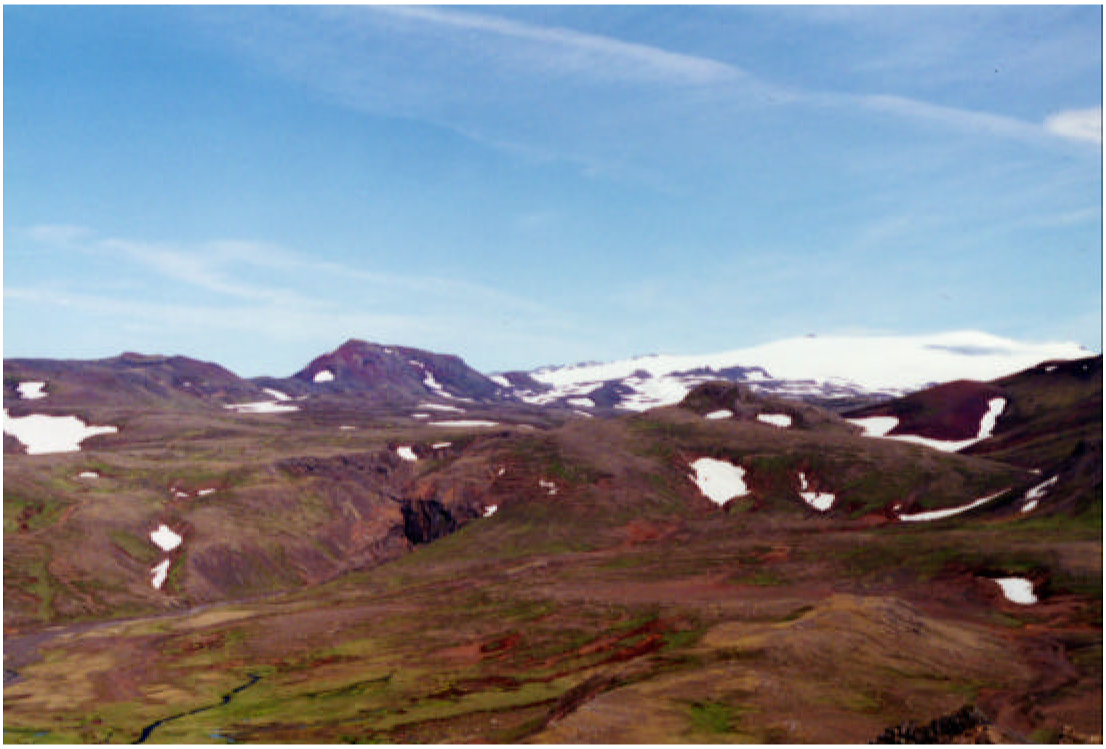


Figure 2-8: Uplands of Vestur-Eyjafjallahreppur, looking east towards Eyjafjallajökull

Figure 2-9: Heathlands on the northern side of Eyjafjöll

Figure 2-10: Þórsmörk, looking east up the Krossá valley

Figure 2-11: Birch forest at Þórsmörk

Figure 2-12: Vegetation and soil degradation on Eyjafjöll

Figure 2-13: Rofabard erosion on Eyjafjöll

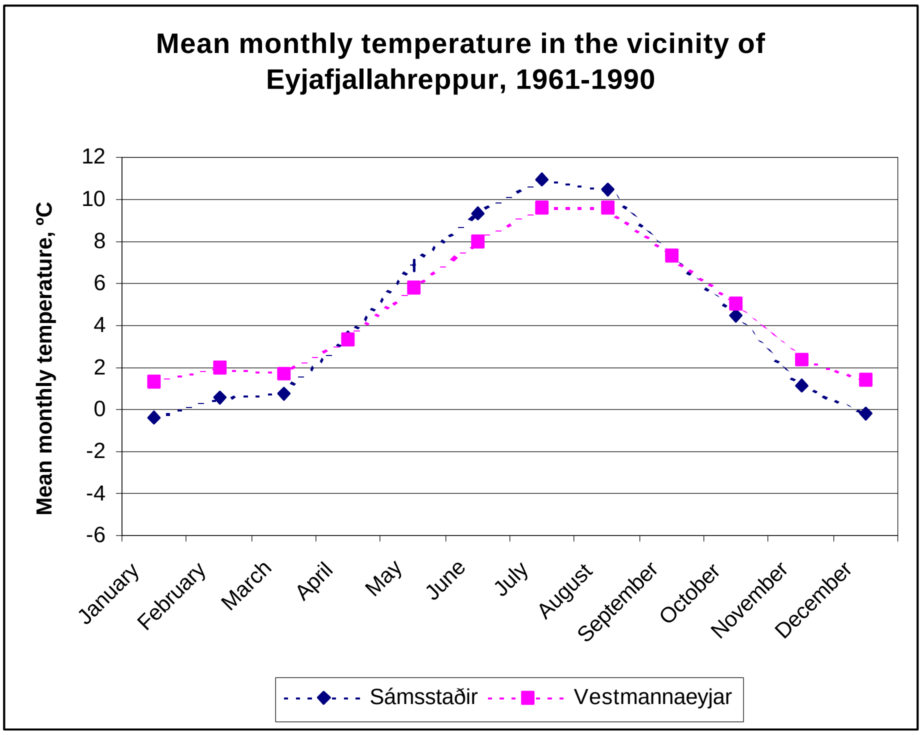
In pre-Landnám Eyjafjallahreppur the lowland vegetation was composed of a mosaic of birch woodland and scrub on the raised ground with mires in the hollows, which were formed by the braided river channels covering the sandur (indicated by peat deposits and macro-fossils found throughout the region (Haraldsson 1981; Påhlsson 1981; Buckland *et al.* 1991). Birch woodland predominated up to 300m (based upon the estimate by Simpson *et al.* (2001) and spatial modelling of Landnám forest cover by Ólafsdóttir *et al.* (2001)). The existence of woodland in Eyjafjallahreppur early in the settlement period is also supported by the occurrence of place names such as 'skógar', 'mörk' and 'holt', all of which refer to woodland or wooded landscape features (Eysteinsson and Blöndal 2000). The uplands above the tree line were covered by a mixture of dwarf shrub and grassy heath, which was replaced by moss heath at c700m at the limits of continuous vegetation cover. The place name evidence supports this assumption, as the upland areas above the farms are suffixed by –heiði, which is cognate with 'heath' and referred to unwooded areas in early Icelandic (Kristinsson

1995). Post-Landnám human impact and climatic deterioration significantly reduced the area of birch woodland, to such an extent that it is doubtful whether there was any remaining in the lowlands by 1700 AD: certainly none exists there today. It is likely that the more inaccessible area of Þórsmörk has always been wooded to some extent. The lowland wood-and-mire landscape was converted into one of heaths and mires, and there was considerable erosion of pastures caused by shifts in the Markarfljót channel (Haraldsson 1981). Since the 1940s extensive drainage and ditching of the lowland has converted some of the mire into grassland for hay or pasture, and barriers built in 1910 have constrained the river’s course. The extensive erosion and subsequent increase in bare ground cover have caused the main changes in the vegetation cover in the uplands.

Archaeological investigations in the region (summarised in Sveinbjarnardóttir (1992) and Haraldsson (1981)) and documentary evidence from Landnámabók (Macniven 2002) suggest that Eyjafjallahreppur was settled early in Iceland’s history. In the 1709 Jarðabók, a total of 50 occupied farms are recorded in Vestur-Eyjafjallahreppur, with two church farms at Holt and Stóridalur (Figure 2-16). The region is still a prosperous farming area today.

2.7 Case study region II: Mývatn hreppur

The region of interest is located in the north east interior of Iceland, centred on Lake Mývatn at 65°36’N, 17°00’W. It is referred to as Mývatn hreppur in Jarðabók, but the modern name is Skútustaðahreppur, referring to Skútustaðir, one of the main settlements in the region. The present boundaries of the hreppur extend south to the edge of Vatnajökull, covering an area of 4900 km^2, although only the northernmost twenty per cent is vegetated and settled. This area is both too large and too complex as a



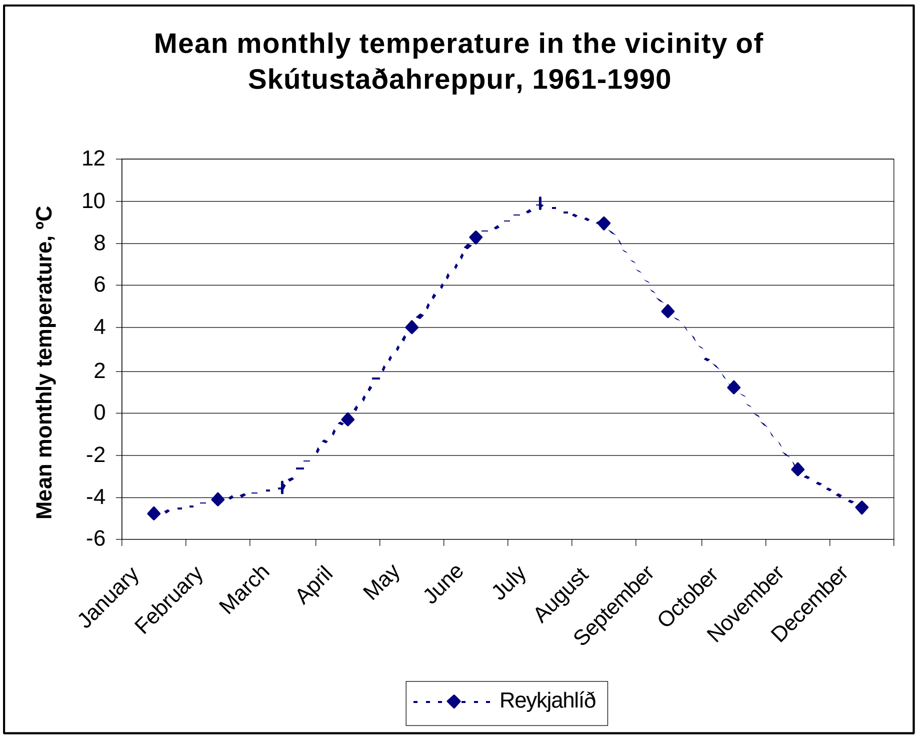


Figure 2-14: Mean monthly temperature curves for the two study regions, 1961-1990 (Icelandic Meteorological Office 2001)

Annual temperature, 1937-1960: Sámsstaðir (5.2 ºC), Vestmannaeyjar (N/A), Reykjahlíð (2.2 ºC)

Annual temperature, 1961-1990: Sámsstaðir (4.6 ºC), Vestmannaeyjar (4.8 ºC), Reykjahlíð (1.5 ºC)

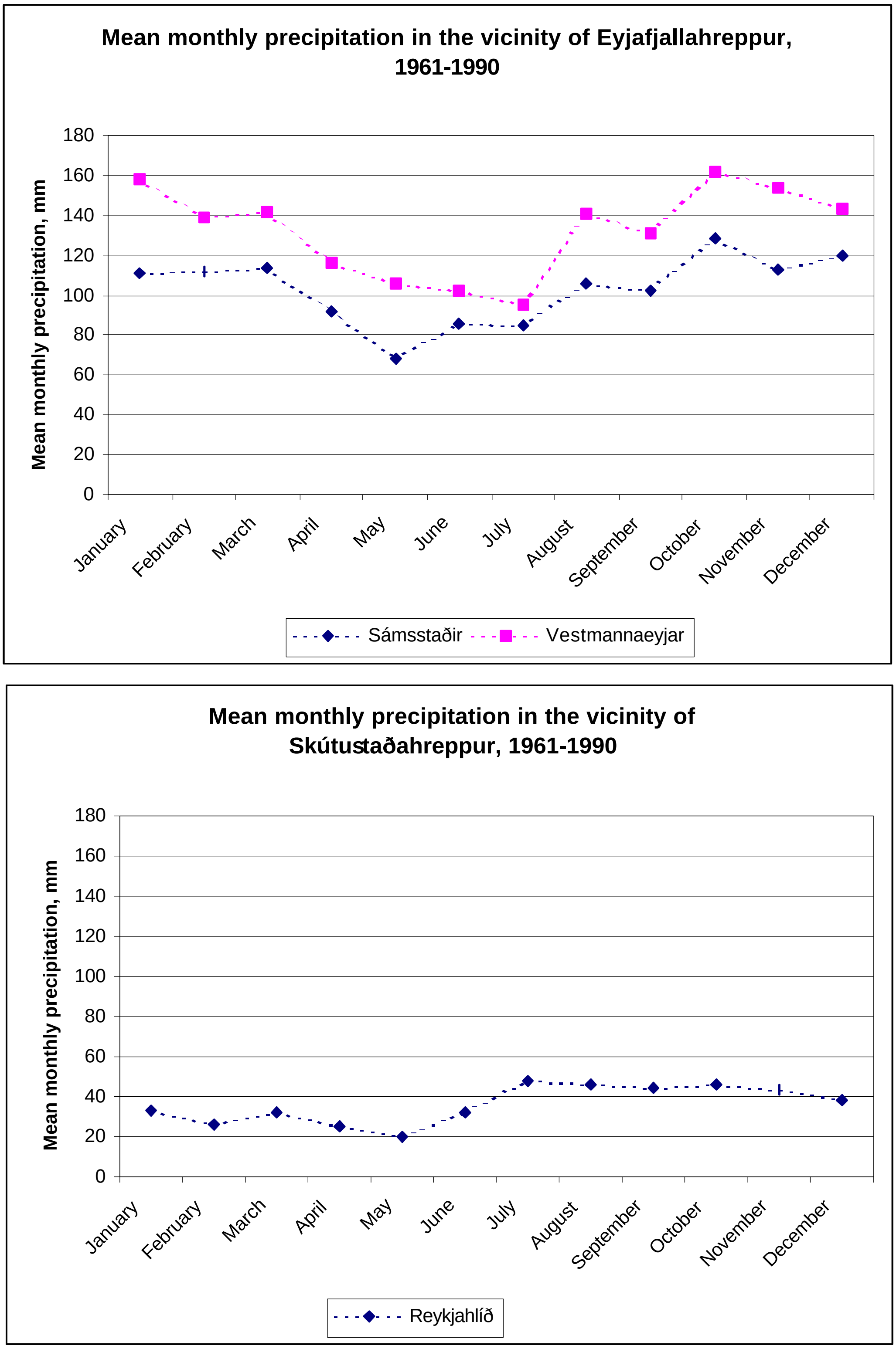


Figure 2-15: Mean monthly precipitation curves for the two study regions, 1961-1990 (Icelandic Meteorological Office 2001)

Total annual precipitation, 1961-1990: Sámsstaðir (1236 mm), Vestmannaeyjar (1589 mm), Reykjahlíð (435 mm).

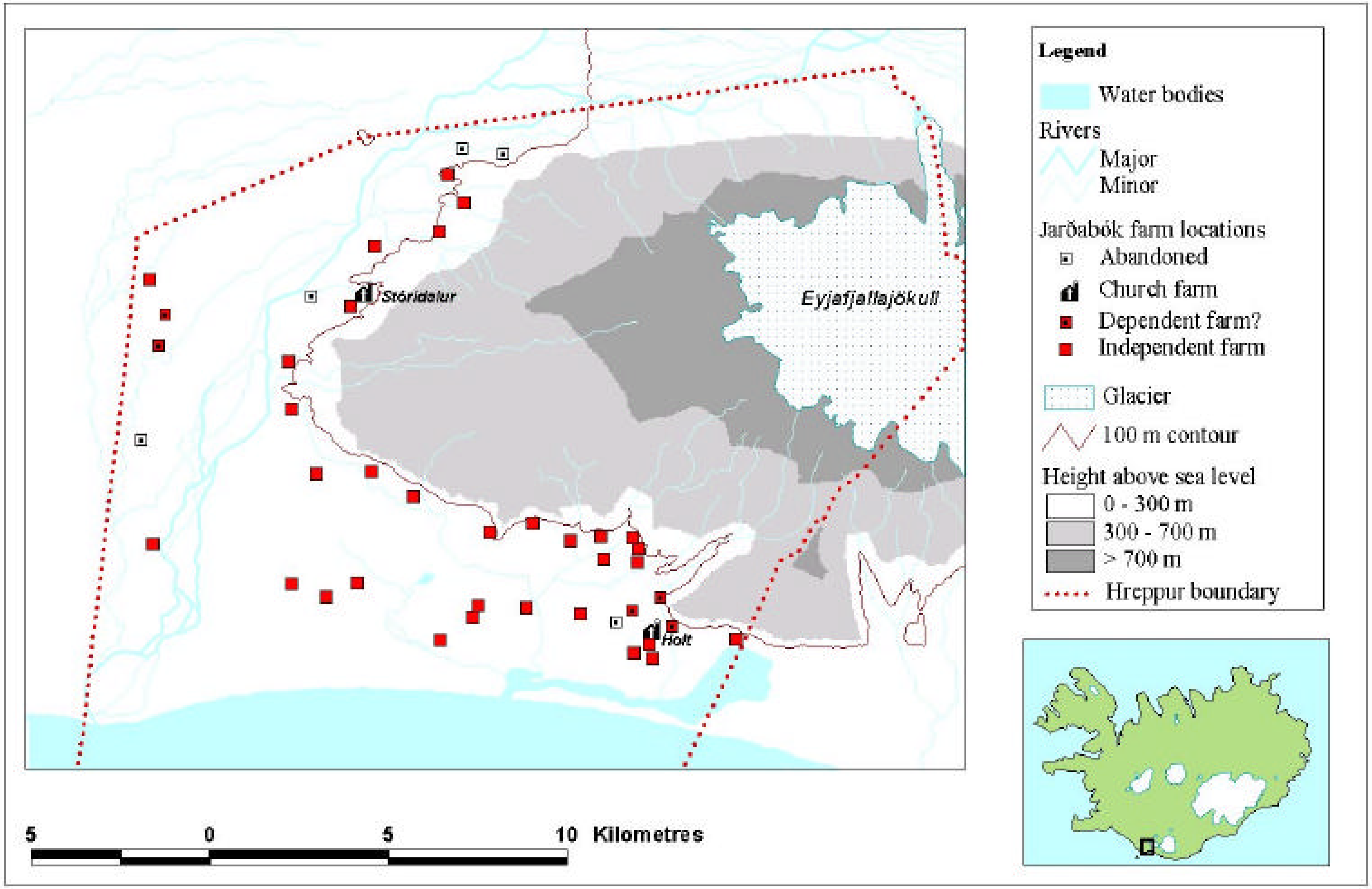


Figure 2-16: Farms mentioned in Jarðabók in Vestur-Eyjafjallahreppur, as located using the modern 1: 50 000 map (Eyjafjallajökull. 1990)

study region for the purposes of this research. The area chosen for the model simulations is the Hofstaðir farm estate (65°37’N, 17°09’W), approximately 16 km^2, located to the north west of Mývatn, beside the Laxá river (Figure 2-17 and Figure 2-18). The area around Mývatn and Laxá, which are the foci of settlement in the region, will be described to establish a context for Hofstaðir.

Mývatn lies at 278 m above sea level and contains over 50 islands and islets. The immediate surroundings of the lake consist of flat or gently undulating vegetated land, with volcanic features such as lava flows, craters and pseudocraters (Figure 2-19). To the east of Mývatn the ground is extensively fissured and faulted, forming a sequence of narrow graben and horst strips (Þorarinsson 1979c). The area west of Mývatn is covered with basalt ridges which have been rounded by glaciation and is now covered predominantly with heath and wetland vegetation; the area to the south of the lake consists of extensive lava fields, extending into the barren areas of the interior (Ólafsson 1979). There is also an extensive area of barren land, Hólarsandur, to the north of the lake, where there have been attempts at reseeding in recent decades (Figure 2-20).

The Mývatn area, like Eyjafjallahreppur, lies within an active volcanic region. During the first 800 years of settlement there was little volcanic activity. This period of quiescence was ended by an intense period of volcanic activity at Krafla from 1724-1729, known collectively as the ‘Mývatn Fires’ (Þorarinsson, 1979c). A second period of activity, including nine eruptions, took place between 1975 and 1984. The bedrock in the Mývatn area mainly consists of basaltic lavas and hyaloclastite rocks (Þorarinsson, 1979c). The dominant soil types in the vegetated area are brown or gleyic Andosols, whilst the barren areas to the south and the north of the lake have a soil cover composed of arenic Vitrisol-Leptosol or cambric Vitrosol-arenic Vitrisol complexes (Soil Map of Iceland 2001).

The immediate area around Mývatn, including Hofstaðir, suffers little or no erosion, according to the Icelandic Soil Erosion Classification (Arnalds *et al*. 2001); however, the extensive barren areas to the south and north of the lake suffer from erosion that is classed as severe, or extremely severe. Sand encroachment onto vegetated land is a particular problem; other erosion forms common in the study area include rofabards, solifluction and gullies. A tephrochronological framework is available for the region (Ólafsdóttir and Guðmundsson 2002) and for the Hofstaðir estate (Simpson *et al.*, in press), but this is not yet as detailed as the one available for Eyjafjallahreppur.

There is a climatological weather station (dating from 1937) within the region, at Reykjahlíð, about 10 km from Hofstaðir. The Mývatn region exhibits a high annual range of temperature (13-15°C) (Figure 2-14), despite its proximity to the Arctic Circle, and experiences a more settled, continental climate than most of Iceland (Einarsson 1979). Due to its location in the rain shadow of the Vatnajökull ice cap, it is also one of the driest places in the country (Figure 2-15), with a total annual precipitation of around 400 mm. Föhn winds linked with this rain shadow effect can raise temperatures in the region to as much as 20-25 ºC on afternoons in mid-summer (Einarsson 1979). Over half of the winter precipitation falls as snow, and a complete snow cover can persist for weeks or even months at a time (Einarsson 1979). This is matched by the large number of frost days in the year (over 150) (Einarsson 1979) (compare this with the estimated frost-free period of

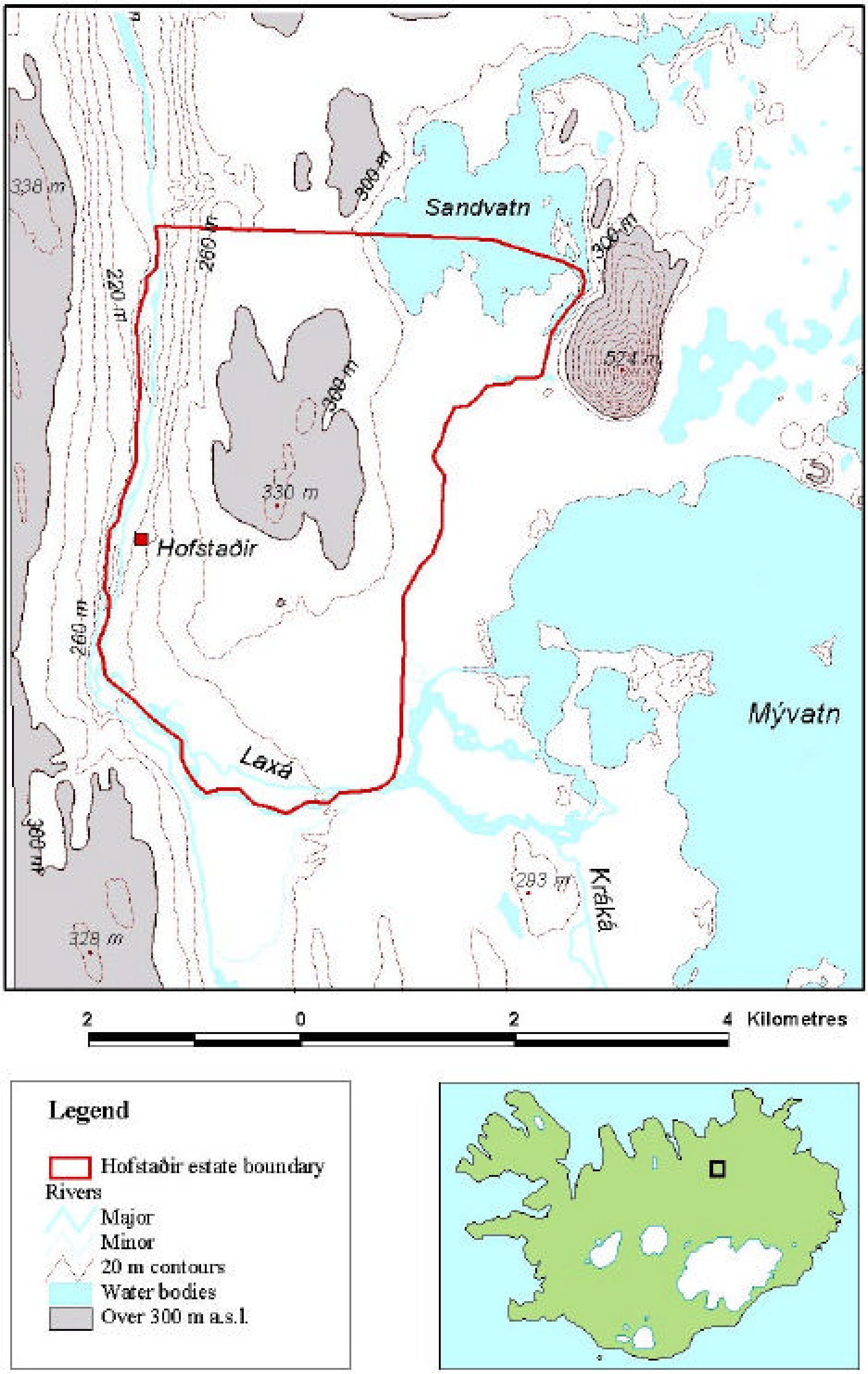


Figure 2-17: The Mývatn hreppur study area

Figure 2-18: View of Hofstaðir farm

Figure 2-19: View of Mývatn from the north

Figure 2-20: Desert area north of Mývatn, with evidence of reseeding

Figure 2-21: Grassy heathland on Hofstaðir estate

60-100 days (Bergþórsson *et al.* 1987). The ice cover on Mývatn may last for up to 190 days (Jónasson 1979).

The vegetation around Lake Mývatn is diverse and prolific. A survey published in 1972 (Jónasson 1972) listed 246 species of vascular plants found within the district. The contemporary vegetation cover is shown on the vegetation maps produced by the Agricultural Research Institute (Vegetation map of Iceland, 1982a and b) (unfortunately these have not been published for the southern study area). The western and southern shores of the lake and the banks of the rivers Laxá and Kraká are covered by sedge/rush heaths, grasslands and bogs/mires (Figure 2-21). The land to the north and northeast of the lake has a mosaic of scattered birch woodland, bog and damp grassland (half bog) (Figure 2-22). The eastern and southeastern areas are covered by grassy heathland, frequently with less than 100% vegetation cover (Figure 2-23). The islands and islets in the lake and the river Laxá have been protected from prolonged grazing, and are densely vegetated with birch, willow and herbs such as angelica (*Angelica archangelica*), meadow buttercup (*Ranunculus acris*), marsh marigold (*Caltha palustris*) and wood cranesbill (*Geranium silvaticum*) (Figure 2-24). No detailed pollen analysis has yet been undertaken in this region, so the precise pre-Landnám vegetation cover is unknown. It is probable that the environmental history is similar to that in other parts of Iceland (see section 1.3.1.3), and that the dense vegetation community now confined to the river and lake islands was more extensive on the mainland in the past.

The Mývatn region is the furthest inland of any of the permanently settled regions in Iceland. Archaeological excavations at Hofstaðir have demonstrated that this area has been settled since very early in Iceland's history, with the earliest building phase at the site dating from the late 9th century AD (Vésteinsson 1996). The region is now the subject of a large interdisciplinary research project (Vésteinsson 1996; Friðriksson and Vésteinsson 1998; Lucas 1999) with excavations at Hofstaðir, Sveigakot (Figure 2-25) and Hrísheimur and ongoing geoarchaeological investigations on the use of winter grazing areas and hay meadows. When the Jarðabók farm census took place in 1712 there were 22 occupied farms in the area, with church farms at Skútustaðir and Reykjahlíð (Figure 2-26).

2.8 Summary

In the absence of suitable grazing models from other parts of the world, the aim of the research will be achieved by constructing a historical grazing model specifically for Iceland. This model, Búmodel, will be spatially based and stochastic in nature, enabling the results to be analysed both statistically and in a GIS. The scale of investigation is at the individual farm level, on a monthly basis during a single year. Model inputs will come from environmental, archaeological and documentary evidence, but the model sub-systems are based upon contemporary Icelandic agricultural information.

Multiple model simulation runs will test the hypotheses for a tightly constrained time period, 1709-1712, in two agricultural districts of Iceland, Vestur-Eyjafjallahreppur and Mývatn hreppur. Both areas have a long history of human settlement, dating back to the 10th century. There is evidence of intense erosion in both districts, but the core settled areas seem to have survived relatively unscathed since early in the historic period. The two

Figure 2-22: Birch woodland/bog/damp grassland mosaic on northwestern shore of Mývatn

Figure 2-23: Dwarf shrub heath and desert south of Mývatn

Figure 2-24: Dense vegetation on islands protected from grazing, Laxá

Figure 2-25: Sveigakot excavation, 2001.

Note the degraded nature of the surrounding soil and vegetation cover.

districts contrast with each other in their locations, climate and topography: Eyjafjallahreppur is a southern coastal area with topographic extremes of lowland plains and rugged upland areas and a relatively mild and wet climate, while Mývatn hreppur is in a northern inland location, with gently rolling topography and one of the driest climates in Iceland. Both districts are the focus of historical environmental and archaeological research, and the data sets produced from this research are closely chronologically defined by tephra layers and radiocarbon dating, thus providing an ideal database for running and testing the model.

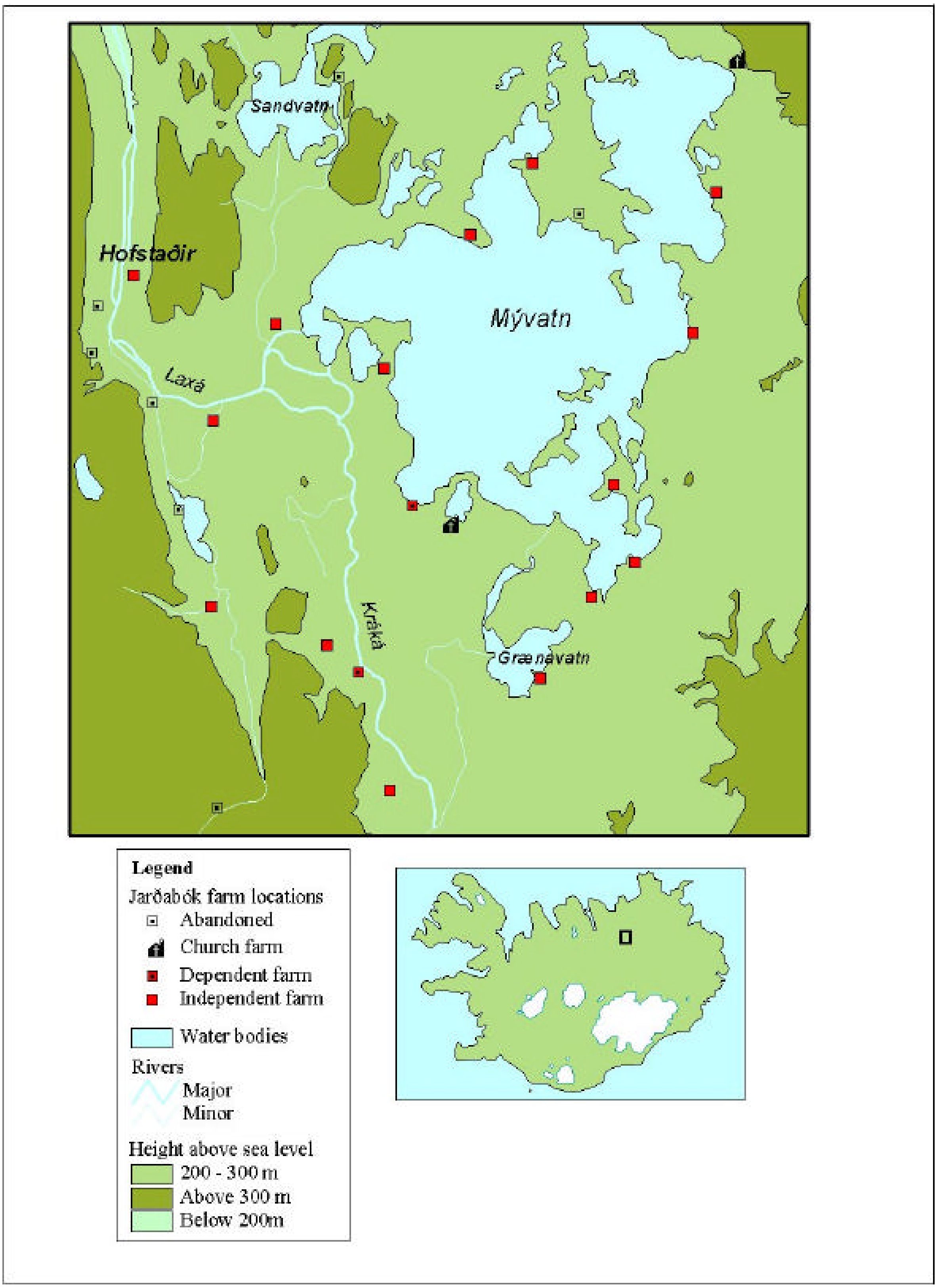


Figure 2-26: Farms mentioned in Jarðabók in the Mývatn region

Chapter 3: The construction of the grazing simulation model I: Inputs

3.1 Introduction

Búmodel has been constructed to identify the spatial and temporal variation in historical grazing patterns and any resulting vulnerability to vegetation and soil degradation. The availability of data has been crucial in this process, and has driven the overall design of the model. Búmodel is based upon contemporary Icelandic data (Table 3-1) with additional information drawn from research in other sub-arctic regions. Búmodel is a mathematical simulation model with a spatial dimension, constructed to run for a period of twelve months. Processes are simulated in separate sub-models, which combine to make the overall model. Some of the model elements are subject to random variation and this is taken into account using Monte-Carlo probability modelling. This necessitates multiple simulation runs with the same set of input parameters, so that the range of possible outcomes can be estimated.

This chapter discusses the inputs to the model. Chapter 4 discusses the processes represented by the different components in the model. The data primarily came from published sources and fieldwork by the author. The fieldwork methods and results are described within the text. Each model component will be discussed in turn following the structure in Figure 3-1.

Table 3-1: Icelandic data sources used in formulating Búmodel

Authors	Date of publication	Contents
Aðalsteinsson	1990	Livestock inputs
Archer & Arnalds	1982	Vegetation-grazing feedbacks
Bergþórsson	1985, 1996	Climatic scenario inputs
Bergþórsson, Björnsson, Dýrmundsson, Gudmundsson, Helgadóttir & Jónmundsson	1987	Climatic scenario inputs
Gísladóttir	1998	Vegetation categories; utilisable biomass
Guðmundsson	1991	Maintenance feed requirements
Guðmundsson & Bement	1986	Vegetation-grazing feedbacks
Jónsdóttir	1994	Vegetation-grazing feedbacks
Jónsdóttir, I.	1984	Vegetation-grazing feedbacks
Magnússon & Magnússon	1990a, 1992	Vegetation-grazing feedbacks; vegetation palatability
Magnússon, Elmarsdóttir, Barkarsson & Maronsson	1999	Vegetation-grazing feedbacks; utilisable biomass
Ólafsson	1973	Vegetation palatability
Ólafsson	1980	Maintenance feed requirements
RALA reports 29,38,50,63,79	1977-1981	Vegetation-grazing feedbacks; utilisable biomass
Steindórsson	1980	Vegetation categories
Thorhallsdóttir & Thorsteinsson	1993	Vegetation palatability
Thorsteinsson	1964	Vegetation palatability
Thorsteinsson	1980a	Vegetation palatability; utilisable biomass
Thorsteinsson	1980b	Maintenance feed requirements; utilisable biomass
Thorsteinsson and Arnalds	1992	Vegetation categories
Thorsteinsson & Ólafsson	1967	Vegetation palatability
Thorsteinsson, Ólafsson & van Dyne	1971	Vegetation-grazing feedbacks; utilisable biomass

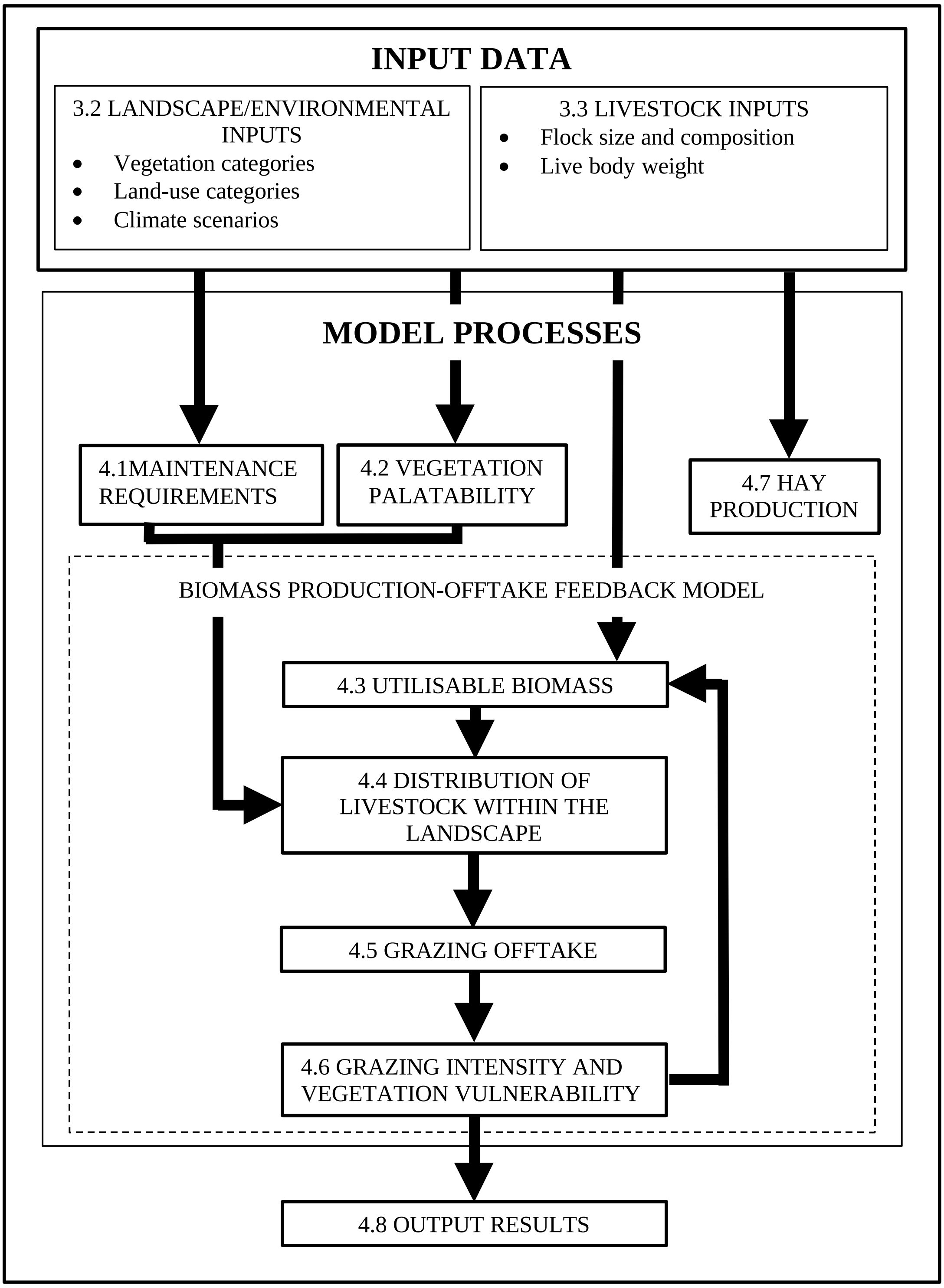


Figure 3-1: Model data structure (numbering relates to chapter sections)

3.2 Landscape/Environmental inputs

3.2.1 The vegetation classification

A vegetation classification is required to assist mapping of the spatial distribution of vegetation within the investigative area. Búmodel operates at a medium scale (10 – 1000 m) so a classification at the plant formation scale (Rieley and Page 1990), e.g. tundra, temperate rain forest, is too simplistic, while one at the plant association scale would be too complex. As the classification is of *grazeable* vegetation, rather than botanical composition *per se*, the scale of related information, such as palatability and productivity, also needs to be taken into account. When the model is applied to past landscapes, the vegetation classification must be simple enough that the past spatial distribution of vegetation can be justifiably inferred from the evidence, while still trying to represent as much of the vegetation diversity as possible.

For Búmodel, Iceland’s various vegetation communities have been simplified into eight grazeable vegetation communities. These vegetation communities were defined according to their botanical composition, based on a synthesis of information from the Icelandic literature and information derived from fieldwork. It is assumed that the vegetation communities in the present (at the scale of this study) are analogous to those in the past (further discussion in section 2.4).

3.2.1.1 Vegetation community classifications in the literature

The Agricultural Research Institute (RALA) undertook vegetation mapping from 1955-1979 (Guðbergsson 1980) (for the purpose of securing base data with which to assess the carrying capacity of the rangelands) and their classification (Table 3-2) was the first comprehensive classification specific to Iceland. The vegetation was classified primarily by its physiographical characteristics, and secondly by dominant plant species (Steindórsson 1980). Other studies have developed their own classifications using the RALA system as a framework. Thorsteinsson and Arnalds, in their 1992 study of the vegetation and soils of Þingvallavatn in south-western Iceland used a classification of six main plant communities and a ‘barren land’ category, based on Steindórsson (1980). These communities were moss heath, dwarf shrub heath, graminoid heath, woodland, cultivated grassland, and wetland vegetation consisting of bogs and fens (Table 3-3). Each of these communities consisted of eight or more plant sociations. Gísladóttir (1998) developed her own classification system for Krísuvíkurheiði in southwestern Iceland, which was also based on Steindórsson’s, but included coverage ratios (Table 3-4).

These two classifications (Thorsteinsson & Arnalds’ and Gísladóttir’s) are of the requisite scale to be used within Búmodel. A provisional list of seven vegetation communities (hayfield, grassy heath, dwarf shrub heath, moss/lichen heath, birch woodland, bog/mire and sparsely vegetated land) was chosen for confirmation in the field. The hayfield community is equivalent to cultivated grassland, and sparsely vegetated land to barren land. The two true wetland communities, bog and fen, are grouped together in a single bog/mire category. The riverine vegetation community, equivalent to halfbog or mire margin, was subsequently added to this list.

Table 3-2 : The Agricultural Research Institute vegetation classification scheme (Steindórsson 1980)

Level I	Level II	Level III
Dryland vegetation	Heath vegetation	Moss heath
		Dwarf shrub heath
		Kobresia myosuroides heath
		Juncus trifidus heath
		Carex heath
		Lichen heath
	Meadow vegetation	
	Snowpatches	*Anthelia* sp. liverwort patch
		Salix herbacea patch
		Dwarf shrub patch
		Gramineae patch
		Forbs patch
		Carex lachenalii patch
	Secondary succession vegetation	
	Forbs	
	Woodland	
	Jaðar (Semibog vegetation)	
Wetland vegetation	Sloping bogs	*Carex* bog
		Trichophorum bog
		Equisetum bog
		Dwarf shrub bog
	Level bogs (fens)	*Eriophorum angustifolium* bog
		Carex rostrata bog
		Carex lyngbyei bog
	Freshwater vegetation	

The botanical composition of the different vegetation communities was investigated in the study areas in Eyjafjallahreppur and Mývatn hreppur. The first fieldwork season in the summer of 2000 was mainly exploratory, as detailed information on the vegetation distribution was patchy, and it was not possible to formulate a fieldwork plan that covered all the vegetation communities of interest and was also scientifically rigorous. The second fieldwork season in 2001 built on the foundations of the previous year's work, and biomass and botanical composition were measured.

Table 3-3: The vegetation community classification for Þingvallavatn (Thorsteinsson and Arnalds 1992)

Þingvallavatn vegetation class	Description
Moss heath	Characterised by thin soils and dominance of mosses, most commonly *Racomitrium* sp. Vascular plants are few and scattered, so plant production is low and of limited grazing value.
Dwarf shrub heath	Dominated by woody species, although the botanical composition depends upon the site conditions. *Empetrum nigrum* and *Dryas octopetala* are most commonly found on dry, shallow soils on wind-exposed sites. *Arctostaphylos uva-ursi*, *Betula nana*, *Salix callicapaea*, *S. lanata* and *S. phylicifolia* require more favourable snow and moisture conditions. *Vaccinium uliginosum* and *V. myrtillus* favour areas with long lasting snow cover, while *Salix herbacea* is a snowpatch species that thrives best under extreme snow cover.
Graminoid heath	Vegetation types where grasses or grass-like plants are dominant. Spilt into three categories: grassland, rush heath and sedge heath. For grasslands the most common grasses are species of *Festuca*, *Agrostis* and *Poa*, together with *Deschampsia caespitosa* and *D. flexuosa*. The grasses are frequently mixed with sedges and dwarf shrubs. Rush heath is characterised by *Kobresia myosuroides* and *Juncus trifidus*, often with scattered dwarf shrubs. Sedges dominate sedge heath, although grasses and dwarf shrubs may invade dryer sites.
Woodland	*Betula pubescens* is the dominant native tree species, while trees of *Salix phylicifolia* and *Sorbus aucuparia* are scattered within the birch woodland. The understorey in protected woodland is lush and composed of shrubs, grasses and tall-growing herbs, such as *Geranium sylvaticum*, *Hieracium* spp, *Taraxacum* spp, *Ranunculus acris*, *Rubus saxatilis* and *Alchemilla vulgaris*. Scattered grazed woodlands are characterised by low trees and shrubs with an understorey of moss and scattered vascular plants.
Wetland	Classified according to degrees of water saturation into halfbogs, bogs and fens. Halfbogs are relatively dry, are not dominated by *Carex* and approach grasslands in species composition. Bogs have intermediate water content and are waterlogged in spring and during persistent heavy rainfall. In the drier bogs *Carex nigra* is dominant up to 2-300 m elevation, then *C. bigelowii* gradually replaces it. Wetter bogs are characterised by *Carex rariflora*, *C. rostrata*, *Eriophorum angustifolium* and *Trichophorum caespitosum*. Fens are saturated with stagnant water and the most common species are *Carex rostrata*, *C. rariflora, C. lyngbyei* and *Eriophorum angustifolium*.
Cultivated grassland	The grass species are largely the same as those in the natural pastures: species of *Agrostis*, *Festuca*, *Poa* and *Deschampsia*, and also *Phleum pratense*. There may be some legumes.
Barren land	These areas usually carry a small amount of very scattered plant cover, either the remnants of earlier vegetation, secondary growth on eroded land, or the vegetation may be classified as alpine.

Table 3-4: Classification system used in Krísuvíkurheiði study (Gísladóttir 1998). Coverage corresponds to the physiognomic layers combined to a total of 100%.

Krísuvíkurheiði vegetation class	Plant species or groups	Coverage of plant species groups
Moss heath	Mosses (*Racomitrium lanigonusum*)	dominant
	Dwarf shrubs (*Empetrum nigrum*, *Salix herbacea*)	frequent
	Graminoids (grasses and sedges)	sparse
	Herbs (*Silene acaulis*, *Thymus praecox* spp. *arcticus*)	sparse
Dwarf shrub heath	Dwarf shrubs (*Empetrum nigrum*, *Calluna vulgaris*, *Salix herbacea*, *Arctostaphylos uva-ursi*, *Vaccinium uliginosum*)	dominant
	Mosses (*Racomitrium* sp.)	frequent
	Graminoids (grasses and sedges)	sparse
	Herbs (*Thymus praecox* ssp. *arcticus*, *Bistorta vivipara*, *Galium* sp., *Thalictrum alpinum*, *Alchemilla alpina*)	sparse
Grass heath	Graminoids (grasses and sedges)	dominate
	Mosses (*Rhacomitrium* sp.)	dominate
	Dwarf shrubs (*Empetrum nigrum*, *Vaccinium uliginosum*, *Calluna vulgaris*, *Salix herbacea*)	dominate
	Herbs (*Thymus praecox* ssp. *arcticus*, *Alchemilla alpina*, *Bistorta vivipara*, *Galium* sp., *Viola* sp., *Bartsia alpina*)	frequent
Grassland	Graminoids (grasses and sedges)	dominant
	Mosses (*Rhacomitrium* sp.)	frequent
	Herbs (*Thymus praecox* ssp. *arcticus*, *Galium* sp., *Cerastium fontanum*, *Bistorta vivipara*, *Viola* sp., *Alchemilla alpina*, *Alchemilla vulgaris*, *Taraxacum* sp., *Ranunculus* sp., *Cardamine nymanii*	sparse
Mire margin	Graminoids	dominate
	Mosses	dominate/frequent
	Ferns (*Equisetum* sp.)	sparse/frequent
	Herbs (*Violaceae* sp., *Taraxacum* sp., *Cerastium fontanum* , *Bistorta vivipara*, *Galium* sp.)	sparse
Sloping fen	Sedges	dominate
	Mosses	frequent/dominate
	Herbs (*Bistorta vivipara*, *Violaceae* sp.)	sparse
Level fen	Sedges	dominant
	Ferns (*Equisetum* sp.)	sparse
Cultivated grassland	Grasses	dominant
	Herbs	sparse
Barren land	Isolated plant species (*Armeria maritima*, *Silene acaulis*)	sparse

Coverage: Dominant – 50% or more; Dominate – more than 20% but less than 50%; Frequent – 11-19%; Sparse – 10% or less.

3.2.1.2 Original fieldwork: botanical composition

Fieldwork was undertaken in Iceland to investigate vegetation composition in the two chosen study areas. This was to ascertain the applicability on the ground of the vegetation classes that had been derived from the literature, and to check that there were no significant vegetation types in the study areas that had been omitted from the classification.

Fieldwork in 2000

Two separate periods of fieldwork were undertaken during 2000, from 28th June-7th July in Eyjafjallahreppur and 1st–7th August in Mývatn hreppur. The fieldwork aim was the investigation of the diversity of vegetation communities in each location and topographical/altitudinal change in the vegetation. This was achieved by recording the different vegetation communities that occurred along a number of transects covering different areas of the landscape (see Figure 3-2 and Figure 3-3). Some of these transects were at the kilometre scale, for the investigation of altitudinal variation, and others were at a scale of tens of meters, looking at the variation in plant communities caused by landscape change (such as river channel changes or lava flows).

2000 fieldwork methodology

The botanical composition was assessed by recording the percentage cover of each plant species found within a five by five metre quadrat (Appendix B1). Moss and lichen species were not differentiated due to field-worker inexperience in identifying these species and because they do not form a significant component of the diet of domestic livestock in Iceland (B. Magnússon, *pers. comm.)*. A total of fifty-one quadrats were recorded in all, 38 in the south and 13 in the north. The plant species recorded were subsequently grouped according to plant type (grasses, sedges and rushes, woody species, herbs, mosses and lichens, horsetails and ferns) following Thorsteinsson (1980a). The percentage cover of each of these plant types within the quadrat was calculated on the scale given in Table 3-5. This composition scale was most useful for the vegetation classification required for the model, which is concerned with the relative palatability of the plant types within the community. In such a situation, an ecological scale such as the Domin scale (Kent and Coker 1992) is less useful as the lower classes, recording the single occurrence of certain species, contribute little to the explanation of the overall palatability of the community. Using field descriptions and the percentage cover of the plant types, each quadrat was assigned to one of the provisional vegetation communities: hayfield, grassy heath, dwarf shrub heath, moss/lichen heath, birch woodland, riverine vegetation, bog/mire and sparsely vegetated land.

Table 3-5: Botanical composition scale for percentage cover of plant types

Scale	Plant type percentage cover
0	0 (absent from quadrat)
1	1 - 10 %
2	11 - 20 %
3	21 - 30 %
4	31 - 40 %
5	41 – 50 %
6	51 – 60 %
7	61 – 70 %
8	71 – 80 %
9	81 – 100 %

Fieldwork in 2001

In 2001, there was one extended period of fieldwork, in Eyjafjallahreppur on 26th July – 1st August, and in Mývatn hreppur from 3rd August- 8th August. Both botanical composition and vegetation biomass were sampled (the biomass measurements are discussed in section 3.6.2). Four of the Búmodel communities were under investigation: grassy heath, birch woodland, riverine vegetation and sparsely vegetated land, as biomass data was already available in the literature for the other communities (RALA 1978-1981, Gísladóttir 1998).

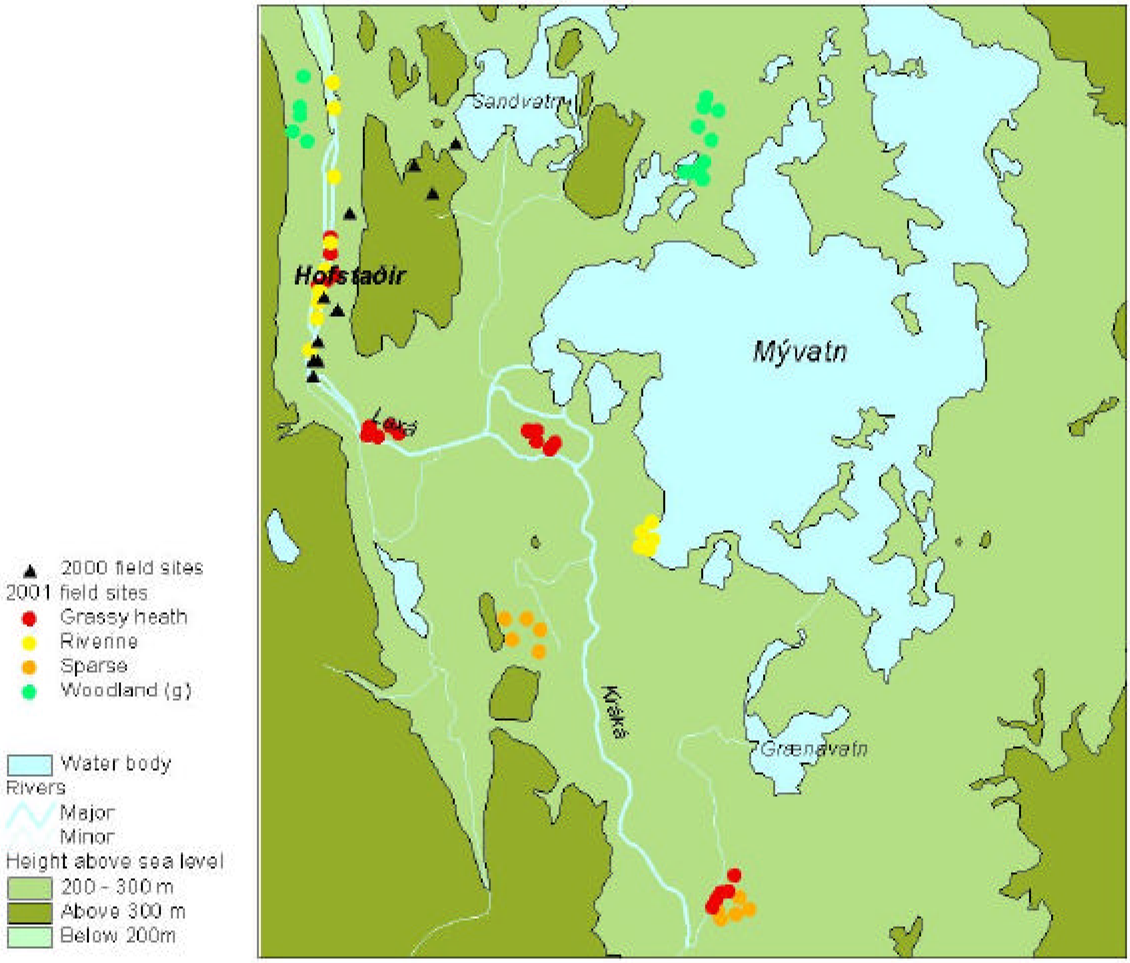


Figure 3-2: 2000 and 2001 fieldwork sites in Mývatn hreppur

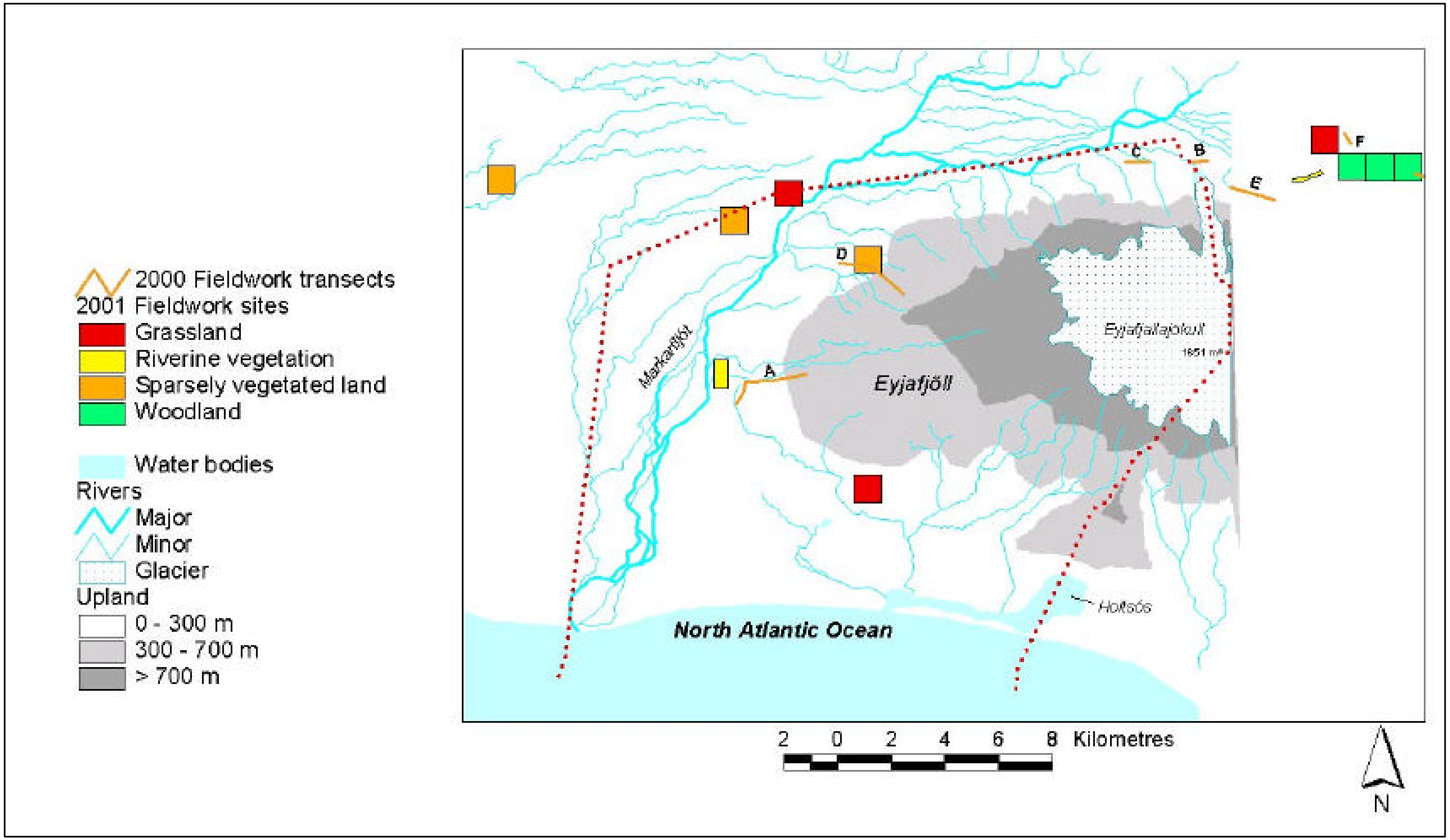


Figure 3.3: 2000 and 2001 fieldwork sites in Eyjafjallahreppur (Topographic data was unavailable for the eastern part of the map)

Both grazed and ungrazed birch woodland sites were visited in order to compare their botanical composition and biomass values (by kind permission of Þröstur Eysteinsson of the Icelandic Forestry Service). It was thought that ungrazed birch woodland might be a suitable proxy for the pre-Landnám lowland dry vegetation cover. There is no ungrazed woodland around Mývatn itself, so measurements were taken at Vaglaskógur national forest 40 km west of Mývatn (17º 54’ W, 65º 43’ N), which reaches to the same elevation (between 100 and 300m), and has been protected from livestock grazing for c. 90 years. No grazed birch woodland existed in Eyjafjallasveit or in the surrounding regions so no sampling was possible in this location.

The Eyjafjallasveit region was problematic for vegetation sampling because the lack of prior vegetation information on the area (there are no published vegetation maps) and problems of accessibility (some areas are inaccessible to vehicles and/or are dangerous to work in). The chosen approach aimed to maximise the use of the available knowledge and to randomise the sampling so that the results could be statistically analysed. This approach was also used in the Mývatn region so that results were comparable, even though a vegetation map has been published for the northern area.

The areas where the vegetation communities were known to exist were shaded on a copy of the topographic map. In the south this information came from a combination of sources: the topographic map (showing areas of scrub woodland and barren areas), the draft vegetation map which covers the upper eighth of the study area, and personal knowledge from fieldwork in 2000. In the north the published vegetation map, covering the entire field area, was used. The kilometre squares that contained any of the four communities were numbered. Three squares were then selected randomly for each vegetation community, omitting squares with a very small coverage of the vegetation community in question (<10%) or squares that were inaccessible due to time or safety constraints (Figure 3-2 and Figure 3-3). The chosen squares were then covered with a 50m lattice. Five sample points were selected within each square, by using pairs of random numbers between 0 and 19 relating to the lattice lines. These positions were translated into GPS positions for locating in the field. As the precise coverage of a vegetation type within each kilometre square was unknown the chosen sample points might not fall within the vegetation community of interest, in which case the next randomly generated position was chosen, and so on. A different approach had to be adopted for the riverine community, which tended to be linearly distributed across small areas. This community was measured by taking random positions along a transect, within the kilometre square.

Botanical composition was sampled within a one metre square quadrat at each sample point. All vascular plant species were separately identified, but the assessment of percentage cover was done using plant types in order to speed up sampling.

The descriptive statistics for the number of plant species are shown in Table 3-6 and Table 3-7. Box-plots showing the range of composition scale values (percentage covers) are given in Figure 3-4, Figure 3-5, Figure 3-6, Figure 3-7 and Figure 3-8. The complete data sets are available in Appendices B1 and B2. The mean species count per quadrat is lower in the 2001 counts, which would be expected given the smaller size of quadrat.

Table 3-6: Vascular plant species counts from 5x5m quadrats surveyed in 2000

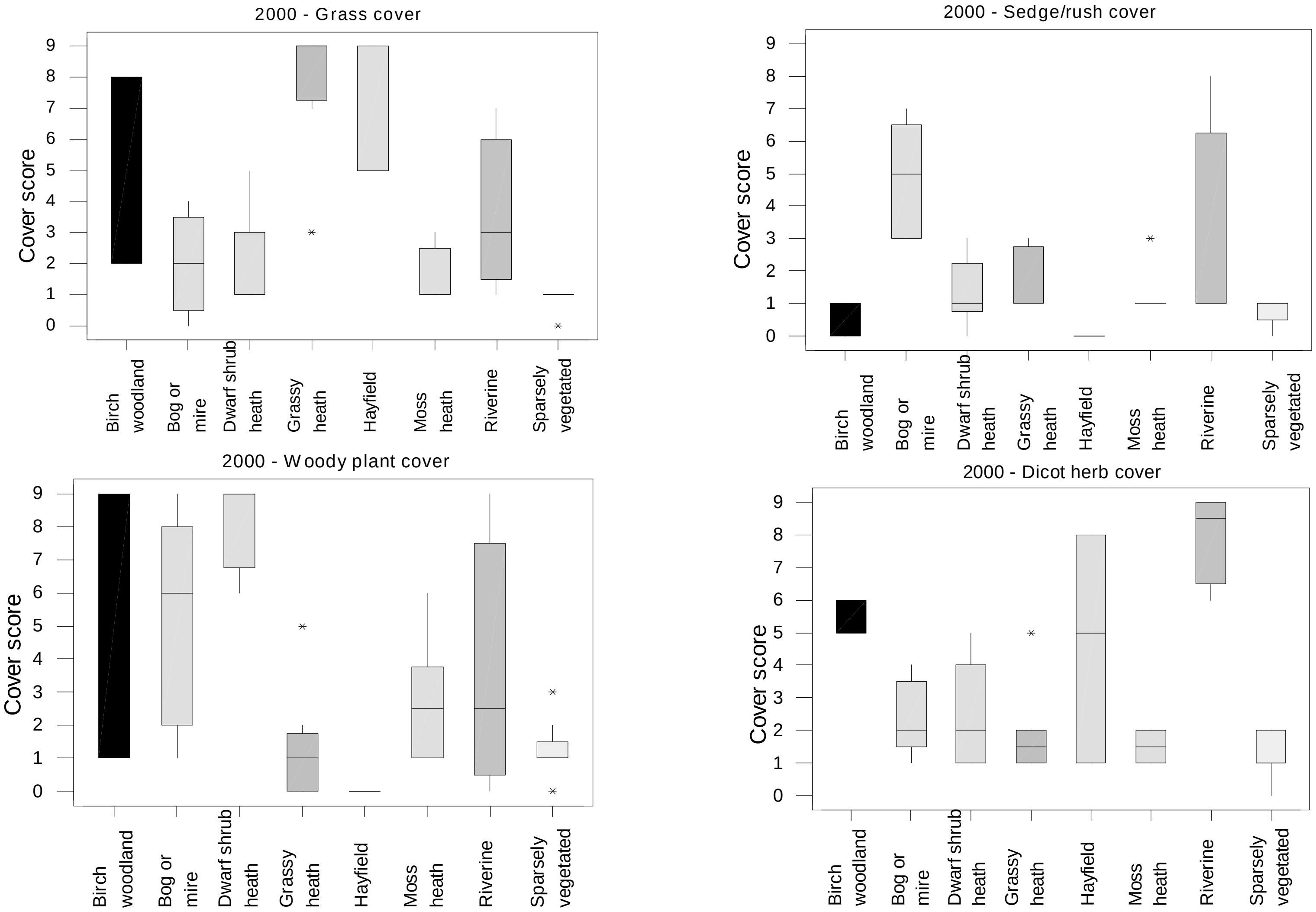
Vegetation community	No. of quadrats	Range of species counts	Mean count per quadrat	St. deviation of counts per quadrat
Hayfield	3	7 – 9	8.3	1.15
Grassy heath	8	9 - 18	13.4	3.74
Dwarf shrub heath	10	14 – 30	19.5	5.82
Moss heath	8	14 - 21	16.6	2.26
Bog or mire	5	10 - 27	16.4	6.80
Riverine	4	12 - 33	22.0	9.35
Birch woodland	2	16	16.0	-
Sparsely vegetated land	9	6 - 21	12.1	4.96

Table 3-7: Vascular plant species counts from 1x1m quadrats surveyed in 2001

Vegetation community	No. of quadrats	Range of species counts	Mean count per quadrat	St. deviation of counts per quadrat
Grassy heath	35	4 - 24	12.6	4.5
Riverine	30	6 - 23	13.2	4.2
Sparsely vegetated land	30	3 - 16	7.3	2.8
Grazed woodland (North)	15	6 - 15	10.6	2.8
Ungrazed woodland	30	4 - 18	11.1	2.7

3.2.1.3 Búmodel vegetation classification

Using this field data and information from the literature the eight vegetation communities were defined in terms of the relative coverage of each plant type (Table 3-8), compared to the total vegetation cover (which could be over 100 per cent) in a unit area. Sparsely vegetated land was defined further as having bare ground comprising more than 70% of the ground cover. The other vegetation types have variable amounts of bare ground within ranges derived from fieldwork observations.


2000 - Grass cover

2000 - Sedge/rush cover

2000 - Woody plant cover

2000 - Dicot herb cover

Figure 3-4: Box plots of plant composition cover scores, showing interquartile range, from 2000 fieldwork (grass, sedge/rush, woody and dicot herb cover scores)

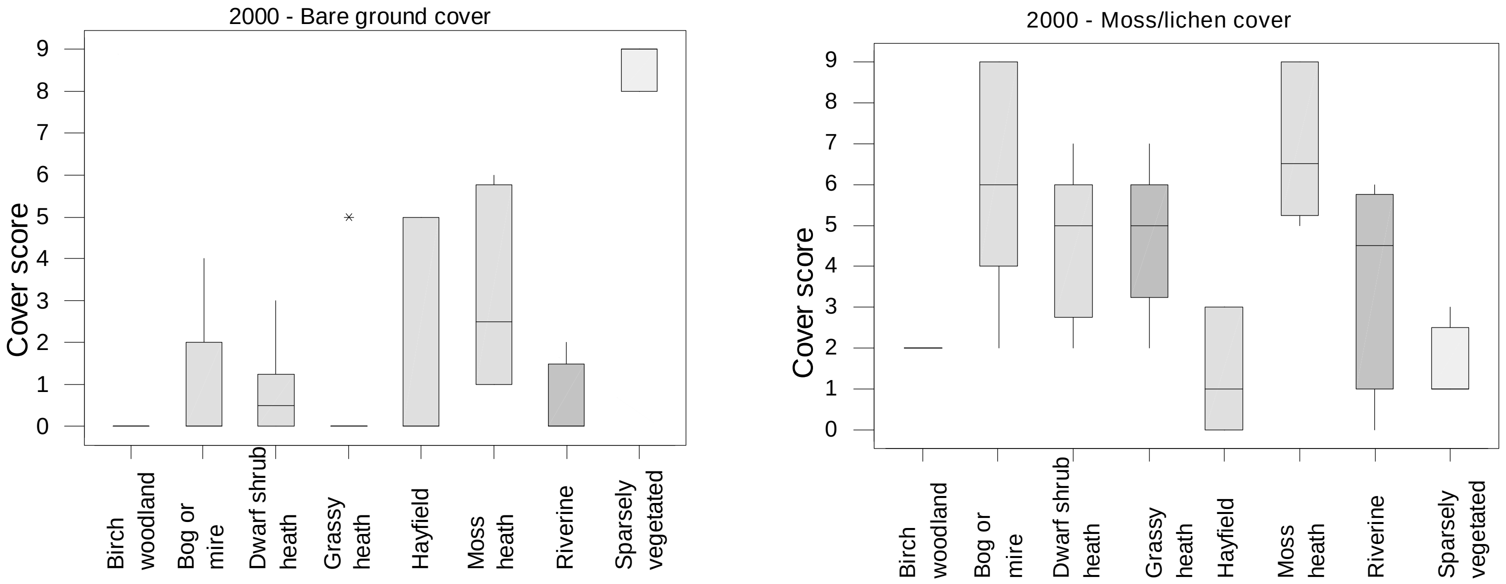


Figure 3-5: Box plots of plant composition cover scores, showing interquartile range, from 2000 fieldwork (moss/lichen and bare ground cover scores)

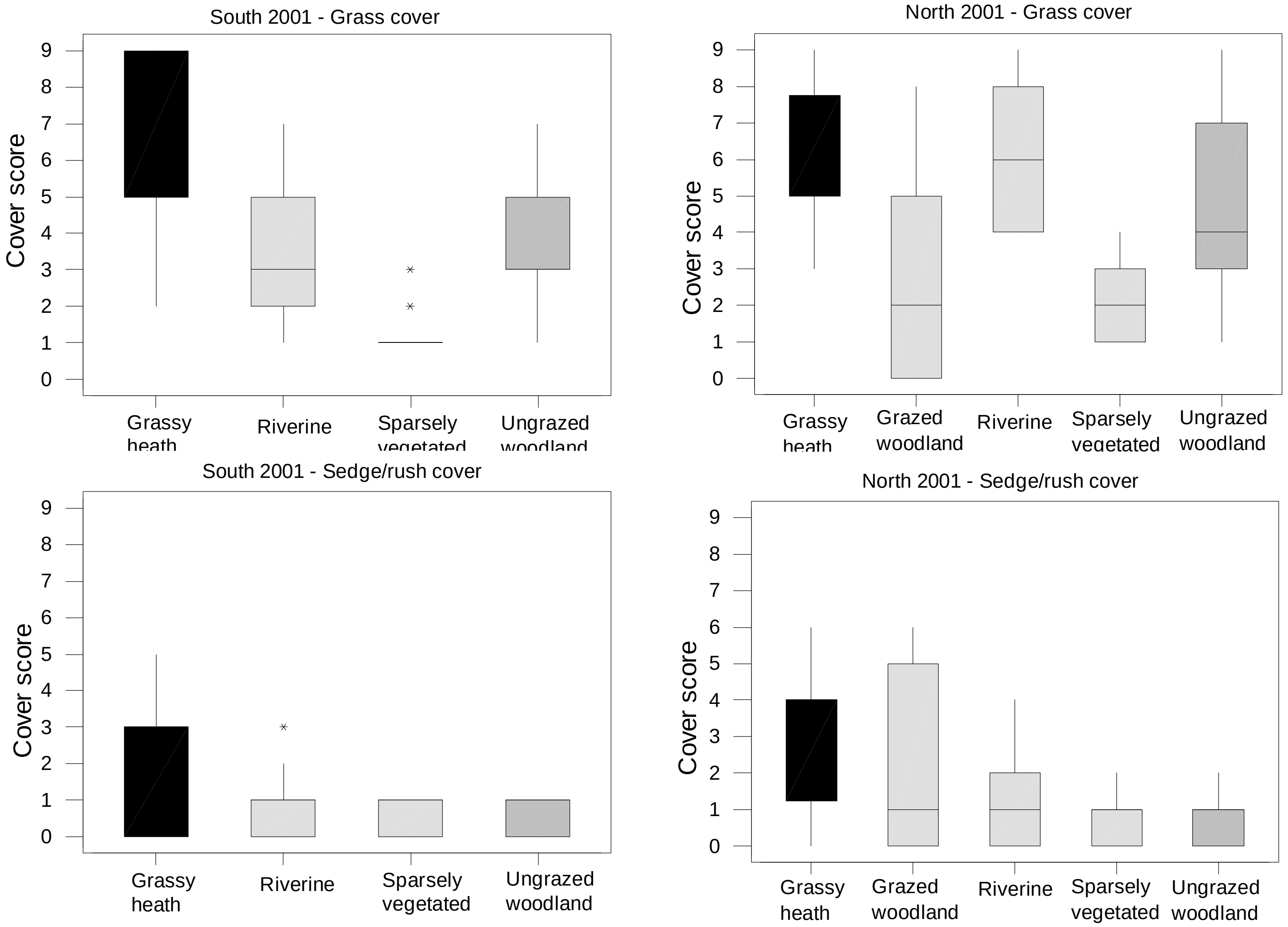


Figure 3-6: Box plots of plant composition cover scores, showing interquartile range, from 2001 fieldwork (grass and sedge/rush cover scores)

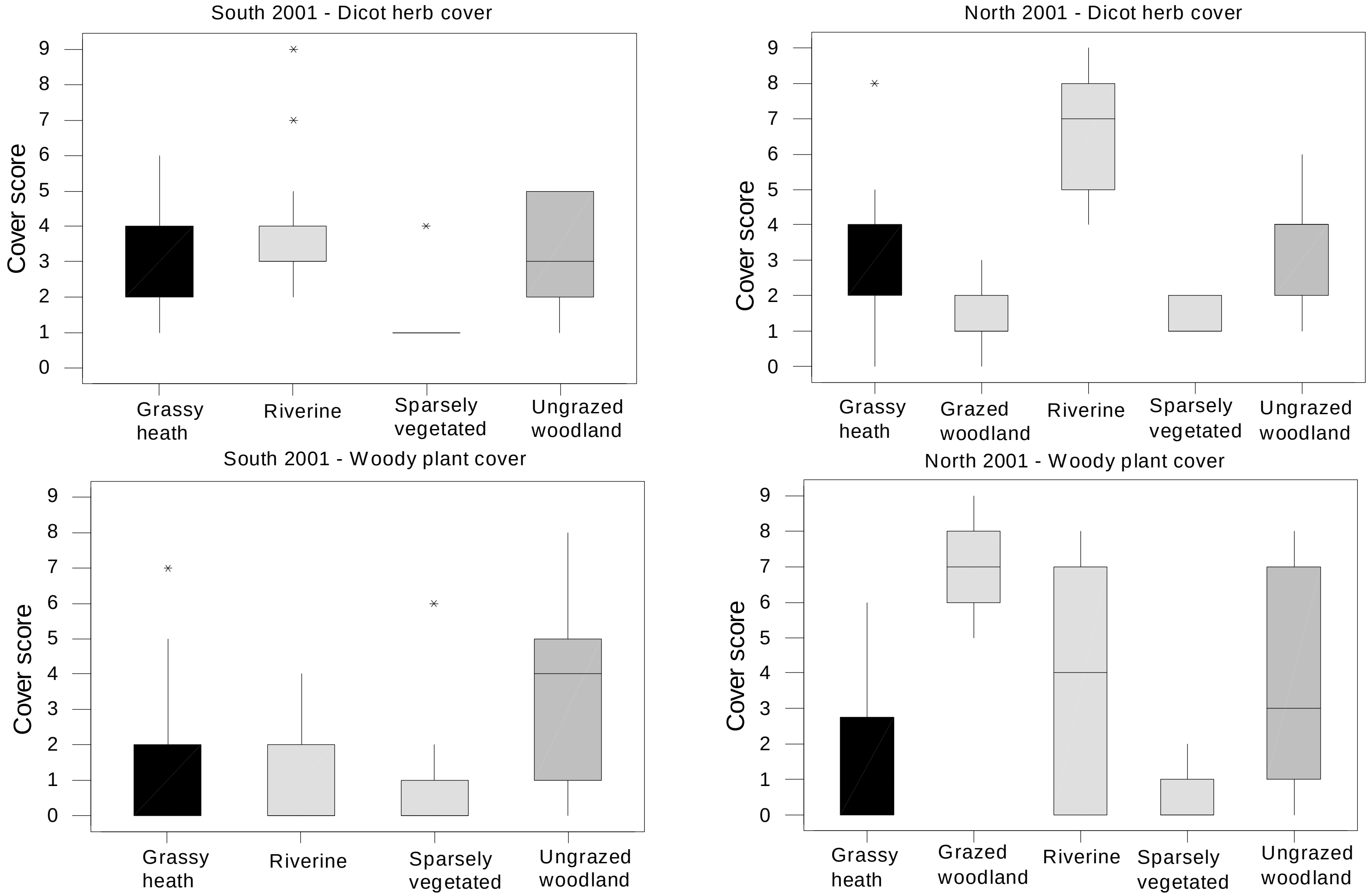


Figure 3-7: Box plots of plant composition cover scores, showing interquartile range, from 2001 fieldwork (dicot herb and woody plant cover scores)

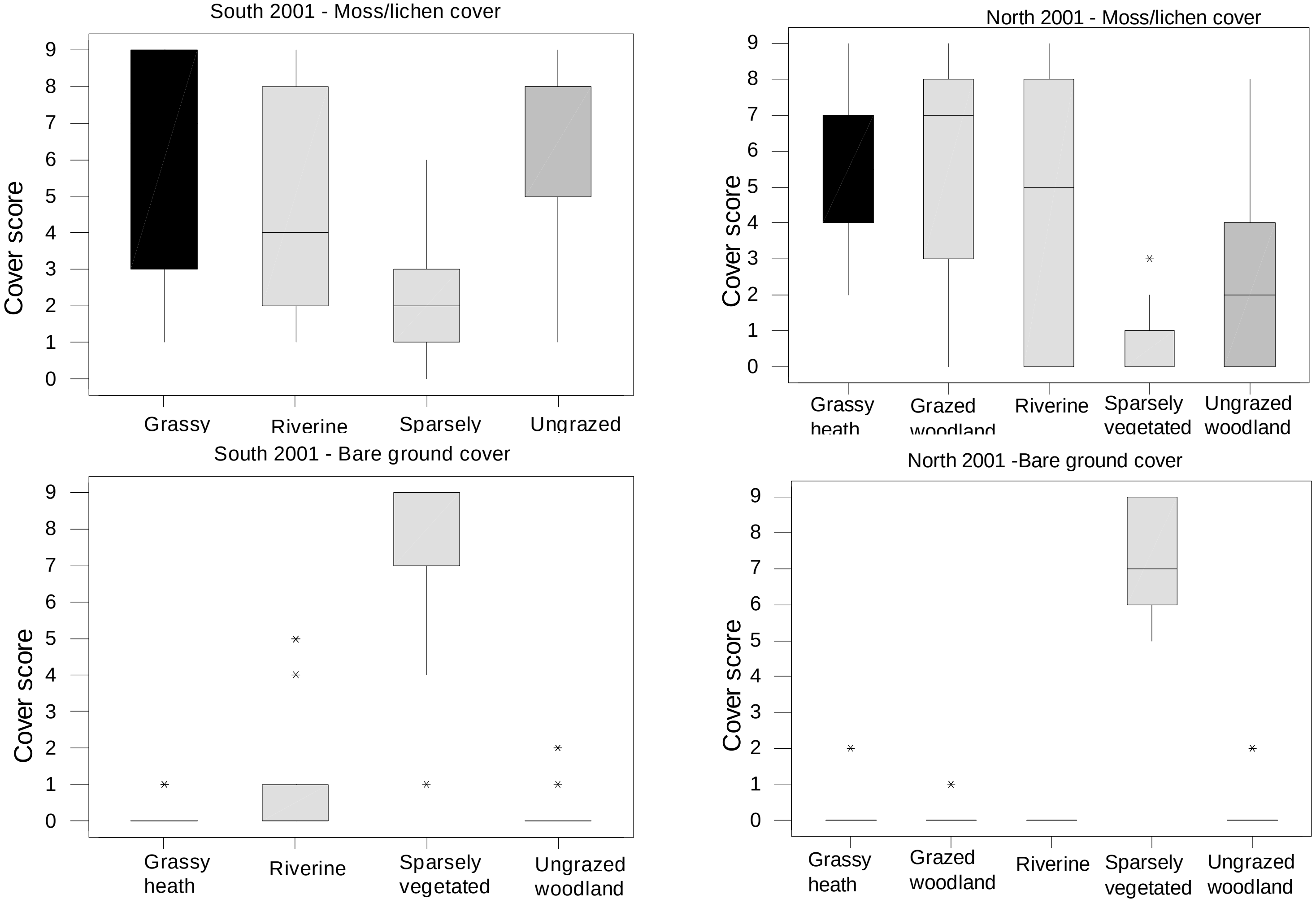


Figure 3-8: Box plots of plant composition cover scores, showing inter-quartile range, from 2001 fieldwork (moss/lichen and bare ground cover scores)

3.2.2 Land use categories

The farm and the surrounding landscape represented within Búmodel can be divided into three zones of activity: the tún or infield area, the lowland outfield area, and the rangeland. Each zone is managed in a distinct way, and the intensity of activity within each zone varies over the year (see section 1.3.2). The extent of each zone can change over time, for example through the abandonment of farmsteads or through landscape change.

3.2.2.1 The *tún* zone of activity

The *tún* area is a relatively small component of the total grazing land, usually centred upon the farmstead itself. It is well defined, being bounded by dykes or walls. In the past it was the only area of cultivated land on the farm, receiving the manure produced by the winter-byred livestock. The *tún* was principally used for hay production, although possibly it was grazed at other times of the year, for example in early summer before the highland ranges became accessible. In Búmodel it is assumed that the tún area is inaccessible to grazing throughout the year.

3.2.2.2 The outfield zone of activity

The outfield is the area of privately owned uncultivated land, outwith the farm buildings and the *tún*, which is the private property of the farm. It was principally used for the grazing of livestock, although some areas of bog or grassland would also have been mown for hay, although not necessarily every year (Aðalsteinsson 1990).

The outfield area could be large and extend some distance from the farmstead itself. It was often enclosed, but sometimes there were no boundaries between the pastures of neighbouring farms, and livestock were allowed to roam freely.

Table 3-8 : Búmodel vegetation community composition

Vegetation community	Grass	Sedges and rushes	Woody species	Dicot herbs	Moss and lichen	Horsetails and ferns	Bare ground	Additional definitions
Hayfield	50 - 95%	-	-	10 - 20%	0 – 15%	-	-	Grasses and herbs are > 85% of total cover
Grassy heath	20 - 50%	0 – 20%	0 – 20%	1 – 30%	1 - 40%	0 – 5%	0 – 15%	Grasses and herbs make up 50-80% of total cover
Dwarf shrub heath	5 – 25%	0 – 20%	40 – 80%	5 – 20%	10 – 40%	0 – 15%	0 – 20%	Woody species are dominant, >40% of total cover
Moss heath	5 – 20%	5 – 15%	5 – 25%	5 – 20%	50 – 95%	0 – 5%	5 – 50%	Mosses and lichens are >50% of cover
Bog or mire	0 – 20%	15 - 50%	0 – 30%	0 – 20%	5 – 40%	5 - 20%	0 – 15%	Sedges and rushes are dominant, ground is permanently or periodically waterlogged
Riverine vegetation	10 - 40%	0 – 20%	0 – 30%	10 - 45%	0 – 30%	0 – 20%	0 – 10%	Herbs must be one of the dominant plant types
Grazed Birch woodland	0 - 30%	0 – 10%	20 - 40%	0 - 15%	15 - 40%	0 - 10%	0 – 15%	Birch trees must be present, but no one plant type need have dominance
Sparsely vegetated land	0 – 15%	0 – 10%	0 – 10%	0 – 10%	0 – 15%	0 – 10%	70-100%	More than 70% bare ground cover

As vegetation can consist of several layers, the total vegetation cover can total more than 100%. The percentages listed above are those of the plant types compared to the total vegetation cover (apart from bare ground, which is a percentage of the actual ground surface area)

3.2.2.3 The rangeland zone of activity

The rangeland was the extensive grazing area beyond the boundaries of the outfield. The vegetation within this area could consist of anything from relatively productive heathland to barren desert (Arnalds *et al*. 2001). It was used only for the summer grazing of sheep and horses and extended into the interior uplands of the country. The rangeland was often owned by the community or *hreppur*, and constituted part of the *afréttur*, or common resources of that community. However, a rangeland area could also be privately owned by one or more individuals, and either used exclusively by the owner(s) or leased to other farmers. Natural barriers, such as rivers or glaciers usually, but not always, defined the limits of the rangeland. If the afréttur extended into the interior desert the furthest boundary could be very indistinct, or even non-existent, as in practical terms the rangeland area was so vast that the sheep rarely strayed beyond the boundaries.

3.2.3 Climate scenarios

The climate of Iceland is discussed in detail in Chapter 1. As Búmodel models vegetation biomass and its utilisation in the past, and climatic variables affect the growth of vegetation, it is necessary to represent these climatic variables in some way within the model. Consistent meteorological observations of temperature are available from Stykkishólmur, on the west coast, from 1845 onwards and for precipitation from 1857, at the monthly time-scale (Figure 1-2). This record is generally fairly representative of the lowlands, both in terms of the mean and the annual range of temperatures (Sigfúsdóttir (1969) in Bergþórsson *et al*. (1987)). However, we also wish to use Búmodel for simulations further back in time, when documentary sources can give a general representation of the prevailing climate (Bergþórsson 1969; Ogilvie 1984, 1990, 1992) but no precise meteorological data is available. The chosen solution to this problem of climatic simulation is to use generalised climatic scenarios rather than attempting to estimate monthly variables from qualitative documentary sources. These scenarios can then be matched to years in the historic period using the available historical evidence. This approach has been used in palaeoclimatic reconstruction in the north of Iceland (Stötter *et al*. 1999).

The climate of Iceland is highly variable at all time scales:

> ‘There is a tendency for clustering of years into sequences of anomalously cool or anomalously warm conditions…periods such as 1860s and the 1880s registered mean annual temperatures more than 2ºC lower than those recorded in the warm 1930s and 1940s.’ (Bergþórsson *et al.* 1987): 398.

Climatic scenarios covering this range of mean annual temperatures have been previously constructed for a study of the impact of climatic variations on agriculture in Iceland (Bergþórsson *et al.* 1987). Using the long series of temperature observations at Stykkishólmur, four scenarios were defined: the baseline or reference scenario, two cold scenarios and a warm scenario. These scenarios will be adapted for the two study areas used in Búmodel.

Precipitation was not included as a parameter in Búmodel. Generally, the availability of water does not appear to be a limiting factor for plant growth in Iceland (see section 4.3.4), although areas in the rain shadows of the large glaciers may suffer from summer moisture stress. It is difficult to draw out the exact impact of precipitation: a short period of intense precipitation may have a great impact upon plant growth but contribute comparatively little to the annual precipitation sum. In addition, precipitation is highly variable on a monthly scale, and it would be difficult to construct representative scenarios where precipitation and temperature considered together had a greater impact upon plant growth than temperature alone.

The nearest meteorological stations to the two study areas are Reykjahlíð in Mývatn hreppur and Sámsstaðir, which is adjacent to the southern study area (Figure 1-2). Both have been operational for a shorter period than the Stykkishólmur station, Reykjahlíð from 1937 to the present day, and Sámsstaðir from 1930 to 1995. Monthly climatic data for these stations is available from the Icelandic Meteorological Office website (Icelandic Meteorological Office 2001).

3.2.3.1 The baseline scenario I

In the study by Bergþórsson *et al*. (1987) the 30-year period 1951-1980 was used as the baseline scenario. The mean annual temperature at Stykkishólmur during this period was 3.7 ºC, which was higher than the long-term mean (1851-1950) of 3.3 ºC.

Table 3-9: The climate scenarios selected for the northern study area, Mývatn hreppur

	I **Baseline**	**II** **Extreme cold**	**III** **Cold**	**IV** **Warm**
	Reykjahlíð (1961-1990)	*1859-1868 type*	*Average of 10 coldest years 1937 - 1995*	*Average of 10 warmest years 1937 - 1995*
Month		**Mean monthly temperature, ºC**		
January	-4.8 ±2.6	-6.6 ±3.3	-5.4 ±2.5	-4.1 ±3.5
February	-4.1 ±2.4	-7.1 ±3.3	-5.7 ±2.7	-2.9 ±1.8
March	-3.5 ±3.1	-8.6 ±3.5	-5.5 ±2.7	-0.7 ±1.6
April	-0.3 ±2.0	-3.4 ±4.0	-1.0 ±1.6	-0.2 ±1.8
May	4.0 ±2.1	1.9 ±2.2	2.5 ±2.2	6.2 ±1.1
June	8.3 ±1.4	6.6 ±1.0	8.0 ±1.5	8.9 ±1.7
July	9.9 ±1.4	9.2 ±1.2	8.9 ±1.5	11.3 ±1.0
August	9.0 ±1.2	8.5 ±0.9	8.9 ±1.2	9.9 ±1.5
September	4.8 ±1.4	5.6 ±1.0	4.8 ±1.7	7.4 ±1.8
October	1.2 ±1.7	0.8 ±1.4	0.2 ±1.9	3.3 ±1.9
November	-2.7 ±2.1	-2.6 ±2.6	-3.8 ±2.4	-1.0 ±2.1
December	-4.5 ±2.0	-4.1 ±2.7	-5.1 ±1.7	-2.3 ±2.4
Year	**1.4 ±0.8**	**0.0 ±1.2**	**0.6 ±0.4**	**3.0 ±0.2**

Table 3-10: The climate scenarios selected for the southern study area, Vestur-Eyjafjallahreppur

	I	**II**	**III**	**IV**
	Baseline	**Extreme cold**	**Cold**	**Warm**
	Sámsstaðir (1961-1990)	*1859-1868 type*	*Average of 10 coldest years 1937 - 1995*	*Average of 10 warmest years 1937 - 1995*
Month	**Mean monthly temperature, ºC**			
January	-0.3 ±2.0	-1.7 ±2.6	-0.7 ±2.3	0.7 ±2.2
February	0.5 ±1.7	-2.2 ±2.6	-0.9 ±1.6	0.8 ±1.7
March	0.7 ±2.1	-3.3 ±2.8	-0.9 ±1.9	3.2 ±1.4
April	3.4 ±1.2	0.8 ±3.1	2.7 ±1.1	3.7 ±1.4
May	6.8 ±1.1	4.9 ±1.8	6.2 ±1.4	8.2 ±0.9
June	9.4 ±0.7	8.7 ±0.8	9.1 ±0.6	10.4 ±0.6
July	11.0 ±0.7	10.7 ±1.0	10.4 ±0.6	12.2 ±1.0
August	10.5 ±0.6	10.2 ±0.7	10.5 ±0.6	11.0 ±0.8
September	7.4 ±1.1	7.8 ±0.8	7.3 ±1.1	9.0 ±1.5
October	4.4 ±1.4	4.1 ±1.1	3.8 ±1.5	5.3 ±1.7
November	1.1 ±1.7	1.4 ±2.1	0.4 ±1.4	2.9 ±1.7
December	-0.2 ±1.7	0.2 ±2.1	-0.7 ±1.5	1.6 ±1.8
Year	**4.6 ±0.5**	**3.5 ±1.0**	**3.9 ±0.3**	**5.8 ±0.3**

For this study the 30-year period 1961-1990 was used as the baseline scenario. The mean annual temperature at Stykkishólmur was 3.5 ºC; at Reykjahlíð, 1.4 ºC; and at Sámsstaðir, 4.6 ºC. The mean monthly temperatures of each scenario are shown in Table 3-9 and Table 3-10.

3.2.3.2 The extremely cold scenario II (1859 to 1868 type)

The coolest decade during the instrumental record at Stykkishólmur was from 1859 to 1868 when the mean annual temperature was only 2.4 ºC. This scenario was chosen by the Icelandic study because ‘many of the most adverse impacts on Icelandic agriculture historically were associated with below-average temperatures, particularly when such conditions occurred in successive years’ (Bergþórsson *et al.* 1987): 407. The Stykkishólmur record is thought to be fairly representative of the lowlands, both in terms of the mean and the range of the annual temperatures (Bergþórsson *et al.* 1987).

Neither of the meteorological records in our study area extends back into the 19th century so it is not possible to use the actual monthly temperature data. However, regression analyses of the Sámsstaðir and Reykjahlíð temperature records, from 1937 to 1995, against the matching Stykkishólmur record showed that there was a high degree of correlation between the records. Therefore it is highly probable that 1859-1868 was also an extremely cold decade in the south and north of Iceland. The regression equations produced by the analysis (Equation 3-1 and Equation 3-2) can be used to predict the mean monthly temperatures for 1859-1868 from the Stykkishólmur record.

[Reykjahlíð] $A = -3.11 + 1.29S$ $s = 1.007$ R-sq. (adj.) = 96.8%

Equation 3-1

[Sámsstaðir] $B = 0.978 + 1.02S$ $s = 0.843$ R-sq. (adj.) = 96.4%

Equation 3-2

Where **A** is the mean monthly temperature at Reykjahlíð (ºC), **S** is the mean monthly temperature at Stykkishólmur (ºC) and **B** is the mean monthly temperature at Sámsstaðir (ºC). All of the coefficients and predictors were significant at the 99.9% level.

Mean annual temperature during this decade was 0.0 ºC at Reykjahlíð and 3.5 ºC at Sámsstaðir (Table 3-9 and Table 3-10). There was no correlation between the mean annual temperature and the total annual precipitation at either station. The main difference between this and the baseline scenario is the much cooler temperatures in winter and spring between January and May.

3.2.3.3 The cold scenario III (average of 10 coldest years 1937 - 1995)

This scenario and the warm scenario were based on the extreme years in the recent period (post-1937) from the observational record. These scenarios represent a ‘typical’ cold or warm year, as opposed to an extremely cold year in scenario II. The ten coolest years from 1937 to 1995 had a mean annual temperature of 0.6 ºC at Reykjahlíð and 3.9 ºC at Sámsstaðir. This scenario is mid-way between the baseline scenario and the extremely cold scenario. Summer temperatures are slightly lower than those in the baseline scenario are, but not significantly so.

3.2.3.4 The warm scenario IV (average of 10 warmest years 1937 - 1995)

The ten warmest years from 1937 to 1995 had a mean annual temperature of 3.0 ºC at Reykjahlíð and 5.8 ºC at Sámsstaðir. Mean temperatures are higher in mid-summer than the other scenarios, and monthly temperatures are also warmer in winter. In scenario IV at Sámsstaðir the mean monthly temperature does not fall below 0 ºC at any point during the year.

3.3 Livestock inputs

In order to model grazing within the agricultural system represented by Búmodel information is required on the number and type of livestock, their basic nutritional requirements and their utilisation of system resources. The Icelandic agricultural system in the pre-modern period was dependent upon its livestock: sheep, cattle and horses. Ideally all three types of livestock should be modelled, but this is not possible with the currently available information, so only sheep are included in Búmodel. The research literature on sheep is much more extensive than that available for either cattle or horses. Modern Icelandic agriculture is dominated by sheep rearing and the basic system of unsupervised grazing in the uplands and over-wintering in the lowlands has not changed overmuch, although indoor feeding in the winter is now much more common. There was not enough information on the basic nutritional requirements and grazing practices of cattle and horses to include them as separate livestock types, although they could be represented within the model as an equivalent number of sheep (Friðriksson 1972). The use of proxy information from livestock from other countries was though to be unacceptable as the Icelandic breeds have been isolated from outside influences since the twelfth century, and there are no closely related and well-studied breeds in Scandinavia or northern Europe which could be used as analogies for Icelandic breeds.

3.3.1 Flock size and composition

Sheep within the model are assigned to one of four cohorts: fertile ewes, lambs, immature or barren ewes and rams/adult wethers (gelded rams). These cohorts may be managed in different ways and have different fodder requirements according to processes such as growth or lactation. Information on flock size and composition has been obtained from historical records, archaeological evidence and the Icelandic historical/agricultural literature.

The majority of the flock would have been composed of fertile ewes and lambs, with a few rams and immature sheep retained for flock replacement purposes (Aðalsteinsson 1990). Wethers were kept for meat and wool production. The farm census undertaken in the early 18th century ((Magnússon and Vídalín 1913-1990)) records the numbers of different cohorts of livestock and indicates that 60% of the flock was made up of fertile ewes. This is a useful comparison for later agricultural records, which sometimes record only the total flock numbers.

The relative proportions of the different cohorts change during the annual cycle with births and the autumn slaughter (natural mortality is not included within Búmodel). The dates of lambing and of slaughter are presently fixed on 1st May and 30th September respectively. Although in the present day the fertility rate of ewes is well over 100%, with frequent multiple births, the fertility rate would have been much lower in the past. The Farmpact model ((McGovern 1995)) developed for medieval Greenland allows the fertility rate to be varied between 50 and 70%, but a rate of 60% is given as being the most realistic as it allows for the human consumption of dairy produce and male and castrated animals. Búmodel allows the exact number of lambs to be specified so that the effect of changes in fertility can be investigated. The number of sheep slaughtered each year would have varied according to their body condition and the outlook for the coming winter, so these numbers can also be specified. Aðalsteinsson (1990) states that lambs equal to 16% of the number of ewes would have to be retained each year to allow for flock replacement. However, farmers might retain more in order to expand their herds or retain fewer if the outlook for the winter was poor.

3.3.2 Livestock body weight

The basic nutritional requirement of an animal can be calculated from its body weight. Within Búmodel the fodder intake of individual sheep (apart from lambs) is restricted to the amount of fodder that is needed for an animal to function normally, i.e. to maintain its bodily functions. Fodder requirements for weight gain are in addition to this maintenance requirement, and only lambs are permitted to gain weight within the model.

Aðalsteinsson (1990) reviews the average carcass weights of different cohorts of sheep in the 19th century. When contemporary live body weight and carcass body weight were compared (RALA 1978a, 1978b, 1979, 1980, 1981) carcass weight was estimated to be 39 % of the live body weight. This ratio is used to calculate the equivalent live body weights of the 19th century sheep cohorts (Table 3-11). It is possible to run the model with any chosen body weight, but the nineteenth century figures indicate realistic weight ranges prior to the introduction of modern farming methods.

Historical and anecdotal evidence indicates that sheep could lose weight over the winter due to lack of fodder. A reduction in body-weight also results in a reduction in the maintenance requirement of the animal. Although Ball *et al.* (1998) found that maintenance requirements declined in the early stages of weight loss when scaled for empty body weight, the relationship between body weight and maintenance requirements is held constant in Búmodel. A reduction in body weight of up to 40% can be explicitly specified, which occurs in December.

Table 3-11 : Estimated live weight of sheep from carcass weights given in (Adalsteinsson, 1990), assuming a carcass percentage of 39 %.

Description	Average carcass weight, kg	Estimated live weight, kg
Adult ewes	16 - 20	41 – 51
Adult wethers, good condition	24 – 32 (max. of 36 kg)	62 - 82
Lambs, separated from dam in summer	9 – 10 (range of 7.5 – 15 kg)	23 – 26
Lambs, suckled dams through summer	13.5	34.5
18 months old sheep	16.0	41
2 year old wethers	22.5	58
Older wethers	26.0	67
Barren ewes	22.5	57
Suckled or milked ewes	15.0	39

Chapter 4: The construction of the grazing model II: Processes and outputs

This chapter describes the process components of the model shown in Figure 3-1. The model processes included in Búmodel are based upon the dominant ecological processes at work in Iceland and the internal process parameters are derived from Icelandic agricultural research.

4.1 Maintenance feed requirements sub-model

The maintenance fodder requirements of individual animals in each livestock cohort are calculated within this sub-model, based upon live body weight and grazing conditions. The sub-model structure is shown in Figure 4-1. In Búmodel, only the maintenance requirement is calculated for adult animals; lambs are treated separately, and both their maintenance requirements and additional fodder for growth are calculated.

In order to predict the amount of vegetation that is removed from the pastures by grazing, it is necessary to know the numbers of livestock in the system, and the quantity of fodder each animal would need to consume for bodily maintenance (and growth, for juveniles). The maintenance requirement is described in feed units, rather than in units of weight, as the energy values of Icelandic vegetation communities range from 0.455 to 0.667 feed units per kg of vegetation dry matter (Table 4-1). The conversion of feed units into units of weight is undertaken in the offtake sub-model (section 4.5). The output of maintenance requirements sub-model is a table for each sheep cohort showing the monthly maintenance feed requirement for an individual animal grazing on each of the land-use categories.

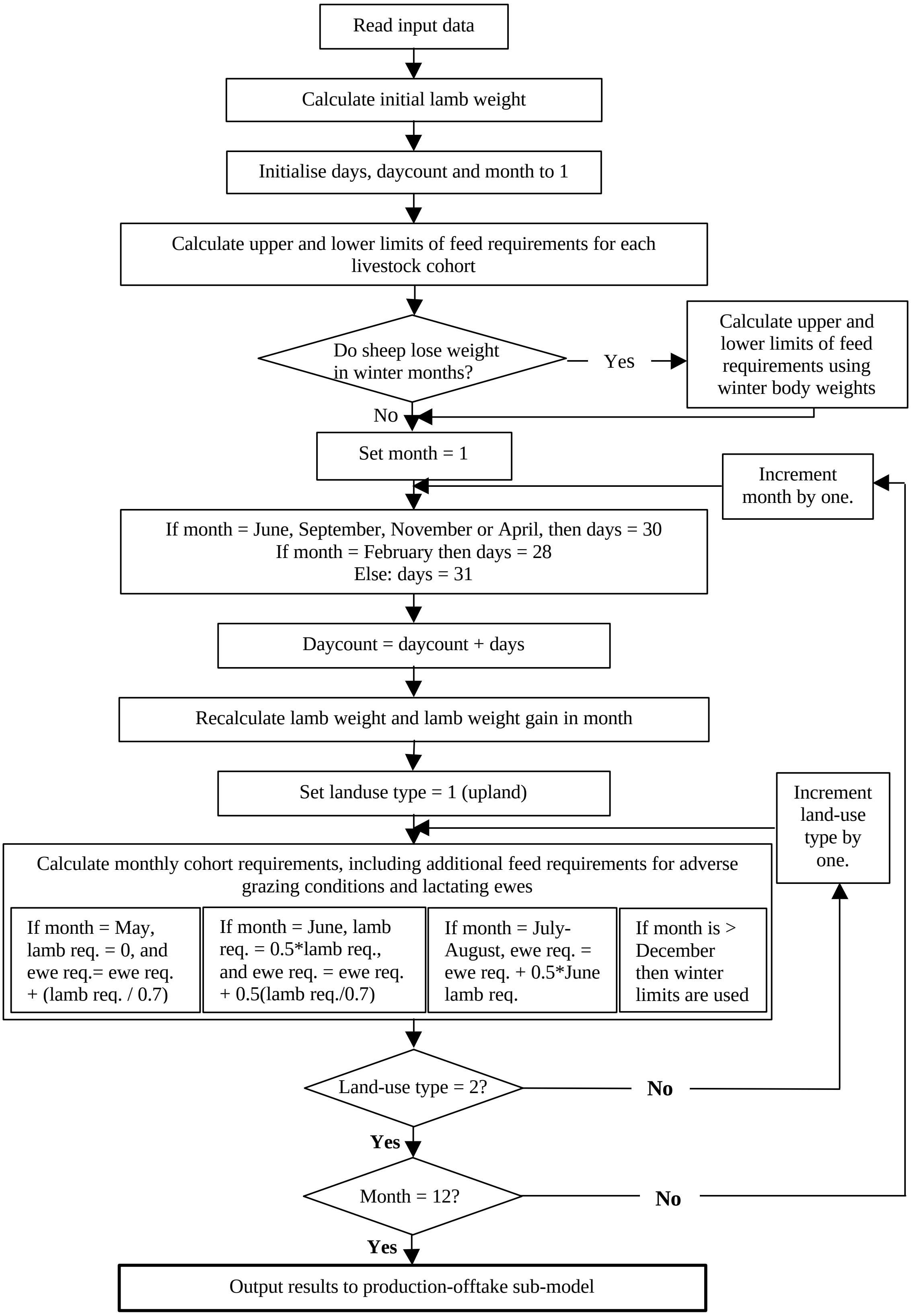


Figure 4-1: Maintenance requirements sub-model structure

Table 4-1: Feed unit value of Búmodel vegetation communities (adapted from Thorsteinsson (1980c))

Búmodel vegetation community	Kg DM/feed unit	Feed units/kg
Grassy heath	1.5	0.667
Dwarf shrub heath	2.1	0.476
Moss heath	1.6	0.625
Bog/mire	2.2	0.454
Riverine	1.6	0.625
Birch woodland	1.7	0.588
Sparsely vegetated land	1.7	0.588

4.1.1 Calculation of maintenance requirements for adult sheep

Maintenance fodder requirements are calculated according to live body weight, and grazing conditions. This calculation is based upon research derived from Breirem in Ólafsson (1980). The feed requirement for a sheep of a certain body weight is given as a range of values (Table 4-2). The upper and lower limits of this range can be plotted, producing an equation of

$$Y = 0.0084x + 0.1737$$

Equation 4-1

for the upper range limit, and an equation of

$$Y= 0.0071x + 0.1383$$

Equation 4-2

for the lower range limit, where y is the feed unit maintenance requirement and x is live weight in kilograms. In the maintenance sub-model the individual feed requirement of each sheep cohort is randomised between the upper and lower maintenance limits

$$\textit{Individual feed requirement} = z * (\textit{upper limit} - \textit{lower limit}) + \textit{lower limit}$$

Equation 4-3

where z is a randomly generated number greater than or equal to 0 and less than 1.

Table 4-2: Maintenance feed requirements for sheep (Breirem in Ólafsson (1980))

Live weight of ewes (kg)	Feed units/day
30 (25-35)	0.34-0.41
40 (35-45)	0.42-0.51
50 (45-55)	0.50-0.60
60 (55-65)	0.57-0.69
70 (65-75)	0.64-0.77
80 (75-85)	0.71-0.85
90 (85-95)	0.77-0.93
100 (95-105)	0.84-1.00

(The feed requirements are based on that of a ewe weighing 50 kg. The energy requirements of heavier and lighter animals are calculated from the body weight, using a factor of 0.75.)

4.1.2 Calculation of fodder requirements for lamb growth

Lambs require energy for growth and development in addition to their maintenance fodder requirements. There is not a growth rate equation directly available for Icelandic lambs, although slaughter weights are known and birth weights can be estimated. In the MLURI Hill Grazing Management Model (Armstrong *et al.* 1997b) lamb live weight is calculated using the number of days since birth (T_L) and the weight, W of the ewe in the previous autumn:

$$\textit{Lamb live weight, kg} = 0.00458T_L + 0.0783W$$

Equation 4-4

Assuming a birth weight of 3.5 kg at the start of May, this gives a 35kg lamb at the end of September. This equation can be adjusted for Iceland, to take account of the lower body weight in autumn. If an autumn weight of 25kg is assumed, and the effect of ewe weight remains constant, then:

$$\textit{Lamb live weight} = 0.00312T_L + 0.0783W.$$

Equation 4-5

This is the equation used in Búmodel. The feed units required for each kilogram of growth increase with age and are given in Table 4-3. The maintenance requirement of lambs is assumed to increase with body weight at the same rate as it does for adult sheep.

Table 4-3: Feed requirements of lambs for growth (Breirem in Ólafsson (1980))

Age of lambs (months)	Feed units/kg of growth
1	1.4
2	1.5
3	1.8
4	2.1
5	2.5
6	2.9
7	3.3
8	3.4
9-12	3.5

Lambs are fed solely on ewes' milk for their first six weeks of life, at the end of which they are weaned. Only 70% of the feed units consumed by the mother for milk production are passed on to the lamb through the milk, and this is taken into account in the model. Milking of the ewes continues after the lambs have been weaned, but lactation declines over the course of the summer, before ceasing entirely in August.

4.1.3 Grazing conditions

The prevailing grazing conditions also influence the maintenance fodder requirements. Maintenance requirements are greater for grazing than byred livestock, and are affected by the location, type and condition of the available pasture, i.e. whether it is cultivated or native vegetation, wet or dry, level or mountainous, sheltered or exposed. Breirem's methods were based upon ewes housed and fed indoors, and the results must be adjusted to take account of the additional energy requirements of sheep living out of doors. The calculated maintenance requirements are adjusted to take account of the variable grazing conditions in Iceland using research by Guðmundsson (1991) in Table 4-4. In Búmodel the grazing conditions can be represented by the land use category and the climatic scenario in combination (Figure 4-2). If the livestock are kept and fed indoors, then no adjustment of the feed requirements is necessary.

Table 4-4: Adjustment in maintenance requirement for different grazing conditions (from Guðmundsson (1991))

Pasture Class	Grazing conditions	Increase in maintenance requirements
1	Good cultivated land, good weather	10%
2	Average cultivated land or good native pasture	25%
3	Heavily grazed cultivated land or average native pasture	50%
4	Mountainous rangeland, long grazing times	75%
5	Poor mountainous rangeland, in bad weather	<100%

4.2 Vegetation palatability and plant preferences sub-model

Vegetation at the landscape scale is spatially and temporally heterogeneous; both between plant communities and within plant communities. This heterogeneity in vegetation promotes a spatially complex grazing pattern, as livestock graze selectively (Arnold and Dudzinski 1978). The selection of certain areas for grazing is governed by their accessibility, and the quantity and palatability of the plants that grow in those areas. Within Búmodel the accessibility of the grazing area is controlled by the GIS component and the quantity of vegetation is calculated within the utilisable biomass sub-model, but some method of representing the palatability of vegetation to livestock is required.

When livestock are able to graze freely in a heterogeneous pasture or rangeland, they show a high degree of preference for grazing certain plant species, at the expense of others (see Thórhallsdóttir and Thorsteinsson (1993) for a review of Icelandic research in this area). These preferred species are not necessarily the most common species within the vegetation community, and are frequently a comparatively small component of the community. The preferences of livestock for certain species seem to be controlled by the digestibility of the plants and their morphology (Ólafsson 1973).

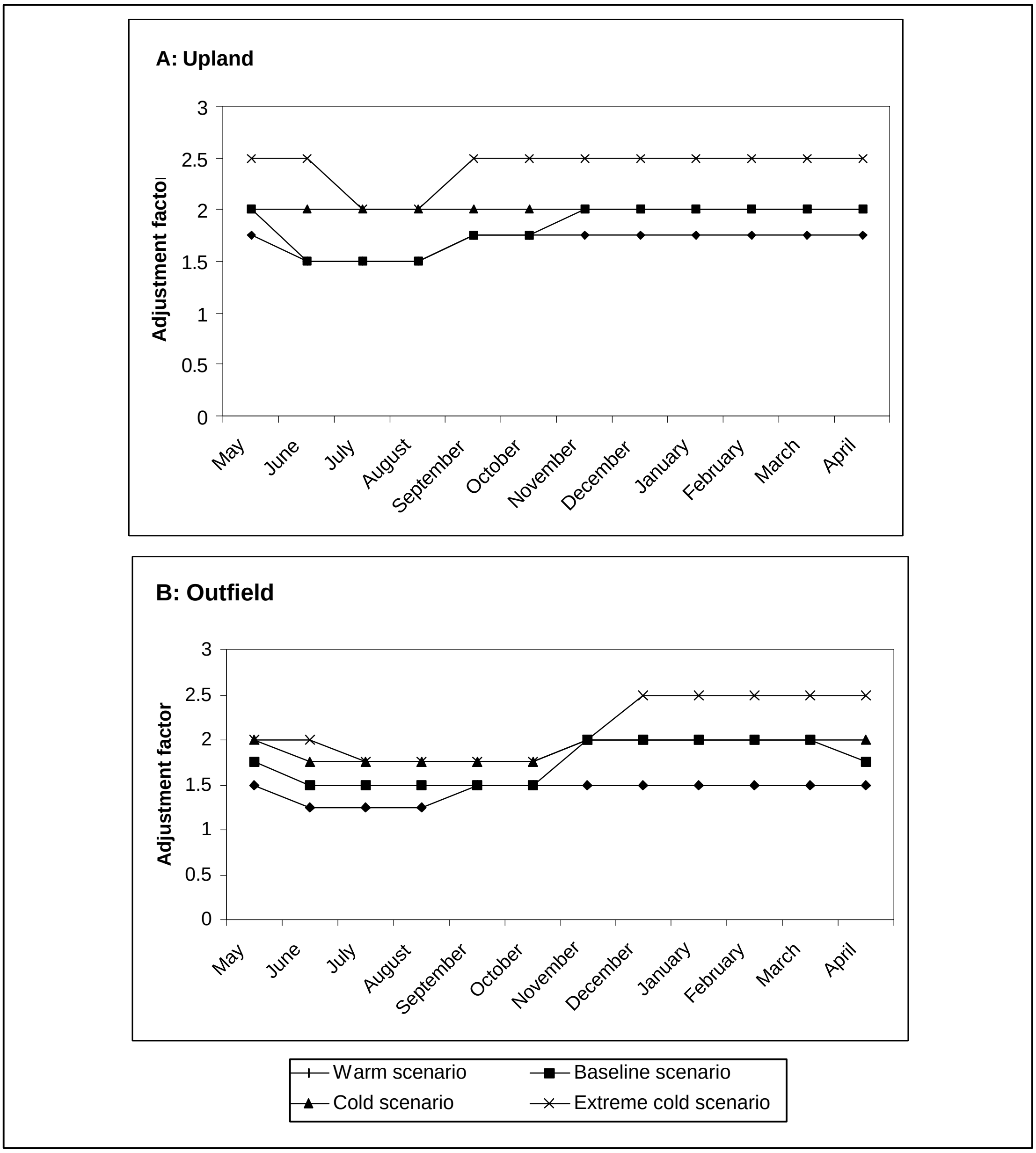


Figure 4-2: Changes in the adjustment factors for feed requirements under different climate scenarios

4.2.1 Components of vegetation palatability

The digestibility coefficient of a forage is the proportion of the total amount (of dry matter, DM) consumed that disappears in the gut (i.e. is not present in the faeces). This coefficient is usually expressed as a percentage. The digestibility of the forage available to a grazing animal affects the amount of forage that an animal can consume per day, i.e. if the forage is less digestible, the animal has to consume more to fulfil its nutritional requirements. However, as livestock are able to graze selectively the digestibility of their diet tends to be much higher than the overall digestibility of the pasture being grazed. Consequently true diet digestibility can only be modelled if the digestible component of every species present, and the change in this digestibility component over the course of the growing season, is known. Unfortunately such detailed information is only available for a small number of plant species in Iceland, and has mainly been collected for fertilised pastures. As most pastures during the pre-modern period were unfertilised, this data is unsuitable for use in Búmodel.

The approach adopted for Búmodel makes use of general information on digestibility and combines it with other information on livestock preferences in order to create a measure of palatability. Research has been undertaken in Iceland on the vegetation preferences and grazing selection of sheep and horses, covering a wide range of vegetation communities (Thorsteinsson 1964; Thorsteinsson and Ólafsson 1967; Ólafsson 1973; Magnússon and Magnússon 1990, 1992; Thórhallsdóttir and Thorsteinsson 1993). The conclusions of this research are consistent:

> ‘although the studies …were conducted in different locations containing a variety of plant communities, using different individuals and methods, the overall results which emerged were the same. The same species were selected:

> *Festuca rubra*, *Calamagrostis neglecta*, *Agrostis* spp., *Poa* spp., *Carex bigelowii*, *Salix callicarpea*, *Polygonum viviparum*, *Galium* spp., and *Equisetum* spp., and the seasonal changes of that selection followed the same pattern.' (Thórhallsdóttir and Thorsteinsson 1993): 68.

Factors other than digestibility contribute to the palatability of a plant species: for example succulence, growth form, and mineral or toxin content (Ólafsson 1973; Arnold and Dudzinski 1978). Succulent plants are preferred to waxy or hairy plants, for example Ólafsson describes *Alchemilla alpina* as being seldom found in the diet even though it is highly nutritious. Thorny plants are also avoided. Erect growing plants are preferred to those with prostrate growth forms as they are easier to graze. Plants with high levels of certain compounds are actively avoided even if they are highly digestible (for example *Lupinus nootkatensis*, a recent introduction to Iceland, which contains high concentrations of bitter alkaloids). Thorsteinsson (1980a) has summarised the relative palatability of common Icelandic plant species (Table 4-5), but these values do not take account of possible seasonal variation.

Sheep, horses and cattle share grazing preferences and aversions for certain types of plant, but sheep are able to be more selective in their grazing, as they have smaller mouth-parts (Grant *et al.* 1987; Magnússon and Magnússon 1990). Larger livestock may have less grazing finesse but are able to utilise a more fibrous diet than smaller animals, so can afford to be less selective when preferred plants are scarce (Rook 2000).

Table 4-5: The palatability rating of common rangeland plant species, from Thorsteinsson (1980a)

Plant type	Low	Medium	High
Grasses	*Nardus stricta* *Holcus lanatus* *Trisetum spicatum*	*Calamagrostis neglecta* *Anthoxanthum odoratum* *Elymus arenarius* *Deschampsia* spp. *Hierochlöe odorata*	*Phleum neglecta* *Agrostis* spp. *Poa* spp. *Festuca* spp.
Sedges and rushes	*Juncus balticus* *Luzula* spp. *Juncus trifidus* *Carex rostrata* *Trichophorum caespitosum* *Carex chordorrhiza* *Kobresia myosuroides*	All *Carex* species except *C. bigelowii, C. rostrata* and *C. chordorrhiza* *Eriophorum Scheuchzeri* *Eriophorum angustifolium*	Dryland *Carex bigelowii*
Herbs	*Gnaphalium supinum* *Dryas octopetala* *Plantago maritima* *Silene acaulis* *Alchemilla alpina* *Cassiope hypnoides* *Bartsia alpina*	*Thymus arcticus* *Thalictrum alpinum* *Sibbaldia procumbens* *Armeria vulgaris* *Potentilla cranzii* *Galium* spp. *Silene maritima* *Menyanthes trifoliata* *Cardamine nymanii* *Rumex acetosella* *Erigeron boreale* *Polygonum viviparum* *Rhinanthus minor* *Cardaminopsis petraea* *Cerastium alpinum* *Viola palustris* *Rumex acetosa* *Potentilla anserina* *Cerastium caespitosum*	*Geranium sylvaticum* *Campanula rotundifolia* *Ranunculus acer* *Trifolium repens* *Epilobium latifolium* *Taraxacum* spp. *Rubus saxatilis* *Trifolium repens* *Alchemilla vulgaris* *Leontodon autumnalis* *Achillea millefolium* *Vicia cracca* *Hieracium* spp. *Angelica archangelica*
Dwarf shrubs	*Calluna vulgaris* *Vaccinium uliginosum* *Juniperus communis* *Betula nana* *Salix herbacea* *Empetrum nigrum* *Loisleuria procumbens*	*Vaccinium myrtillus* *Salix callicarpea* *Salix phylicifolia* *Salix lanata* *Betula pubescens* *Arctostaphylos uva-ursi*	
Ferns		All ferns and horsetails	

4.2.2 Seasonal variation in vegetation palatability

During the summer livestock prefer grasses above other plant-types, as they are highly digestible (with a digestibility coefficient of over 70%). They have a high proportion of leaf- to stalk-material, compared with woody species, which livestock prefer as it is less fibrous. With maturity the digestibility of grasses declines, and the value of the digestibility coefficient drops to around 35-45% by the end of the growing season as the plants enter senescence. As a consequence of this decline in digestibility, grasses are less preferred by livestock in winter, and tend to be replaced in the diet by evergreen woody species such as *Empetrum nigrum* or *Calluna vulgaris,* whose utilisation is very low during the summer. This switch in preference between grasses and shrubs from summer to winter has been observed in both Iceland (Ólafsson 1973; Thorsteinsson 1980a) and Scotland (Grant *et al.* 1976). The explanation for this switch is that the woody shrubs maintain their digestibility year-round, and also retain green leaves in winter, which are more attractive to grazing animals. It should be noted that the *Salix* species found in Iceland (*S. callicarpea*, *S. herbacea*, *S. lanata* and *S. phylicifolia*) and *Betula pubescens* also seem to be highly palatable to sheep in the summer. If they are available for grazing, they can form 20-40% of the diet of sheep grazing on highland ranges or in forest (Thórhallsdóttir and Thorsteinsson 1993).

Sedges and rushes form a relatively small component of the diet, between 5 and 20% of the diet over the year, although they are grazed more frequently during the summer months. The exception is *Carex bigelowii*, which is a highly selected species. The palatability of herbs (which are often referred to as forbs in the Icelandic literature) is dependent upon the species and cannot be easily generalised. Those species found in dry and sparse environments, for example *Dryas octopetala* and *Silene acaulis,* are less palatable than those found in more densely vegetated areas. Herbs are often readily consumed where they are available during the summer months, but they form a minor part of the diet in winter, as most species die back in autumn. The most preferred species, such as *Geranium sylvaticum* or *Angelica archangelica*, have been grazed so heavily in the past that they are now only found within areas protected from grazing.

The consumption of horsetails (*Equisetum* spp.) and ferns is highly variable, depending upon their availability, but in general they are preferred more in early summer rather than in late summer. There is no evidence in the Icelandic literature that livestock have any significant preference for lichen or moss; it is therefore assumed that livestock will graze vascular plants in preference and that mosses and lichens form an insignificant part of the diet.

In summary: if all plant types are freely available for grazing, grasses will form 60-85% of the diet from May through to September but only 20-40% of the diet in winter. Woody plants form less than 10% of the diet from May to September, but they become a more important component in early winter, rising to 65-80% of the diet from December to March (Thorsteinsson 1980a; Thórhallsdóttir and Thorsteinsson 1993). Sedges and ferns will form up to 20% of the diet in summer, but only 10%, or less, from September to May. Herbs may form 20% or more of the diet in summer (particularly in early summer) but only 2-3% during the rest of the year. The botanical composition of the diet will also vary according to the vegetation community and the variety of plant species that are available to grazing livestock. Changes in dietary composition have been observed at high stocking rates in both Iceland and Scotland (Grant *et al.* 1976; Magnússon and Magnússon 1992):

> ‘A disproportionate increase in utilisation at high stocking rate occurs in some species…it is possible that, as preferred species become less available, the additional grazing pressure is placed on species which are intermediate on the

> preference ranking scale and are relatively neglected at lower stocking rates.' (Grant *et al.* 1976): 866.

The available information can be aggregated to assign relative palatability values to each plant type within the vegetation communities used in Búmodel. These palatability values are defined on an ordinal scale of low, medium and high palatability. Plant species within each plant type do not necessarily have the same palatability, but species commonly found in the same vegetation community are usually similarly palatable. Consequently the palatability values of an individual plant type are not consistent across all vegetation communities.

Palatability may change between seasons, as plants undergo senescence or translocate nutrients below ground in winter (Archibold 1994). A two-season split, summer and winter, is used in Búmodel. The palatability values assigned to each plant type are listed by vegetation community in Table 4-6.

4.2.3 Construction of the plant preferences sub-model

On the basis of vegetation community composition and assumptions about vegetation palatability, the plant preferences of livestock may be modelled over both space and time. The structure of this sub-model is shown in Figure 4-3. The spatial distribution of vegetation communities in the study area is recorded in the GIS model, which is then exported to Búmodel in MS Excel in tabular form. The seven vegetation communities used in the grazing model are grassy heath, dwarf shrub heath, moss heath, bog or mire, riverine, birch woodland and sparsely vegetated land. These communities are defined according to their percentage cover of six different plant types, and of bare ground. The plant types are: grasses, sedges and rushes, woody species, herbs, mosses and lichens, and horsetails and ferns.

Table 4-6: Palatability values of plant types in each Búmodel vegetation community

Vegetation community	Grasses	Sedges and rushes	Woody species	Herbs	Moss and lichen	Ferns and horsetails
	Palatability of plant types in summer					
Grassy heath	High	Medium	Medium	Medium	0	Medium
Dwarf shrub heath	High	Low	Low	Medium	0	Medium
Moss heath	High	Medium	Low	Medium	0	Medium
Bog or mire	High	Medium	Low	Medium	0	Medium
Riverine	High	Medium	Medium	High	0	Medium
Birch woodland	High	Medium	Medium	High	0	Medium
Sparsely vegetated land	High	Low	Low	Medium	0	Medium
	Palatability of plant types in winter					
Grassy heath	Low	Low	Medium	0	0	Low
Dwarf shrub heath	Low	Low	Medium	0	0	Low
Moss heath	Low	Low	Low	Low	0	Low
Bog or mire	Low	Low	Low	0	0	Low
Riverine	Low	Low	Low	Low	0	Low
Birch woodland	Low	Low	Medium	0	0	Low
Sparsely vegetated land	Low	Low	Low	Low	0	Low

For each vegetation community, plant type 'allocation' is randomised within its cover range using a uniform probability distribution function:

$$\textit{Plant type cover allocation} = z * (\textit{upper limit} - \textit{lower limit}) + \textit{lower limit}$$

Equation 4-6

where *z* is a randomly generated number greater than or equal to 0 and less than 1.

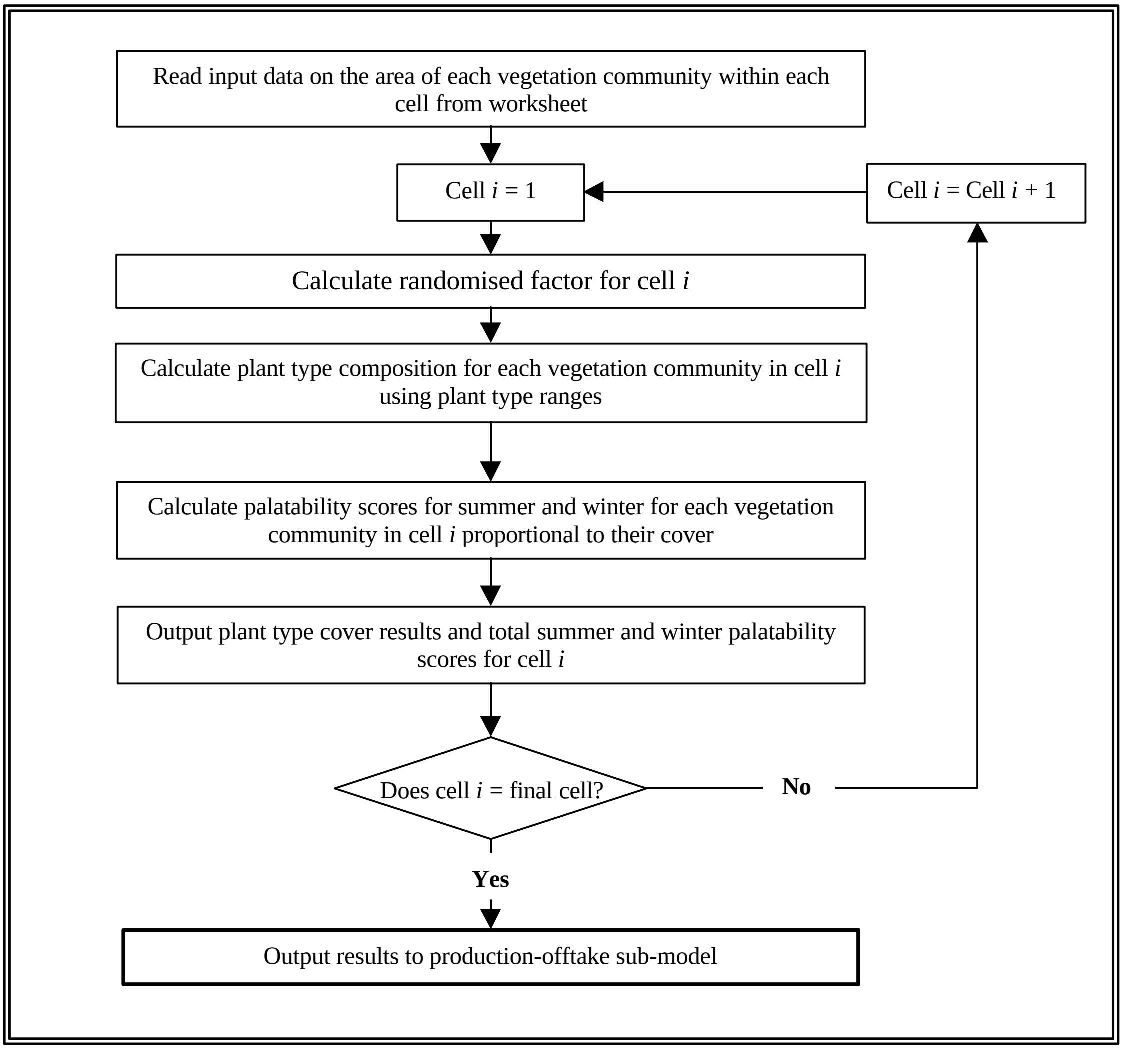


Figure 4-3: The structure of the plant preferences sub-model

The defining plant types are allocated in the first instance, i.e. the woody species cover in the dwarf shrub heath community is calculated first. After the defining plant types have been allocated the remaining, or secondary, types are considered to be of equal importance. To avoid discrimination against certain plant types (as would occur if the remaining area were allocated to each plant type in an ordered list) the cover values of the secondary types are calculated from their ranges. These cover values are then adjusted so that the total cover of the secondary types is equal to 100% cover minus the cover of the defining types. Figure 4-4 shows a worked example for a dwarf shrub heath community.

A palatability score is then calculated for each cell based on the palatability rating and cover of each plant type within the cell. Plant types with low palatability are given a score of 5, those with medium palatability have a score of 10, and the plant types with the highest palatability have a score of 15. These scores are simply a way of quantifying high, medium and low palatability and have no further meaning. For a single cell the maximum score is 15, as for a cell that contains only the most palatable vegetation. Vegetation communities that consist of a limited number of species have a narrow range of palatability scores. The communities with more variability in their botanical composition, such as bogs, can have a wide range of palatability scores.

4.3 The utilisable biomass sub-model

4.3.1 Utilisable biomass and growing season

Utilisable biomass (UB) is the term used for the vegetation that is available to grazing livestock; it is defined as the quantity of grazeable vegetation (including the dead component) covering a unit of area at any one time, and is expressed as kilograms of dry matter per hectare. As such it includes all herbaceous plant material above the ground or above the moss/lichen layer within the sward. UB is different to productivity, which is concerned with the rate of production of herbage over time. The UB available at any time depends upon the amount of vegetation growth and decay previous to that time and upon the intensity of grazing.

Random factor, z = 0.6	
The dominant plant type is woody	
WoodyType = (upper – lower)*z + lower	= (0.8 – 0.35)*0.6 + 0.35 = **0.62**
Rem1 = 1 - WoodyType	= 1 – 0.62 = **0.38**
MossType = (upper– lower)*z + lower	= (0.4 – 0.1) * 0.6 + 0.1 = **0.28**
GrassType = (upper– lower)*z + lower	= (0.25 – 0.0) * 0.6 + 0.0 = **0.15**
SedgeType = (upper– lower)*z + lower	= (0.20 – 0.0) * 0.6 + 0.0 = **0.12**
HerbType = (upper– lower)*z + lower	= (0.20 – 0.05) * 0.6 + 0.05 = **0.14**
FernType = (upper– lower)*z + lower	= (0.15 – 0.0) * 0.6 + 0.0 = **0.09**
SecondarySum = MossType + GrassType + SedgeType + HerbType + FernType	= 0.28 + 0.15 + 0.12 + 0.14 + 0.09 = **0.78**
Rem2 = Rem1 – SecondarySum	= 0.38 – 0.78 = **- 0.4**
AdjMoss = MossType/SecondarySum * Rem2	= (0.28 / 0.78) * -0.4 = **-0.14**
MossCover = MossType + adjMoss	= **0.14**
Repeat for Grasstype, SedgeType, HerbType and FernType	
TotalCover = WoodyType + MossCover + GrassCover + SedgeCover + HerbCover + FernCover	= 0.62 + 0.14 + 0.07 + 0.06 + 0.07 + 0.04 = **1.0**

Figure 4-4: Worked example of plant type allocation for a dwarf shrub vegetation community

The production of new utilisable biomass takes place during the growing season, which is the period of the year when the climatic regime and incoming solar radiation permit plant growth. The growing season is generally defined as the period when the mean four-weekly air temperature is above some base level (soil temperature can be used but observational records are less widely available) (Broad and Hough 1993). In Iceland this base level temperature is taken to be 4.4ºC for all plant types (*pers. comm.* from Borgþór Magnússon and Ólafur Dýrmundsson), although others have used a value of 4ºC (Guðmundsson 1974; Friðriksson and Sigurðsson 1983), or even 3ºC for common grasses and cereals {Bergþórsson 1985}. This threshold temperature is lower than the one of 6ºC used for the temperate regions (Broad and Hough 1993). The length of the growing season is between four and six months in the south of Iceland (between May and October) and three and five months in the north (between May and September) (Icelandic Meteorological Office 2001). It is possible that some leaf production continues outside the growing season at temperatures above freezing point, but the utilisable biomass thus produced is negligible.

Although growth continues throughout the growing season, the rate of growth is governed by the mean temperature and received solar radiation. The highest growth rates occur at the start of the growing season in June (c.70 kg/ha/day in Reykjavík), when the received solar radiation is highest, although mean air temperature does not peak until late July-August (Broad and Hough 1993; Þorvaldsson 1996). Production drops off rapidly in July to c. 25 kg/ha/day, and then declines more gradually to zero production by the end of September (Friðriksson and Sigurðsson 1983).

4.3.2 A review of utilisable biomass measurements in the literature

The literature on biomass production in Iceland is reasonably extensive, but patchy in terms of spatial and temporal coverage. A wide variety of vegetation communities have been studied at a number of locations throughout Iceland, but few have been studied in detail in more than two locations. Information on utilisable biomass is mostly available for discrete vegetation communities, but some measurements are given for ‘open rangeland’. Much of the Icelandic vegetation could be broadly characterised as tundra, and many of the open rangeland communities, particularly at high altitude, have very low yields of utilisable biomass, which are difficult to measure accurately. With reference to the low productivity of Iceland’s vegetation Friðriksson (1972) stated: ‘in many places where the soil is sandy or gravelly with sparse vegetation, the crop is scarcely more than one or two hundred kg per hectare, and often considerably less. In some moorland and dry grassland areas, the crop is larger and can be more than 3,000 kg but in undrained marshland areas …it has hardly exceeded 1,000 kg.’

The published biomass measurements have all come from sites that are also subject to grazing. Because grazing modifies growth, the shape of the growth curve under a grazing regime is not equivalent to a growth curve under zero grazing with the consumed fodder removed. In the cases from the literature where grazing pressures have been given as well as biomass measurements the results from the light grazing pressure have been used.

National estimates of the annual yield of Icelandic vegetation communities are available but these should be treated with caution as only the average values are available (Table 4-7), with no details of sampling locations or descriptive statistics.

Table 4-7: Annual yield of plant communities (means 1962-1978) from Thorsteinsson (1980a)

Plant community	Búmodel community equivalent	Yield, kg DM ha^{-1} below 400 m elevation	Yield, kg DM ha^{-1} above 400 m elevation
Moss heath	Moss heath	179	215
Dwarf shrub heath	Dwarf shrub heath	1292	796
Woodlands with grasses-horsetails	Birch woodland	1012	-
Woodlands with dwarf shrubs	Birch woodland	1103	-
Woodlands with grasses-dwarf shrubs	Birch woodland	2063	-
Grasslands	Grassy heath	648	609
Rush heaths	Grassy heath	502	609
Sedge heaths	Grassy heath	453	435
Semi-bogs	Riverine vegetation	1136	687
Bogs	Bog or mire	1010	543
Fens	Bog or mire	850	1023
Secondary succession vegetation	Sparsely vegetated land	591	479

Table 4-8: Estimated utilisable biomass in 1996 from Gísladóttir (1998). The figures in brackets are the number of sample plots harvested.

Plant community †	Búmodel community equivalent	Early season utilisable biomass, kg/ha	Late season utilisable biomass, kg/ha
Moss heath *	Moss heath	60 ± 10 (2)	60 ± 10 (4)
Dwarf shrub heath	Dwarf shrub heath	1350 ± 650 (71)	1620 ± 550 (80)
Grass heath	Grassy heath	1020 ± 380 (18)	1170 ± 610 (48)
Grassland	Grassy heath?	660 ± 200 (75)	980 ± 500 (123)
Mire margin	Riverine vegetation	830 ± 140 (10)	1280 ± 300 (20)
Sloping fen	Bog	530 ± 170 (12)	1170 ± 220 (20)
Level fen	Bog	1670 ± 280 (10)	1750 ± 300 (20)
Cultivated land *	Hay meadow	830 ± 190 (4)	3390 ± 420 (6)

* *Measured in 1991 and regarded as being of minor importance in the study.*

† *Refer to Table 3-4 for details of plant community composition*

At a regional level Gísladóttir (1998) gives the biomass of vegetation communities in Krísuvíkurheiði in southwestern Iceland in 1996 in both early (June to mid July) and late summer (mid-July to late August/September) (Table 4-8). The yield values from the two sources (Gísladóttir and Thorsteinsson) are in broad agreement over the late season biomass of the bog and riverine vegetation but there are large discrepancies between the other vegetation categories.

4.3.2.1 The RALA grazing research programme

An additional source of information on standing herbage (equivalent to UB) comes from the five-year rangeland grazing research programme undertaken by the Icelandic Agricultural Research Institute (RALA) in the 1970s and 1980s. Controlled grazing experiments took place at locations around Iceland, enabling an investigation of inter-annual variation and the impact of grazing intensity. Only the analyses were available, rather than the raw data itself. The experimental sites are described in Table 4-9 and their locations are shown in Figure 4-5.

Table 4-9 : RALA grazing experimental sites

RALA experimental site	Location	Elevation, m	Vegetation
Alftaver	south	15	very poor grassland, rich in mosses
Auðkúluheiði	northern interior	470	moss heath with low growing shrubs and grasses
Hestur	west	50	undrained and partly drained bog
Kalfholt	south west	20	drained sedge bog
Eyvindardalur	east	600	mixture of bogs, fens, dryland and gravelly flats

Standing herbage was measured between June and October from 1976 to 1979/80. Bar charts of the mean standing herbage on all grazing pressures (low, medium and high intensity) are shown in Figure 4-6, Figure 4-7 and Figure 4-8. These demonstrate the differences in utilisable biomass between vegetation communities and the changes in the quantity available over the summer months. It was not possible to calculate standard deviations from the available data.

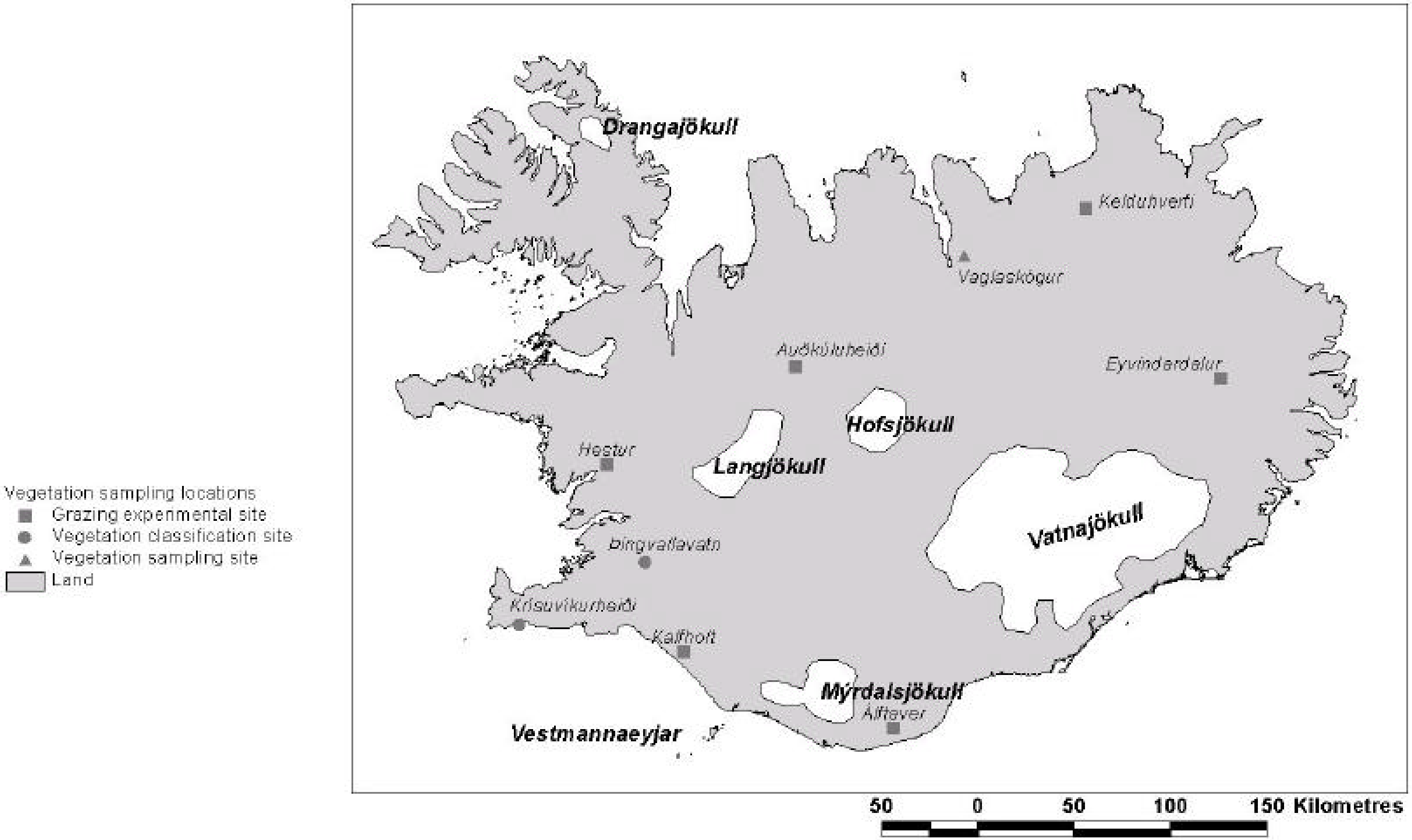


Figure 4-5: The location of the vegetation sampling sites that were used to parameterise Búmodel

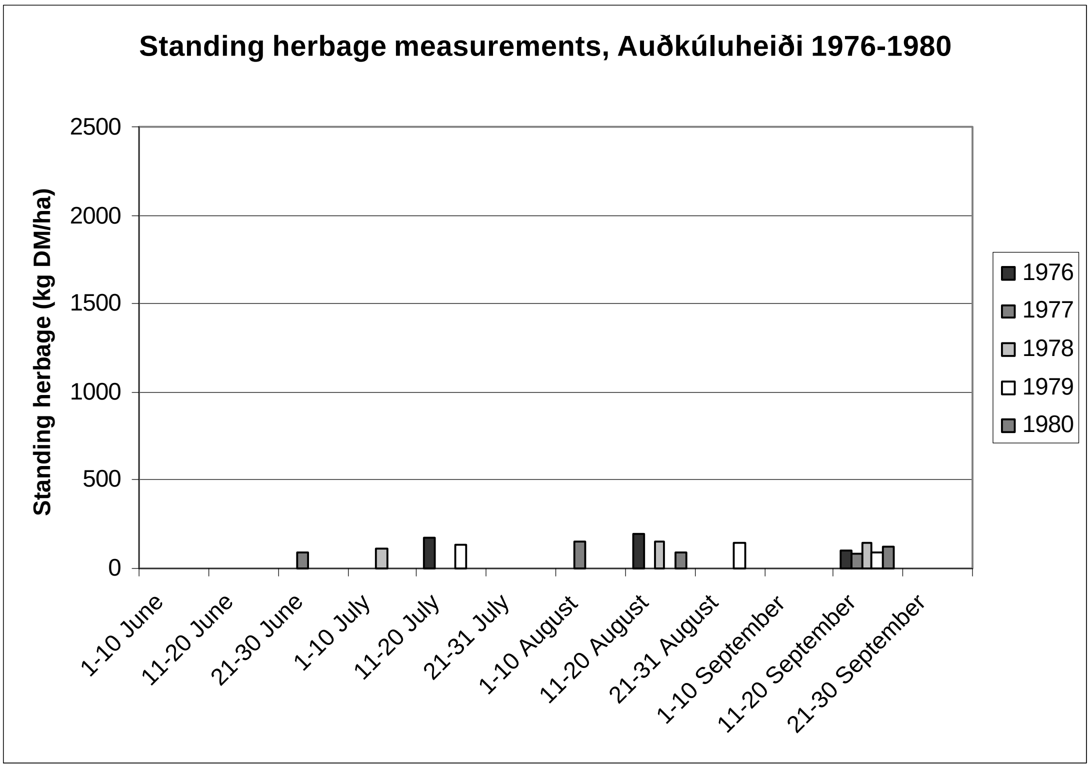
The two sites dominated by mosses, Álftaver and Auðkúluheiði, both have very low amounts of standing herbage, although the latter has higher maximum values. In contrast the other dry site, Eyvindardalur, has standing herbage values that are twice as high as the first two sites. The bog sites at Hestur and Kalfholt have much higher quantities of herbage, with drained or partly drained bogs being more productive than undrained ones, due to greater dominance of grasses.

The highest recorded herbage value occurs in late July-mid August at Álftaver, and mid-late August at Auðkúluheiði and Eyvindardalur, which are further north and at higher elevations. The Hestur site shows a less distinct ‘peak’ as there are high values in both late July and mid September, but at Kalfholt the highest values occur towards the end of the growing season. Notes in the original RALA reports record that 1976 had favourable growing conditions and rapid growth, with the lowland bogs having reached maturity (not necessarily coincidental with peak biomass) by mid July, Álftaver by mid August and Auðkúluheiði by mid-September. In contrast vegetation growth was very slow at most sites in 1979, which was one of the coldest years in the twentieth century in Iceland.

Attempts to investigate possible links between climatic variables and standing herbage were hampered by the lack of appropriate climatic data. The experimental sites were often tens of kilometres from the nearest meteorological station. Although the temperature record from Stykkishólmur station is a good predictor for other lowland stations in Iceland (section 3.2.3), correlation of temperature variables and seasonal mean and peak mean standing herbage were not significant at the 95% level (and Auðkúluheiði and Eyvindardalur were in the highlands). Attempts at regression analysis suggest that the length of time since the start of the growing season and the mean winter (November-April) temperature can be used to predict the quantity of standing herbage at a point in time. However, difficulties with data precision (such as the definition of a start date for the growing season) led to this analysis being omitted from Búmodel.

4.3.2.2 The horse grazing pasture project

At a less locationally specific, rangeland level, a study of horse grazing pastures measured rangeland biomass at sites in different areas of the country (Magnússon *et al.* 1998, 1999). This study was undertaken because of concerns over the condition of horse grazing pastures. Sampling was undertaken in the counties of Eyjajfjörður, Skagafjörður and Húnavatnssýsla in the north, and Árnessýsla and Rangárvallassýsla in the south. The pastures were composed of mires, grasslands and peatlands but the vegetation type was not differentiated in the analysis. Grasses (*Deschampsia caespitosa, Agrostis capillaris, Festuca rubra*) and sedges (*Carex nigra, C. bigelowii*) were the dominant herbaceous species. Rangeland in good or excellent condition had a much wider range of herbage biomass values (from 230 to 4450 kg ha^{-1} for rangeland in good condition) than rangeland in the poorest condition classes (171 to 391 kg ha^{-1} in the very poor condition class). The mean UB of rangeland in excellent condition was 2,136 ± 1,333 kg ha^{-1}, whereas rangeland considered to be very poor condition had a mean UB of 271 ± 85 kg ha^{-1} (data supplied by Borgþór Magnússon, measured in the autumn of 1996). There was a higher mean coverage of graminoids on rangeland in good condition, and lower bare ground cover.



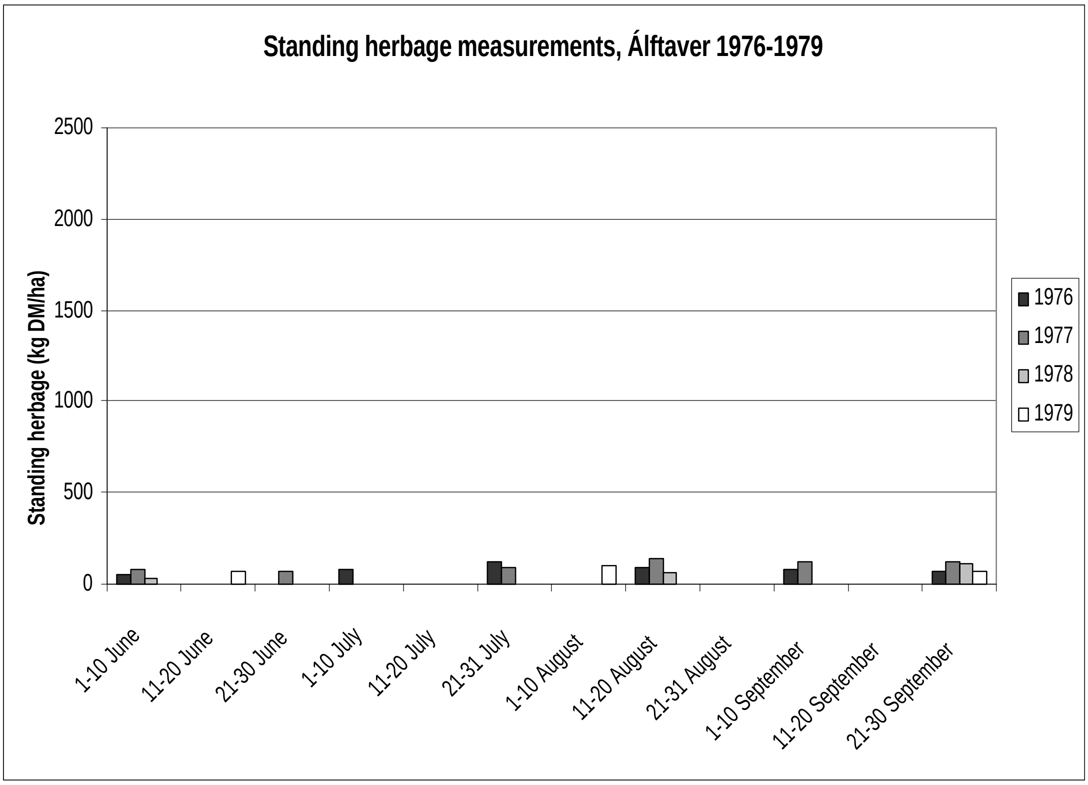
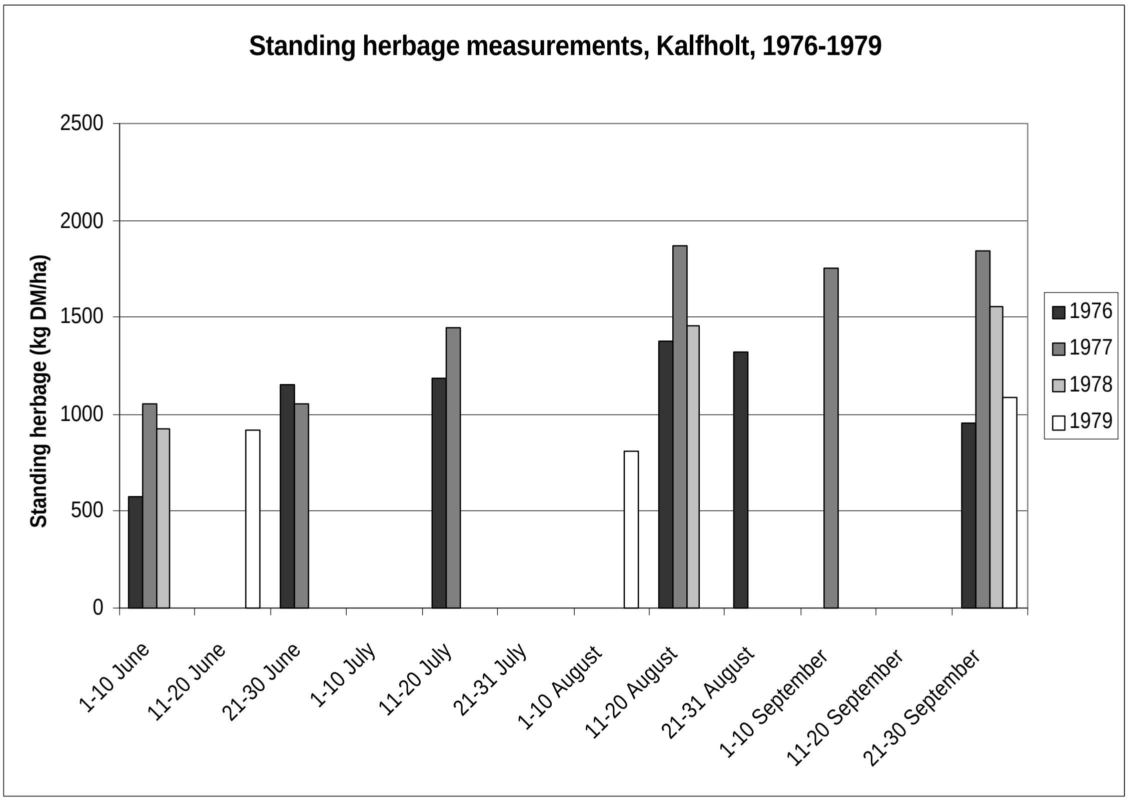


Figure 4-6 Standing herbage at Álftaver and Auðkúluheiði 1976-1980



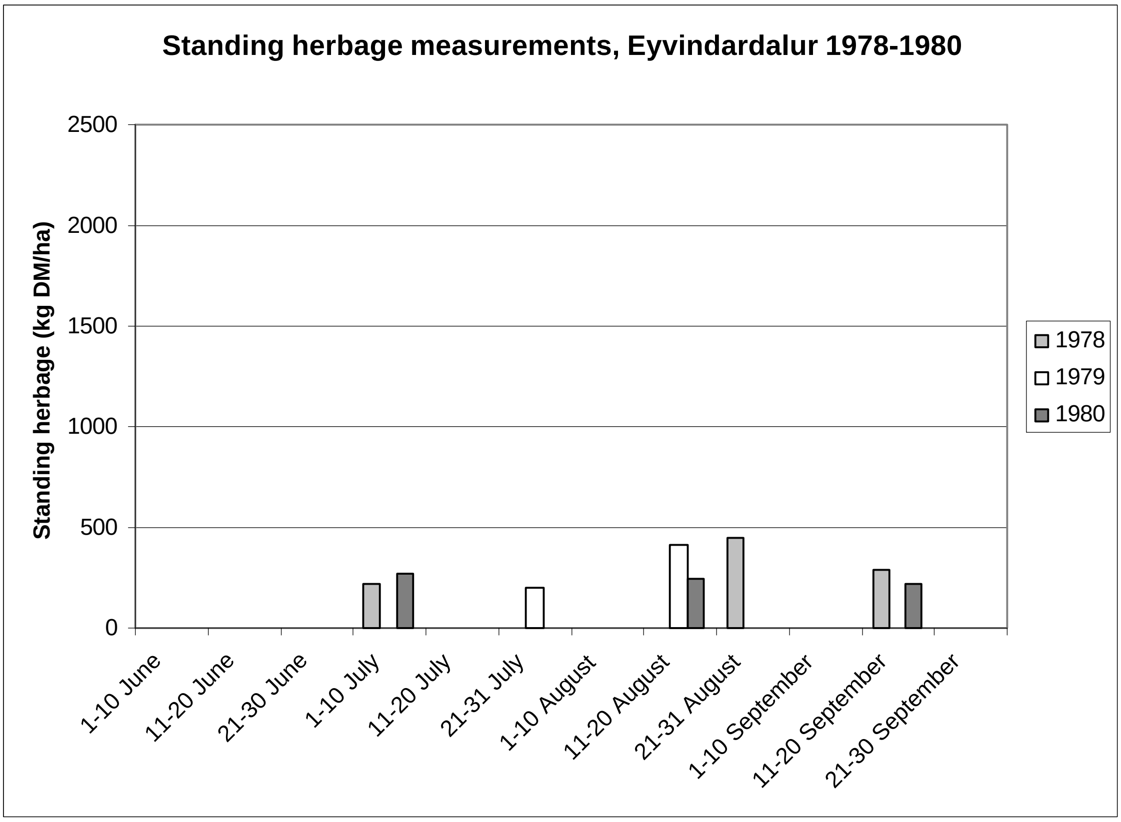
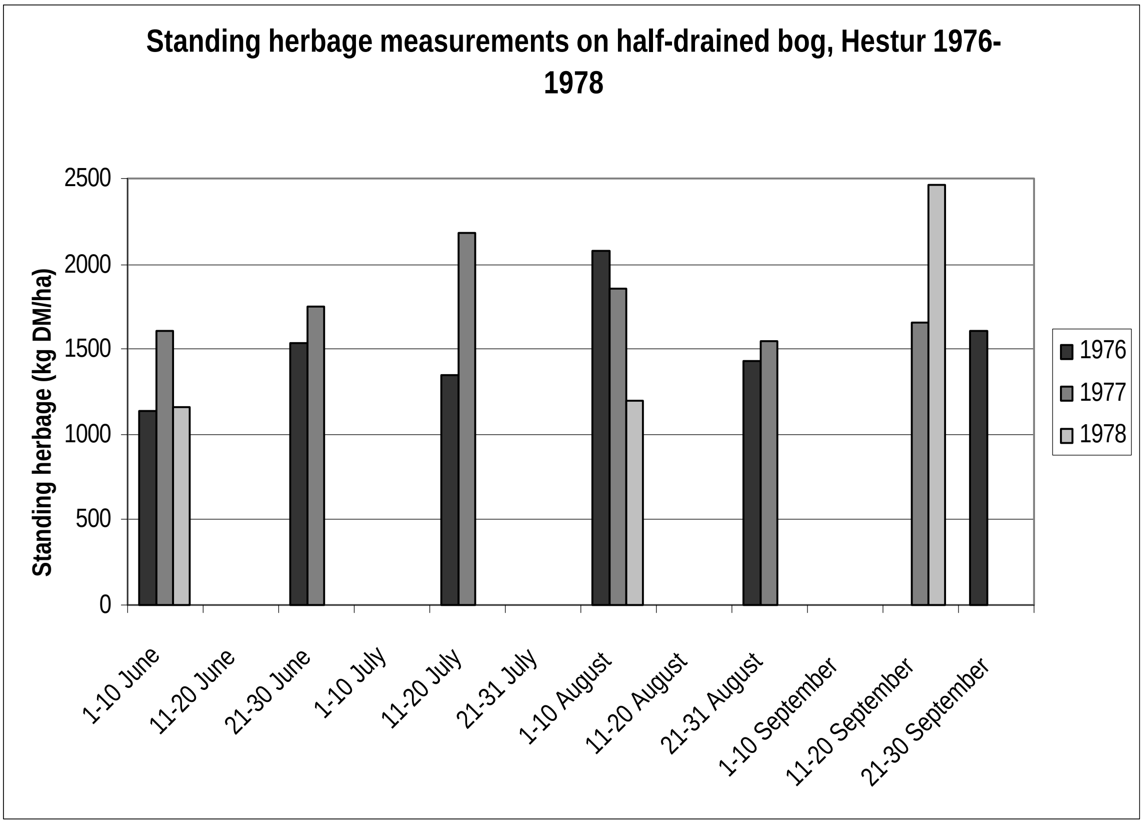


Figure 4-7: Standing herbage at Kalfholt and Eyvindardalur 1976-1980



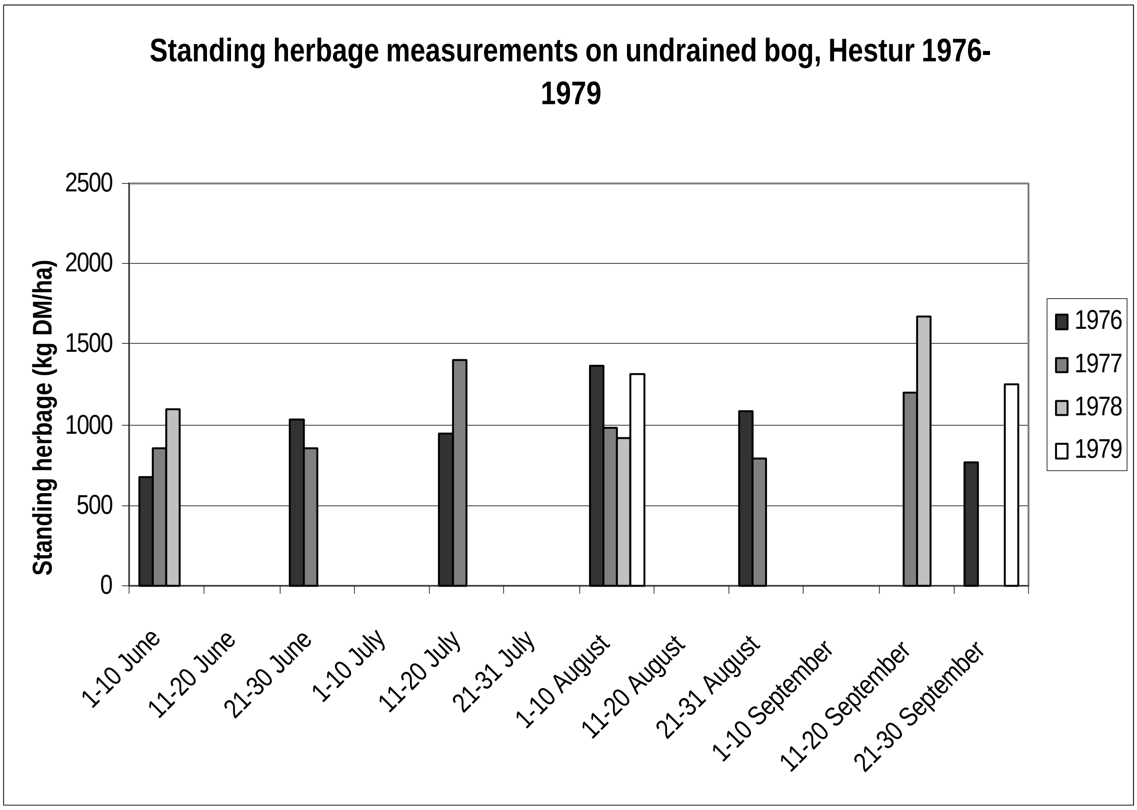


Figure 4-8: Standing herbage on undrained and half-drained bog at Hestur 1976-1979

4.3.3 Original fieldwork: utilisable biomass

Utilisable biomass sampling was undertaken in the two study areas, Eyjafjallahreppur and Mývatn hreppur, in July and August of 2001. This was done for two reasons: firstly, to obtain UB figures for Búmodel vegetation categories that were under-represented in the literature, and secondly to gain an understanding of the degree of within-community variation in UB within the same growing season. Time and resource constraints did not allow utilisable biomass to be sampled throughout the growing season; however, the peak season biomass measurement is accepted as a satisfactory measure of the annual herbaceous biomass production in alpine/sub-arctic regions (Webber 1974; Körner 1999). Biomass is considered to have reached its peak in Iceland in early August (*pers. comm.* Borgþór Magnússon), so the fieldwork samples are representative of peak season biomass. UB samples were taken at the same time as the botanical composition surveys described in section 3.2.1.2.

Utilisable biomass measurements were taken using the harvested quadrat method (Moore and Chapman 1986), with all utilisable biomass within a 20 cm by 20cm sample square being clipped and bagged. As the aim of the sampling was to assess the amount of biomass available for grazing all herbaceous material above the ground or moss layer was removed. Leaves and new woody material (i.e. the current season's growth) was clipped from dwarf shrubs, but sturdier woody material was not. If the vegetation within the one metre quadrat was homogenous a single 20x20cm sample from the centre of the quadrat was clipped for biomass measurement. Otherwise three 20x20cm squares, randomly located within the quadrat, were clipped. Biomass was very low at the sparsely vegetated land sample sites, so in these cases the entire 1x1m square was clipped. In some cases it was not actually possible to sample the biomass in the sparsely vegetated quadrats as the utilisable biomass within the square was estimated to weigh less than two grams in total.

The clipped and bagged plant material was weighed on the day of collection to ascertain its fresh weight and dried in Reykjavík by Elín Ásgeirsdóttir of the Agricultural Research Institute at 65 ºC for twenty four hours. After transportation back to Stirling, all moss, lichen or soil was removed by hand from all the dried samples so that only utilisable biomass was measured, and to ensure comparability between samples from the two study areas. The samples were then weighed again. Some samples had to be removed from the analysis at this stage because the paper bags had split during transit back to the UK, and some of the contents had been lost.

Statistical analysis of utilisable biomass samples

The mean peak season UB for the four sampled vegetation types are shown in Figure 4-9. Descriptive statistics for the samples are given in Table 4-10. It can be seen that the mean peak UB is very similar between the two locations for the grassland, riverine and sparsely vegetated land vegetation communities. One-way ANOVA analysis of the difference between the grassland and riverine communities in the southern and northern study areas revealed no significant difference in UB values between the two locations. A Kruskall-Wallis non-parametric test on sparsely vegetated land (as the samples were not distributed normally) also revealed no significant difference between the two.

In the south, samples were taken both inside and outside a national park boundary, Þórsmörk, which allowed statistical testing of the impact of grazing upon peak UB in this area. A one-way ANOVA comparing the biomass on grazed and ungrazed grassland in the south found that there was no significant difference between the two.

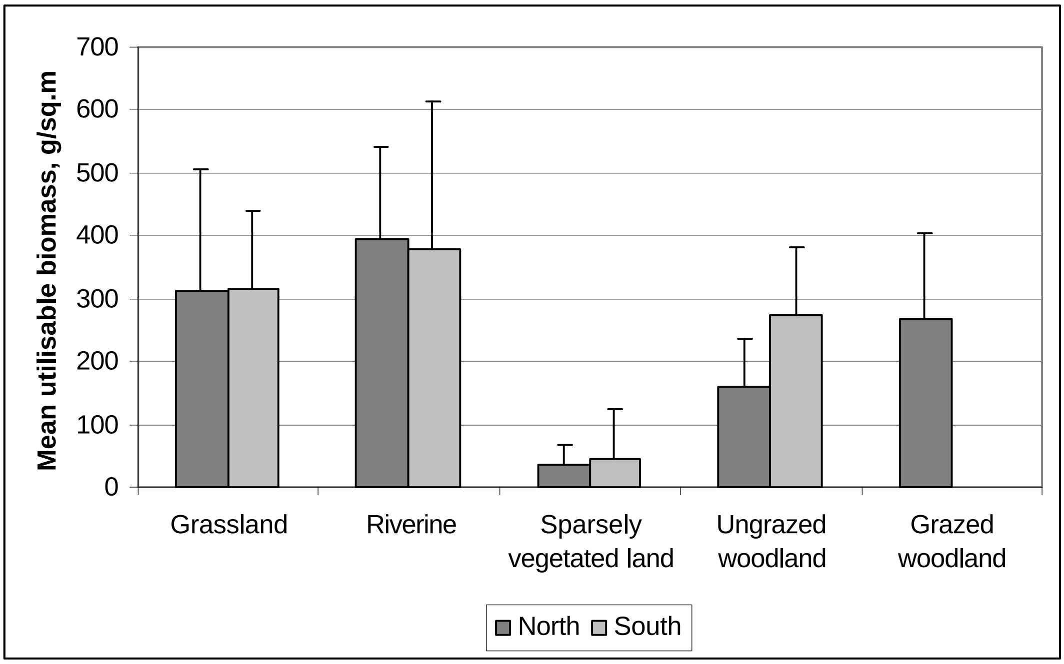


Figure 4-9: Mean peak season utilisable biomass values (g m^{-2}), with one standard deviation, for sampled vegetation communities in the northern and southern field areas.

Table 4-10: Descriptive statistics for utilisable biomass (g m^{-2}) samples collected in 2001 (moss and lichen component removed)

Vegetation Community	N	Mean, g m^{-2}	Median, g m^{-2}	Standard Deviation, g m^{-2}	SE Mean, g m^{-2}	Mini-mum, g m^{-2}	Maxi-mum, g m^{-2}	Anderson-Darling Normality test value
North: grassland	15	312.9	252.5	194.2	50.1	49.2	692.5	0.140
North: riverine	14	393.2	380.0	147.6	39.5	160.0	685.3	0.868
North: sparsely vegetated land	14	36.05	25.8	30.0	8.0	2.4	108.3	0.074
North: grazed woodland	15	266.6	214.3	136.0	35.1	84.6	556.3	0.047
North ungrazed woodland	15	160.0	127.2	74.4	19.2	63.3	265.0	0.044
South: grassland	12	313.6	280.3	126.0	36.4	171.5	537.0	0.168
South: riverine	12	378.9	318.5	234.3	67.6	97.3	945.7	0.220
South: sparsely vegetated land	9	44.4	7.8	79.4	26.5	2.1	233.6	0.000
South: ungrazed woodland	15	273.4	267.0	108.5	28.0	99.7	467.3	0.618

Comparisons between the woodland samples were more complex. A Mann-Whitney non-parametric test on the difference between the ungrazed and the grazed woodland in the north could not reject the null hypothesis that they were from a common population ($p = 0.0620$). (Although a Ryan-Joiner normality test on the two samples found that they were both normally distributed, and a two-sample t-test found significant difference between the two population means ($p<0.05$)). Neither were the population medians of the northern grazed woodland and the southern ungrazed woodland significantly different from each other ($p< 0.005$). However, a Mann-Whitney comparison of the ungrazed woodland in both locations did find a significant difference between the two samples ($p<0.005$). It is suggested that the difference between the woodland sample sets is related to the openness of the canopy rather than the differences in grazing.

All of the vegetation communities sampled had high standard deviations compared to the sample means. The mean standard deviation was 48% of the population mean (excluding the sparsely vegetated land samples, which were extremely skewed). This gives an indication of the wide variation in utilisable biomass to be found within vegetation communities in one growing season, and within relatively confined regions.

4.3.4 The impact of climate upon utilisable biomass

The highly variable climate of Iceland cannot fail to affect its vegetation cover. However, the scale and direction of the climatic influence is often difficult to isolate from factors such as grazing pressure. Vegetation that has been lightly grazed and is in good condition is more resilient to climatic variation than is vegetation in poor condition. Quantitative work in this area within Iceland has concentrated upon the hay yield and the effect of climate upon pasture grasses, and these may not always be suitable analogies for other plant types.

The most influential climatic variable is temperature, governing the length of the growing season, maturation, and rates of growth and senescence. Mean summer temperature is an important influence upon peak biomass, but in Iceland the mean winter temperature also exerts a considerable influence. This is because the mean winter temperature is linked in a number of ways to the length of the growing season, and also shows a greater range of inter-annual variation than the mean summer temperature. Mean annual temperature can serve as a figure for comparison with the climatic record (Bergþórsson 1969). It is estimated that a shift in mean annual temperature of 1ºC would increase or reduce the rangeland carrying capacity by 10 to 20 % (Dýrmundsson and Jónmundsson 1987). This estimate is difficult to translate into terms of available biomass but may provide a useful comparison for the model outputs.

Cooler mean winter temperatures affect the production of biomass in two ways: they are associated with a delayed start to the growing season; and they are associated with slower growth rates once the growing season has commenced. For grasslands in Iceland the mean winter temperature has a greater impact on the amount of utilisable biomass in the following summer than does the mean summer temperature, with cold winters being more effective than cold summers in restricting the growth of grass (Bergþórsson 1985; Bergþórsson *et al.* 1987; Thorvaldsson and Björnsson 1990). This influence is due to a number of inter-related factors: winter killing of grasses in very cold weather, prolonged snow cover and/or frozen soil delaying plant growth in spring, or spring kill of grasses because of water lying on top of impermeable frozen soil.

The temperatures of seasons and years are also auto-correlated in Iceland season (Bergþórsson 1985), so a cool spring is likely to follow a cold winter, delaying the start of the growing season. Cold winters reduce growth rates in spring, lengthening the time between the onset of growth and the point at which grass fields 'become green' i.e. when a certain leaf area had been achieved. An increase in temperature and precipitation after the onset of growth shortens the time for grass fields and pastures to become green (Þorvaldsson 1996). At Reykjahlíð by Mývatn (within the northern field area) the mean date of onset of spring growth on grass fields is 3rd of May, with fields becoming green by the 27th May. The shrubby pasture (*trjágróður*) at this site becomes green by 13th June, on average. At Sámsstaðir in the south (adjacent to the southern field area) the mean date of onset of spring growth in the grass fields is 26th April, with fields becoming green by 14th May. The grassland pasture at this site becomes green by 1st June on average. The study by Þorvaldsson found that the variation in pastures becoming green was three weeks. However, as the onset of growth is progressively delayed the amount of incoming solar radiation increases with longer day length, increasing energy inputs, so the time period between onset of growth and grass fields and pastures becoming green is actually shortened when the start of the growing season is delayed.

The shorter the growing season, the less production can take place. A shorter growing season is usually, but not always, associated with cooler summer temperatures. The impact of these factors is illustrated by the differences in growth of *Deschampsia caespitosa* culms at a field station in Reykjavík: their average length in the very cold year 1979 was half that of culms in 1975-1980. The actual increase of culm length with accumulated temperature seems to be similar in all years, although the 1979 culms had a smaller initial length (Friðriksson and Sigurðsson 1983).

Climatic variations influence overall yields: in the mild period before 1964 the average yield of hay per hectare per year for the whole of Iceland reached 4,500 kg but in the following cool period the yield dropped to 2,200 kg (Friðriksson 1972). Particularly poor grass yields in an individual year seem to have knock-on effects on the yield of subsequent years. In addition, 'Winter warmth seems to be favourable only to a certain degree, possibly because a very warm winter can induce an untimely start of grass growth.' {Bergþórsson 1985}: 113-114.

Although precipitation shows wide variation between different parts of the country and between years, it does not appear to be a limiting factor in plant growth in Iceland (Thorsteinsson 1986; Björnsson and Helgadóttir 1988). Water stress can affect biomass production in Iceland but its effect is relatively small compared with the large impact of temperature variations (Björnsson and Helgadóttir 1988). Wet summers can have a severe impact on the hay yield, as there are greater losses of hay during the hay-drying process: 'in wet summers up to 30-40% of digestible dry matter can be lost, whereas under favourable conditions the loss is only 7-10 %' (Gudmundsson, 1977, in Gudmundsson (1987)): 489.

UB might be expected to decline with increasing height above sea level, in that mean air temperature declines with elevation, according to the lapse rate. Hence the mean summer temperature and the length of the growing season should also decline with increasing elevation, as it takes longer for the mean air temperature to rise above the threshold temperature of 4.4 ºC. For example, observations in an eighteen year period, 1969-1981, show that at Reykjavík (50m above sea level) there were 144 days when the mean air temperature exceeded 4 ºC, with a mean daily temperature of 9.1 ºC, whereas at 640 m above sea level at the Hveravellir mountain station, there were only 89 days when the temperature rose above 4 ºC, with a mean daily temperature of 6.9 ºC (Friðriksson and Sigurðsson 1983) (locations shown in Figure 1-2). In Iceland the lapse rate is estimated to be 0.6-0.7 ºC for every 100m increase in elevation (Thorsteinsson 1986). This results in a delay of the onset of the growing season by three days for each increase of 100m elevation (Guðmundsson 1974), with the total reduction in the length of the growing season being twice that.

However, this relationship between utilisable biomass and altitude can be confounded by other factors, such as soil type, water availability and biotic history. In Scotland, for example, there is not a linear relationship between altitude and herbage production, as the peak values occur at intermediate altitudes (c. 350m) (Hill Farming Research Organisation 1979). Botanical composition also changes with increasing altitude, so it is difficult to compare similar vegetation types at different altitudes. Although Thorsteinsson gives annual yield values for vegetation types above and below 400m (Table 4-7), other studies give a less clear picture. For example, in the horse grazing project, in the northern sites herbage biomass was negatively correlated with height above sea level (Spearman's rank, $p = 0.001$), but this relationship was weaker in the south ($p = 0.013$). These correlations could not be translated into effective regression equations for predicting the change in biomass with elevation because the wide variation in herbage biomass at low elevations meant that any regression equation had poor explanatory power.

4.3.5 Intra-annual change in utilisable biomass

The different plant species that are commonly grazed have different growth characteristics, which affect the amount of utilisable biomass available from individual plant types at different times of year. In cool regions, such as Iceland and Alaska grasses grow rapidly during the early growing season, but this period of rapid growth lasts less than a month, after which growth declines to zero during the winter months (Archer and Tiezen 1980; Archibold 1994). This pattern can be seen in Figure 4-10. Production adds new material to the utilisable biomass pool, and this material is gradually removed by the processes of senescence and litterfall (in the absence of grazing or mowing). The rates of these two processes can be estimated from the leaf life span of grasses. Other herbaceous, non-woody plants are assumed to have the same growth characteristics.

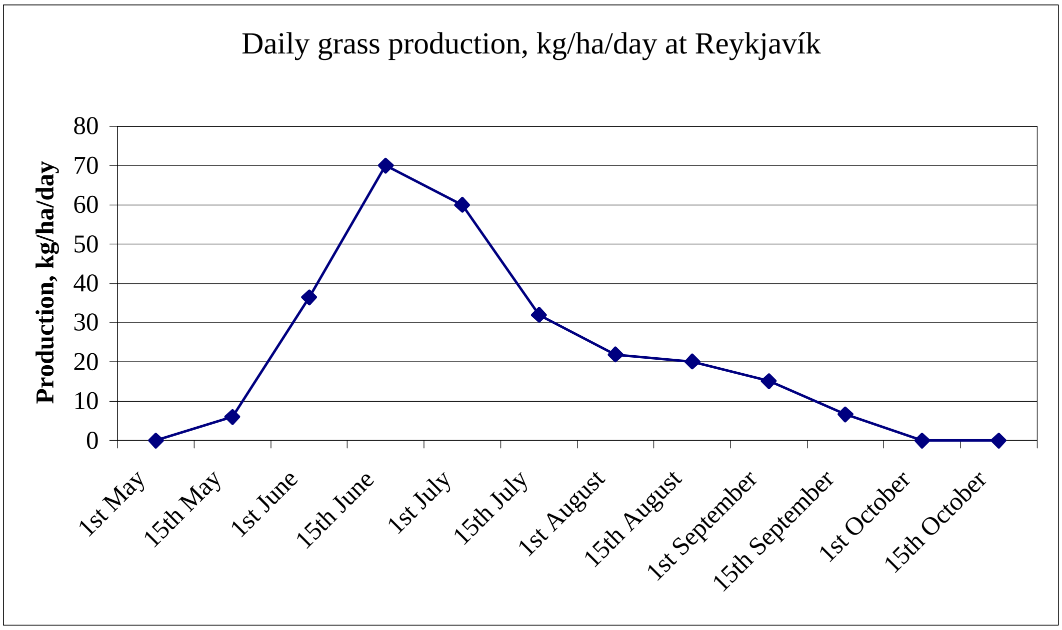


Figure 4-10: Daily grass production at Reykjavík, from Friðriksson and Sigurðsson (1983)

Herbaceous leaf life spans (from leaf emergence to litterfall) decline with increasing latitude from temperate regions (82 ± 5 days) to sub-arctic (76 ± 2 days) to high arctic regions (48 ± 2 days) (Prock and Körner 1996). Leaf life spans also decline with shortening growth periods. Two leaf life-span regression equations, referring to plants growing at high elevations, are given by Prock and Körner:

$$\textbf{Life-span (days)} = -1.88 * \textbf{Latitude} + 187.2 \qquad R^2 = 0.60$$

Equation 4-7

$$\textbf{Life-span (days)} = 0.46 * \textbf{Growth period (days)} + 24.7 \qquad R^2 = 0.63$$

Equation 4-8

For the two sites at Reykjavík and Hveravellir, mentioned previously, this would equate to a leaf life span of 65 days, when calculated from latitude alone. When leaf life spans are calculated from the growing period the estimated value at Hveravellir is also 65 days, but 91 days at Reykjavík (which is near sea level).

Grass leaves are estimated to remain green between four and six weeks in the lowlands (although this period may be shorter at high altitudes (Archibold 1994)), so dead material starts to accumulate in the sward early in the growing season. Dead material remains in the sward for eight weeks in the lowlands, and then decomposes into the organic layer. It is assumed that litterfall and decomposition does not occur in the winter months because of low temperatures, so some of this material survives over the winter until the start of the next growing season.

In contrast to grasses, woody plants take several weeks to begin producing photosynthetic tissue once the growing season has commenced, and their growth rate is more consistent throughout the growing season. Consequently the utilisable biomass produced by these plants increases steadily over time, only reaching a plateau towards the end of the growing season. Following the example of the Hill Grazing Management

Model (Armstrong *et al.* 1997a), senescence and litterfall from the current year’s shoots are assumed to be negligible.

Information on the growth characteristics of sedges and rushes in sub-arctic regions is relatively sparse. Utilisable biomass measurements at the RALA experimental bog/mire sites at Kalfholt and Hestur show a steady increase in biomass in the first half of the growing season, suggesting growth. Biomass then gradually decreases until the end of the growing season, although in several instances there was an increase in biomass again at the end of the growing season. The assumed growth pattern is therefore rapid growth in early growing season, starting soon after the threshold temperature is exceeded, followed by gradual die back over the rest of the season before more rapid death from November onwards (Wilby, *pers. comm.*).

As mosses and lichens are excluded from the estimation of utilisable biomass their growth characteristics are not considered here. Both are resistant to freezing and have relatively high rates of photosynthesis at low temperatures and low light levels, so their growth is not necessarily restricted to the summer months (Archibold 1994). As such they might provide a food source for livestock if no other vegetation is available, but there is no method of quantifying their palatability and nutritional value.

4.3.6 Formulation of growth curves for Búmodel

Mean monthly utilisable biomass (UB) curves are used within Búmodel to calculate the available utilisable biomass, rather than explicit production and senescence figures (as used in the HGMM (Armstrong *et al.* 1997a)). The monthly mean UB curves for each vegetation community are calculated from biomass measurements from fieldwork and the published literature, and information on the growth characteristics of the common plant types within that vegetation community. There can be considerable variability in the quantity of UB available in different patches of the same vegetation community within a relatively small geographical area. In order to accommodate this natural variation in productivity, minimum and maximum UB limits are fitted around the mean biomass curve. A value of ±55% of the mean monthly UB was chosen, in order to standardise variability across all vegetation communities. This was based on the mean figure for the standard deviations and interquartile ranges as a percentage of the mean and median UB values derived from fieldwork and the literature. A fixed percentage produces low variability for communities with low mean UB values and high variability for communities with high mean UB values.

The mean monthly UB is also affected by the length of the growing season and temperature parameters, represented by the climatic scenario. The influence of the different climate scenarios upon the mean monthly utilisable biomass is shown in Table 4-11. Fieldwork results showed no significant difference in peak UB between vegetation communities in the south and the north of Iceland (section 4.3.3). The absence of a regional influence is possibly due to the influence of local factors that have not been included in the model, such as exposure, precipitation and the prior condition of the vegetation. These factors can interact and their relative influences are unknown, so they have not been explicitly included in the model. The natural variation in UB within a single growing season will in any case incorporate much of the variation due to these factors.

The mean monthly UB curves constructed for each vegetation community are shown in Figure 4-11, Figure 4-12, Figure 4-13 and Figure 4-14 (note that the moss heath and sparsely vegetated land graphs have different axes scales from the other vegetation community graphs because of their much lower UB). Búmodel calculates the ±55% limits around the mean monthly UB curve. The UB for a community patch within each cell is selected randomly from within these limits. A random number, drawn from a uniform distribution between 0 and 1, was transformed so that it equated with one drawn from a standard normal distribution between –1 and +1 around a mean of 0. (The normal probability distributions was generated 'from standard uniform variates by inverting the cumulative density function, which, for distributions based on the standard normal model, was approximated by an empirical equation with a reported error of less than 2.3 x 10^{-4} (Milton and Stegun (1970)' in Whelan, Facchi and Gandolfi (in prep.)). An individual random number was calculated for each cell and used for each vegetation community within that cell. The monthly UB was then calculated from within the range of ±55% of the mean UB using the equation:

$$\textbf{Monthly UB for community a} = \mathbf{z * (0.55 * mean\ UB_a) + meanUB_a}$$

Equation 4-9

where **z** is the random factor between –1 and +1.

Table 4-11: The influence of the climatic scenario upon the utilisable biomass

Growing season parameter	I Baseline scenario	II Extreme cold scenario	III Cold scenario	IV Warm scenario
Start of growing season	May	June	June	May
End of growing season	September	September	September	October
Time of peak UB	July	August	August	July
Change in production relative to baseline scenario	100%	60%	80%	130%

Utilisable biomass is calculated at the beginning of each month in the model run. In the summer months (April to September) the UB of each vegetation community in each cell is calculated according to the climate scenario, and is only modified by overgrazing (section 4.6.1). In winter (October to March) UB is calculated thus:

$$UB_i = (\text{Available } UB_{i-1} - \text{Consumed } UB_{i-1}) * L_i$$

Equation 4-10

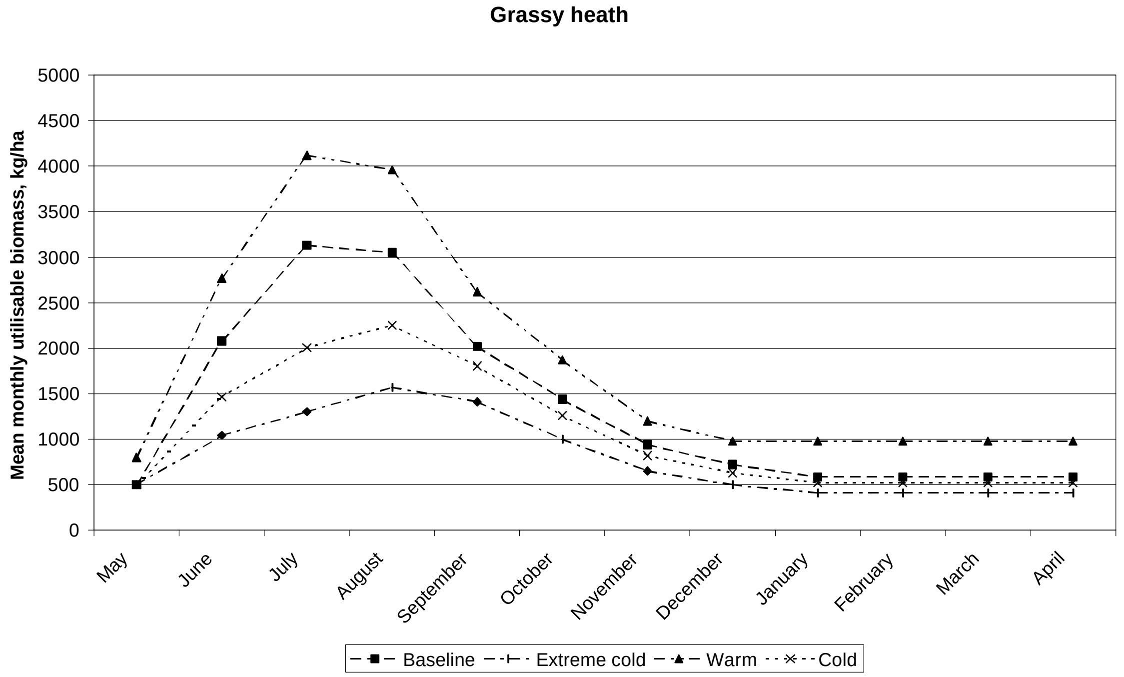
i being the month, and L being the litterfall rate in that month, calculated from the UB curve as the proportional change in biomass between month *i*-1 and month *i*.

4.4 Livestock distribution sub-model

Búmodel is spatially based, in order to represent the spatial complexity of the landscape. It is assumed that livestock are able to range freely across this simulated landscape, although they are constrained by the land-use category to which they are assigned (section 3.2.2). The extensive literature on the behaviour of free-ranging livestock is reviewed in Arnold and Dudzinski (1978), with one of the main conclusions being that:

> ‘Animals are not dispersed randomly in any environment, and free ranging domestic animals may exhibit extreme non-randomness in the use of resources of the environment, particularly the vegetation.’ (Arnold and Dudzinski, 1978: 51)

The way in which livestock use environmental resources, and hence their distribution across a landscape, is related to the spatial distribution of vegetation and water resources, the topography, the weather and social behaviour. Most of the available research relates to sheep, but there is a limited amount of information available for cattle and horses, although none of this research is specific to Iceland.



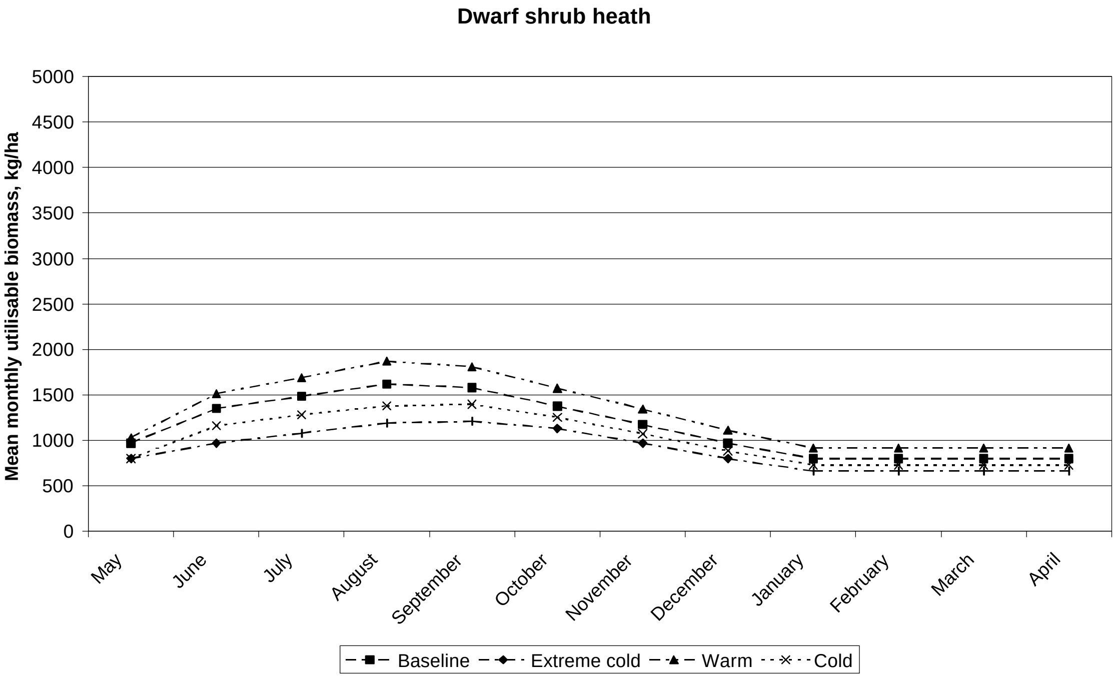
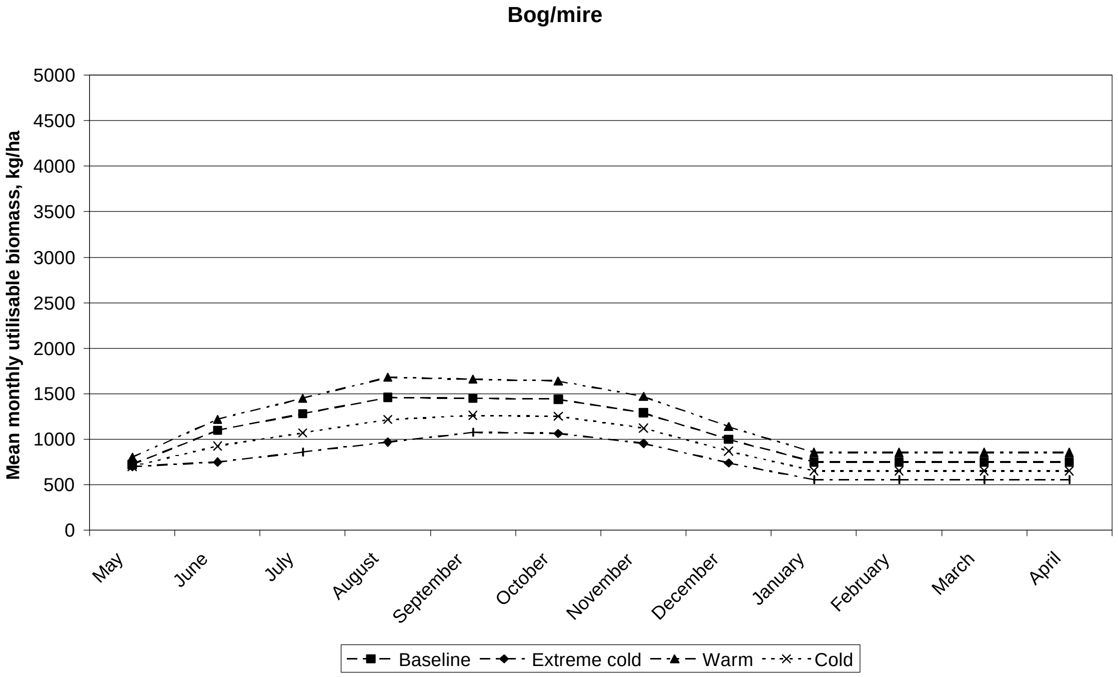


Figure 4-11: Mean monthly UB curves for the grassy heath and dwarf shrub heath communities under different climate scenarios



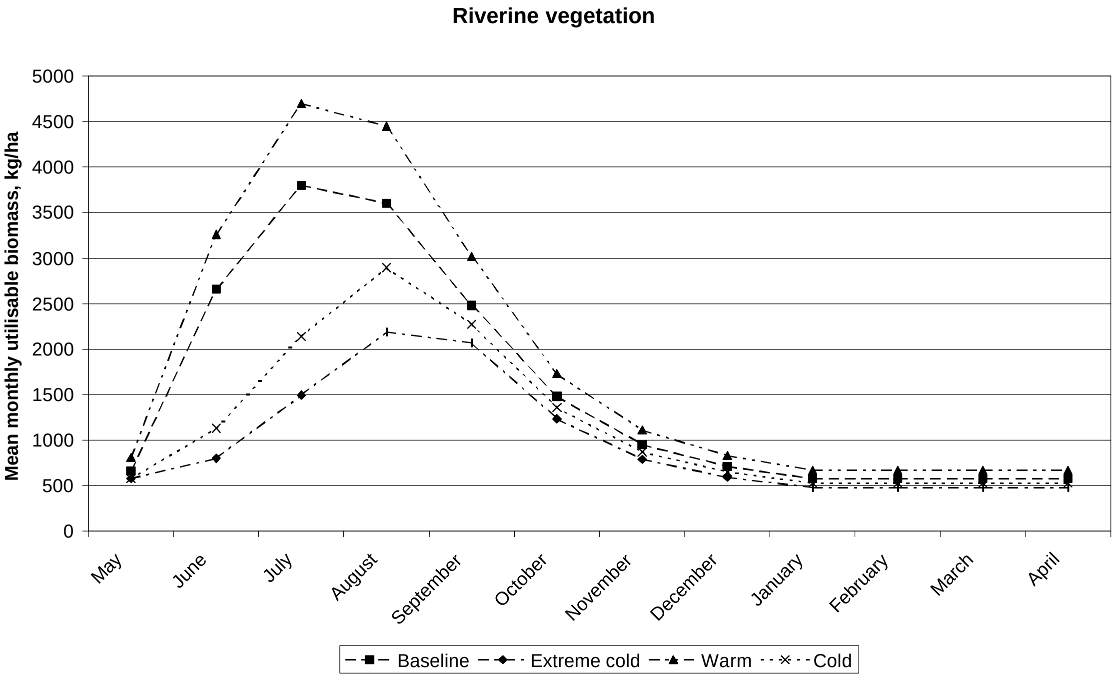
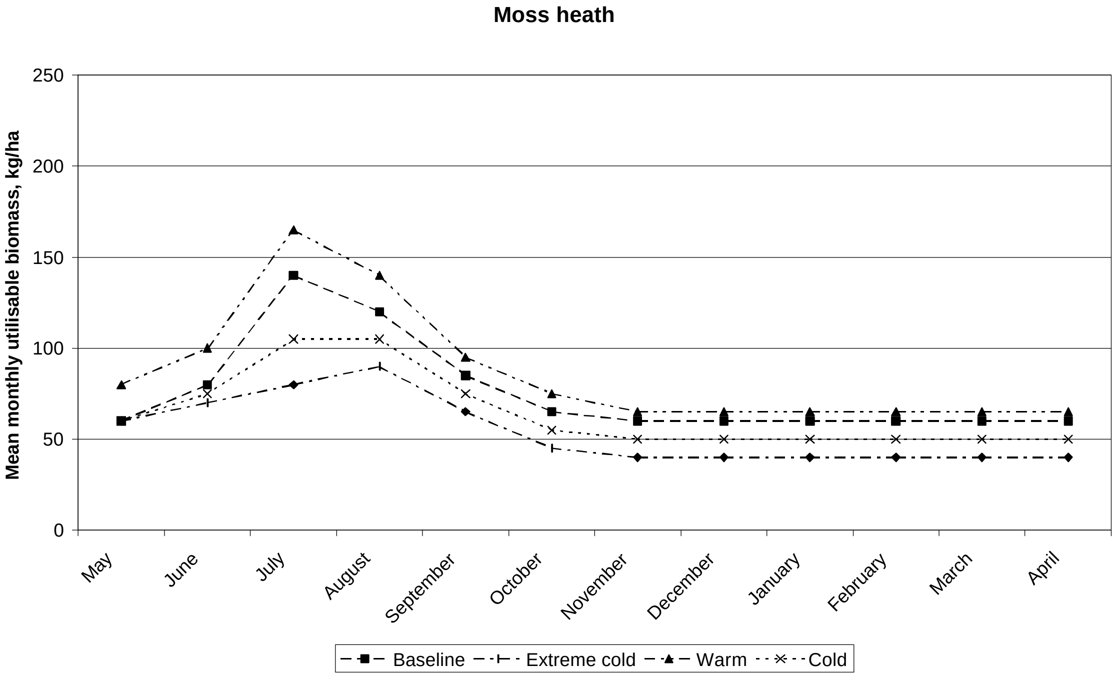


Figure 4-12: Mean monthly UB curves for bog/mire and riverine vegetation communities under different climate scenarios


Moss heath

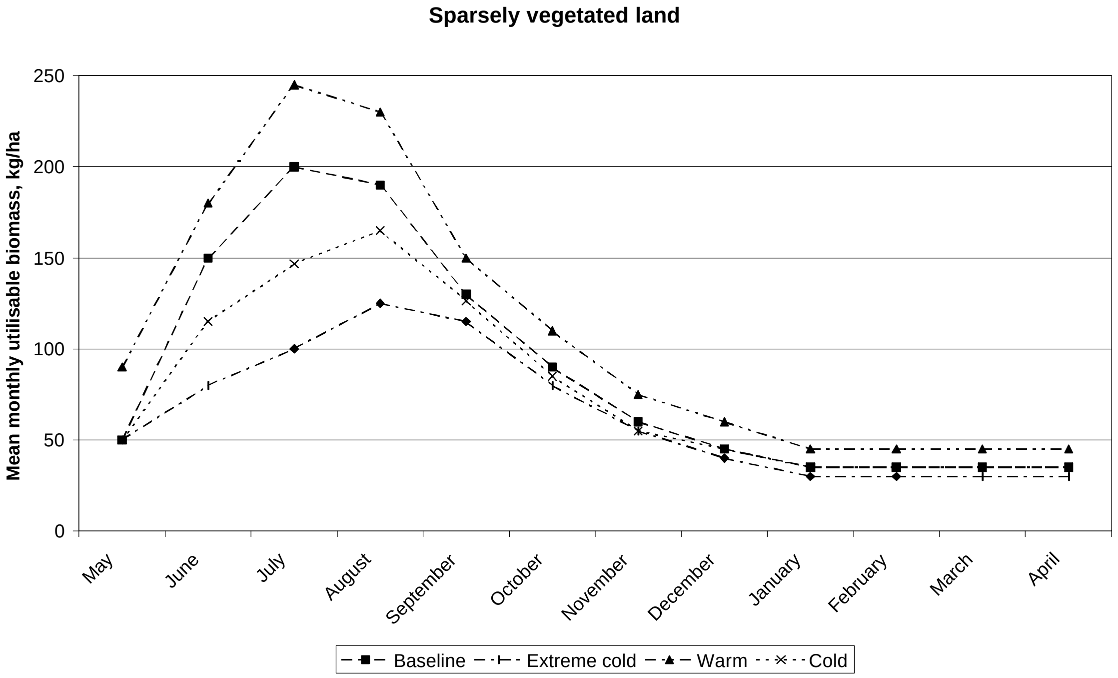

Sparsely vegetated land

Figure 4-13: Mean monthly UB curves for moss heath and sparsely vegetated land vegetation communities under different climate scenarios

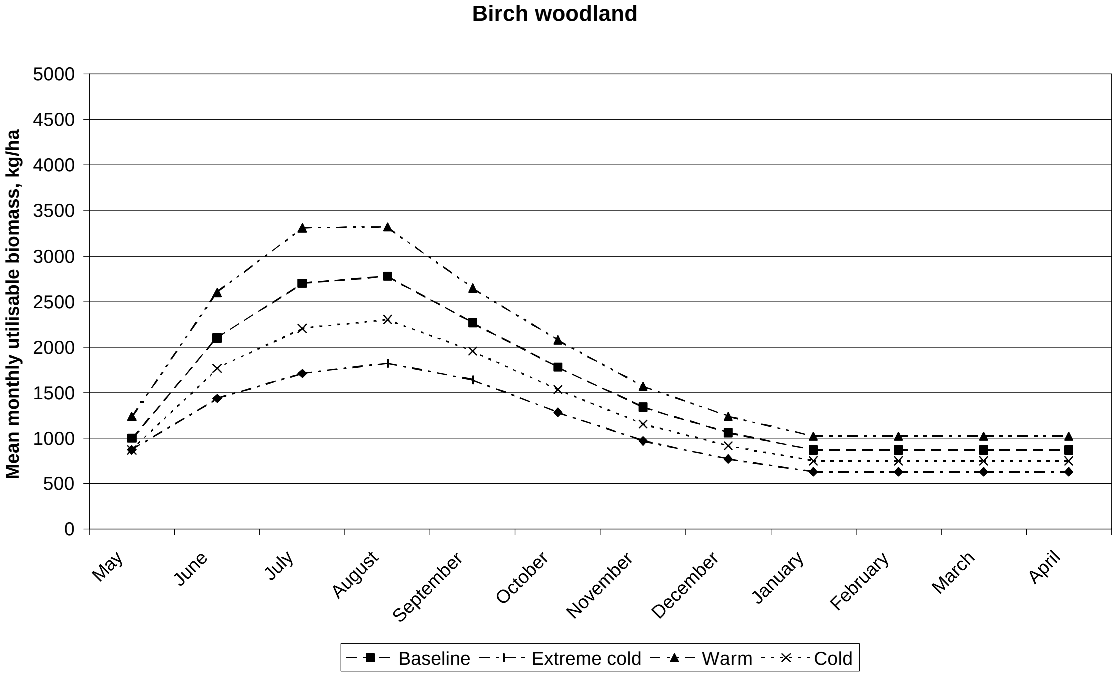


Figure 4-14: Mean monthly UB curve for birch woodland under different climate scenarios

In Búmodel, livestock are assumed to utilise the available vegetation resources in the landscape according to the spatial and temporal distribution of the most preferred vegetation communities. Topography and other factors will modify this vegetation-dependent distribution. Livestock cannot graze on very steep slopes, and prefer sheltered sites in strong winds. However, if a preferred grazing area is in an exposed location sheep will continue to graze there except in the most severe weather conditions. The extent of the rangeland and the location where livestock are first released might also affect the distribution of animals over short time-scales. As the distribution of livestock is re-calculated on a monthly basis in Búmodel, it is assumed that livestock could have theoretically travelled to any location within the available area within a month.

‘Flocking effects’ also influence the distribution of livestock across the landscape, leading to the uneven use of resources. However, research on hill breeds of sheep in the British Isles in similar conditions to those in Iceland show that hill breeds tend to be the most widely dispersed of all sheep breeds, and dispersion increases when pasture conditions are poorer (Arnold and Dudzinski, 1978). Studies on Scottish Blackface sheep in the Cheviots (from Hunter (1964) in (Arnold and Dudzinski 1978)) document the development of home ranges by hill sheep, which is governed by social competition, with some sheep forced to graze in areas with less favoured plant communities. The small influence of ‘flocking effect’ and the concept of home ranges for hill sheep suggest that Icelandic sheep will be widely distributed within a landscape, according to the availability of preferred vegetation. Personal observation during fieldwork supports this assumption, as any observed sheep were in small, scattered groups, usually consisting of a ewe and several lambs.

Although research in arid areas shows that the availability of water can have an important influence on the distribution of livestock (Pickup 1994; Weber *et al.* 1998), it was not considered to be a limiting factor in Iceland. Sheep will move a maximum of 3-4 km from water, and cattle will move over 8 km if forage conditions are poor (Arnold and Dudzinski 1978). Fresh water is generally accessible in Iceland and livestock can often obtain most of the moisture they need from green vegetation.

The effects of topography and exposure upon the distribution of livestock can be taken into account by excluding or weighting steep, inaccessible or exposed areas from the map of grazeable areas within the GIS. During the winter months, the distribution of livestock is also restricted by the need for shelter and vegetation that is not covered by snow. The areas available for winter grazing can be constrained by the modeller within the GIS.

In summary, livestock have dietary preferences for different types of vegetation, and fulfil these by preferential grazing. It is assumed, therefore, that within a spatially diverse landscape, livestock are distributed according to the distribution of the most preferred vegetation communities. This distribution will vary through time as the amount of utilisable biomass (UB) changes through interactions between plant growth, plant death and decomposition (removal from the system), and grazing. The distribution of livestock within a single month, a, can be expressed in the equation

$$S_i = S_n \frac{P_i H_i}{\sum_{i=0}^{n} P_n H_n}$$

Equation 4-11

where S_i is the number of sheep in cell i in month a, S_n is the total number of sheep in all cells n, P_i is the palatability score of cell i, H_i is the utilisable biomass in cell i in month a, P_n is the sum of palatability scores in all cells and H_n is the sum of all the utilisable biomass in all cells, n.

The distribution of livestock across the landscape in each of the land-use categories (upland, outfield, or infield) is calculated at the start of each month. This monthly distribution is not intended to represent a number of sheep confined to a 25 hectare cell for a month, but to model the average grazing intensity in the cell in that month. The greater the number of sheep assigned to the cell, the greater the grazing intensity. However, the number of livestock in any given cell is limited by the quantity of available utilisable biomass. Livestock consumption of biomass cannot exceed 100% of the available UB. Any ‘excess’ livestock are re-distributed evenly among the remaining cells in the land-use category. If consumption exceeds 100% of the utilisable biomass in all of the available cells in any one month then Búmodel halts that simulation run and flags up a warning message (for a single run) or records a simulation failure (for multiple runs).

4.5 Offtake sub-model

Búmodel distributes livestock as a whole over the upland or outfield area, rather than distributing individual cohorts. Therefore it is necessary to calculate the intake of an average animal (the number of sheep divided by the sum of their total offtake (as calculated in the maintenance sub-model). For each cell, this average sheep intake is multiplied by the sheep density of the cell (as calculated in the livestock distribution sub-model), giving the total offtake required from that cell. Each vegetation community within the cell will contribute towards the offtake; the size of the contribution is calculated using the relative palatability of each vegetation community compared with the palatability of the other vegetation communities available within the cell. The offtake requirement in feed units from each vegetation community is converted into kilograms of dry matter, based upon the feed unit value of the community in question. The sum of the feed requirements removed from each community is the total utilisable biomass removed from that cell.

4.6 Grazing intensity and the biomass production feedback loop

Grazing or browsing of vegetation by animals affects the production of UB by the alteration of normal plant growth and development. ‘Typically, grazed plants reorganise carbon and nutrient allocation patterns following defoliation in order to replace the foliage lost to herbivores…[which is] generally done at the expense of root growth and activity' (Archer and Arnalds 1982): 57. Most range plants can withstand a certain amount of grazing without detrimental effects, but particular factors are important, such as the frequency, intensity and the stage of plant growth when defoliation takes place. Young plants are much more susceptible to grazing than mature ones. Heavy grazing early in the growing season can dramatically decrease plant vigour and production during the rest of the growing season and into the next (Archer and Arnalds 1982). Certain plant types are also more susceptible to grazing than others: shrubs are usually the most vulnerable. This is because it takes them longer to re-establish a photosynthetic surface than graminoids, which have rapid leaf turnover and lose proportionally less energy and nutrients when grazed (Archer and Tiezen 1980). Although shrubs are more vulnerable than graminoids they are also less likely to be grazed in the first place (Table 4-12).

Table 4-12: Summary of growth form characterisitcs related to herbivory (from Archer and Tiezen (1980))

Growth form	Photosynthetic rate	Leaf longevity	Probability of being eaten	Ability to recover from defoliation
Graminoid – single shooted	High	Medium	High	High
Graminoid- tussock forming	Medium	Medium	High	High
Deciduous shrub	High	Short	Medium	Medium
Evergreen shrub	Low	Long	Low	Low
Forbs (Dicot herbs)	Medium	Medium	Medium	Medium

The effects of a single defoliation differ from those of repeated defoliations/grazing:

> 'While the response of *Eriophorum* to a single defoliation was increased leaf production at the expense of below-ground structures, multiple defoliation imposed at 10-day intervals for up to two growing seasons resulted in decreased leaf production, further weight loss in storage structures, and a curtailment of

> root growth. Leaf growth response during the first season of chronic defoliation was similar to that of a single defoliation. During the subsequent growing season, however, leaf length and weight were depressed markedly to 25 to 50% of control values, depending upon the date clipping was initiated' (Archer and Tiezen 1980): 546.

In this case (in Alaska) one full season of recovery was insufficient to restore leaf growth to control levels. Late season defoliation appears to more detrimental to leaf production in subsequent years than early season defoliation does, probably because plants then enter winter dormancy with reduced carbohydrate and nutrient levels.

The quantity of standing biomass remaining from the previous growing season also seems to affect spring growth, although explanation and quantification of this effect remains obscure. Winter and early spring grazing reduces the herbage yield of pastures in the spring, with greater yield reductions in heavily grazed pastures as opposed to lightly grazed ones (Laws and Newton 1987). In general, it seems that heavy grazing during the previous winter or spring reduces growth and yield in an individual growing season, whereas overgrazing during the summer or autumn affects growth in the subsequent season.

Overgrazing can result in a change in botanical composition, as plants weakened by overgrazing are more vulnerable to replacement by competing species. Kristinsson (1979) has advanced a model of how grazing-induced vegetation change might occur in the uplands of Iceland, from a diverse, herb-rich shrub community to a prostrate, sparsely vegetated community dominated by unpalatable species: mosses, sedges and rushes. This change in the vegetation community is matched by a massive reduction in vegetation productivity, to 1/7 of the original productivity. In overgrazed systems livestock also have to travel further to find suitable fodder, so the risk of trampling may also be increased. Trampling damages plants, compacts soil and may break open the vegetation layer, thus increasing the risk of frost damage and erosion.

4.6.1 Grazing utilisation thresholds

Although the fact that overgrazing leads to vegetation degradation is undisputed, it is difficult to predict exactly where and when degradation will be initiated in a grazed landscape. Many factors are involved: climate, vegetation cover, grazing management, and soil condition, and degradation is the product of the interaction of these factors over time. Búmodel is not meant to predict the occurrence of degradation *per se*, but to predict the areas that may be *vulnerable* to degradation. This is done by modelling the utilisation of vegetation biomass by grazing livestock over space and time.

Utilisation by livestock is calculated in two ways in Búmodel. The first, the monthly utilisation, is the amount of UB removed from an cell by grazing in a single month as a percentage of the total UB available in that cell at the beginning of the month. The second, cumulative utilisation, is the sum of all UB removed since the start of the growing season up to, and including, the current month as a percentage of the peak UB (as a proxy for annual production). The cumulative utilisation gives a better representation of the utilisation in summer, while the monthly utilisation gives a better representation of the utilisation in the winter and spring months.

As discussed above, over-utilisation of the UB in summer months has an impact on growth in subsequent months. In Búmodel this is simulated by reducing the mean UB of a vegetation patch (within a cell) by 20% if the utilisation in that patch in the preceding month exceeded a certain threshold. These thresholds are based on the ‘percentage utilisation of the annual yield of plant communities under proper grazing’ (Thorsteinsson 1980b). It is not possible to calculate the annual yield due to a lack of information on productivity rates for all Búmodel vegetation communities, however the utilisable biomass at the peak of the growing season is considered to be an acceptable proxy (Friðriksson 1972). A 40% utilisation threshold is used for the grassy heath, moss heath, riverine, birch woodland and sparsely vegetated communities; an utilisation threshold of 15% is used for dwarf shrub heath, and a threshold of 35% for bog/mire. These thresholds have been developed from the results of the RALA grazing experiments (section 4.3.2.1). Over-utilisation during the winter months would similarly result in a reduction in production in the following growing season, but as Búmodel only runs for a single year, this is not included in the model.

4.6.2 The biomass production-offtake feedback sub-model

The utilisable biomass, livestock distribution and offtake sub-models are all linked in the biomass production-offtake sub-model, shown in Figure 4-15 and Figure 4-16. The amount of utilisable biomass in each cell is calculated at the beginning of each month, but the offtake, monthly utilisation and cumulative utilisation are calculated at the end of the month.

4.7 Hay making sub-model

Hayfields were the only areas of land on a typical Icelandic farm that were enclosed and deliberately fertilised. Therefore they were something of a special case in the farm landscape and are treated separately from the outfield and upland pastures. A simple model was designed to calculate hay yield, based on work by Bergþórsson *et al.* (1987). This model expresses the mean hay yield on improved grassland as a function of temperature and nitrogen fertiliser application. Both the mean summer temperature (May to September) and the mean temperature of the previous winter (October to April) are used as parameters in the model. The hay yield predicts the total hay harvested, whether one or two cuts took place. The hay yield should be differentiated from dry matter yield, as hay contains at least 15% moisture, although the two are broadly equivalent because of hay losses during haymaking.

There is historical evidence for the impact of climatic variables upon hay yields in the pre-modern period. An analysis by Ogilvie (1984) on hay yields in the past (1601-1780) found that cold springs were related to poor grass growth, and that the final hay harvest was related to winter temperature in all regions of Iceland. She also found a significant relationship between summer rainfall and grass growth and harvest in all regions, although both high and low rainfall tended to produce poor grass growth. This relationship may be related more to the ease of harvesting than to the yield. The north of Iceland was found to be more sensitive to variations in climate than the other regions.

The original model proposed by Bergþórsson was based upon hay yield, fertiliser application and temperature data from the period 1901-1975. This period was one of significant change in the Icelandic pastoral system, as the use of artificial fertilisers increased after the mid-20th century and the species composition of hayfields shifted from a mix of grasses, herbs and sedges to a few fast-growing, high-yielding grasses, such as *Phleum pratense* (Amorosi *et al.* 1998). The impact of artificial fertilisers will be ignored in the present model, as their introduction falls outside the time period of

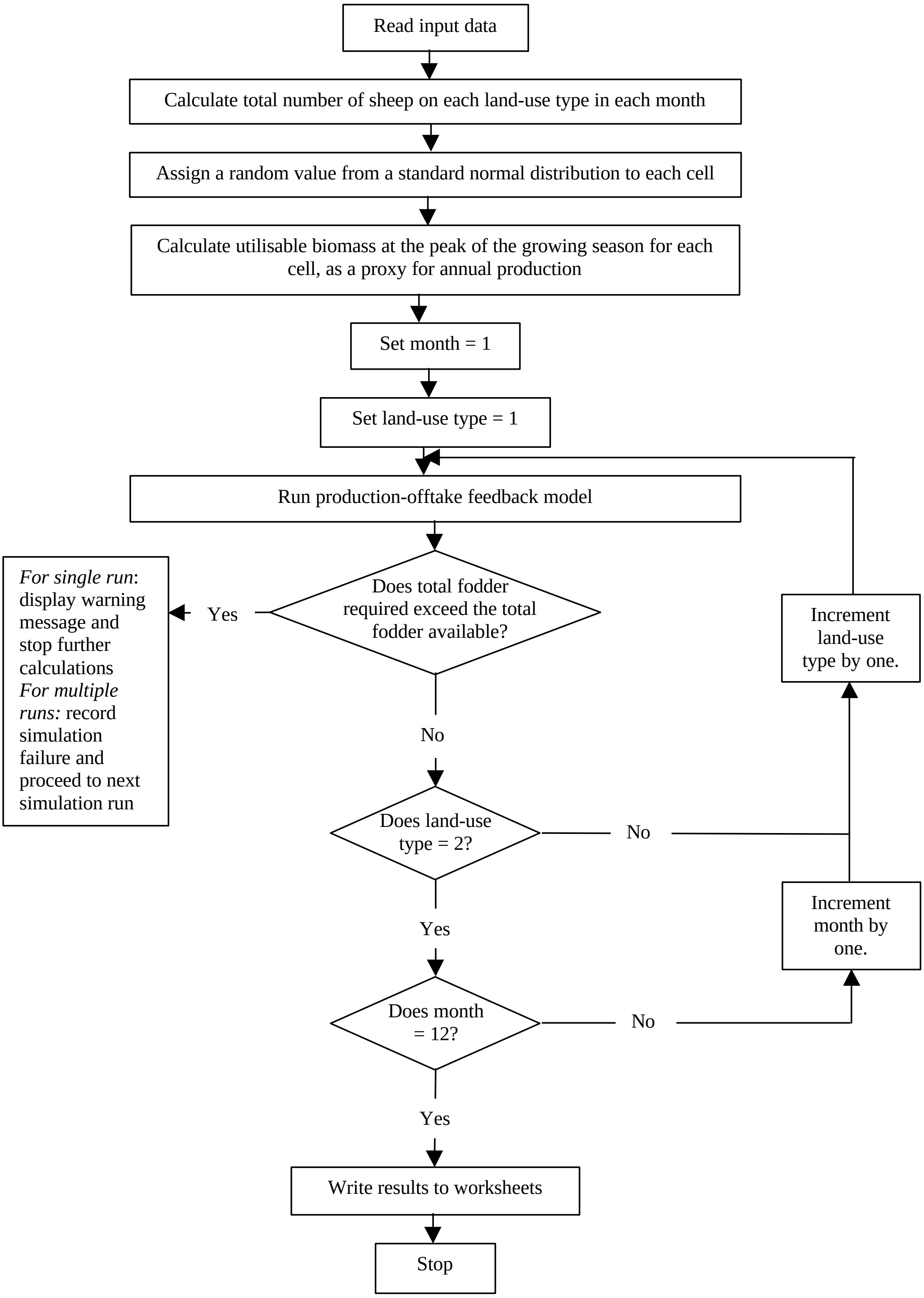


Figure 4-15: Structure of the utilisable biomass sub-model

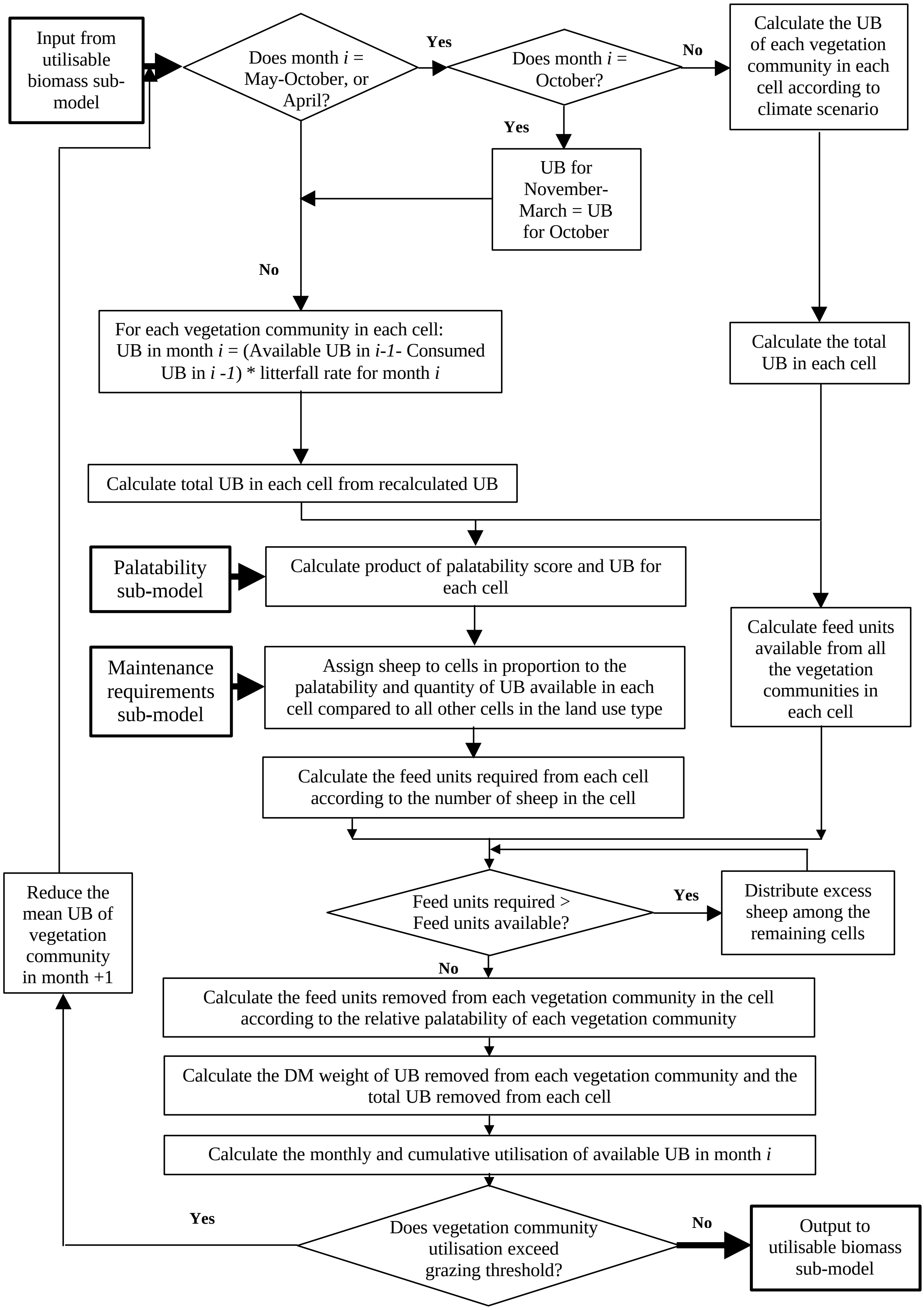


Figure 4-16: Structure of the production-offtake feedback sub-model

interest. Prior to their introduction, the principal sources of fertiliser were household ash and manure from the animals that were wintered indoors (Aðalsteinsson 1990), although seaweed may have been used in some areas. Thus the availability of nitrogen fertiliser for hay fields was largely dependent upon the availability of manure. This, in turn, was dependent on the number of animals housed indoors through the previous winter. During the time they were kept inside the livestock were fed on hay, although some outdoor grazing may also have taken place.

Measures of manure application and nitrogen content are estimated from indirect evidence. The nitrogen content of manure can be quite variable, as it is dependent on the composition of the livestock's diet and the moisture content of the manure, which can be between ten and eighty per cent. Inefficient storage and application of the manure could also result in reduction in nitrogen content. Consequently, any estimate of nitrogen applications on hayfields in the past will be an approximation. Bergþórsson (1987) estimated that one hundred kilograms of hay contains approximately 1.8 kg of nitrogen, on the other hand the manure that is produced from feeding livestock with this hay is 0.8-0.9 kg of effective nitrogen fertiliser (if the manure is well preserved). It is estimated that approximately two thirds of the manure produced was applied, and the rest was either used as fuel or lost through wastage. Farm records from the early 20th century Bergþórsson *et al.* (1987) report applications of 15 tons of manure per hectare, prior to the introduction of artificial fertilisers. Assuming 0.3% of this amount is effective nitrogen, this produces an application of 45 kg of N per hectare. Other sources give a mean effective nitrogen content of 0.6 % (0.3 - 2.2 %) for cattle manure (Berryman 1965 in Briggs and Courtney (1985)), 0.9% for sheep manure and 0.5% for horse manure (Barker and Walls 2002).

So the amount of effective nitrogen fertiliser produced by livestock wintered indoors can be estimated from the quantity of hay that these livestock consume. If the hayfield area is also known, then the potential application of nitrogen per hectare can be calculated. This figure, together with mean winter and summer temperatures, are used as parameters in the regression equation for calculating hay yield. The regression equation calculated by Bergþórsson was:

$$\boldsymbol{Y = (0.29 + 0.0729\,S + 0.0794\,W)\,(1820 + 28.1\,N - 0.051N^2)}$$

Equation 4-12

Where ***Y*** is the hay yield from improved grassland (kg/ha), ***S*** is mean summer temperature (May-September) at Stykkishólmur (°C), ***W*** is the mean winter temperature (October-April) at Stykkishólmur (°C) and ***N*** is the total fertiliser nitrogen (kg/ha of improved grassland). This equation is a good predictor of hay yields over long time periods, but over-estimates yields where nitrogen applications are low (as in the early 20th century). A second regression equation was calculated using the same parameters, but based on data from 1901 to 1940 only, in the period before the widespread use of artificial fertilisers. Estimated nitrogen applications in this period were below 70 kg/ha. The use of best sub-sets regression in MINITAB gave the following linear regression equation:

$$\boldsymbol{Y = -66 + 226W + 186S + 25.8N}$$

Equation 4-13

$$\mathbf{R^2 = 80.2\% \quad R^2\,(adj.) = 78.5\%}$$

The parameters are identical to those in Equation 4-12. As this regression equation is linear it may not be a good predictor of yields when high levels of nitrogen are applied, but it is not anticipated that the model will be used for this purpose. The yield adjusts by 226 kg/ha for every ºC change in the October-April temperature, and by 186 kg/ha for every ºC alteration in the May-September temperature. If the mean annual temperature is adjusted by 1 ºC (equivalent to 1 ºC change in the same direction for both the summer and winter temperatures) then the yield is increased or reduced by 412 kg/ha. This value is very similar to the change in dry matter yield of 447 ± 81 kg/ha for a 1 ºC change in annual temperature where no nitrogen is applied (Björnsson and Helgadóttir 1988). As the temperature parameters are calculated from the Stykkishólmur meteorological record in western Iceland, this regression equation is thought to be a reasonable predictor of hay yields in lowland sites in Iceland.

Additional validation was carried out by predicting hay yields from 1941 to 1945 (from Bergþórsson *et al.* (1987), when nitrogen fertiliser applications were between 65 and 80 kg/ha and climate conditions were generally mild. The regression equation predicted hay yields well, with a correlation coefficient of 0.95 and a root mean square error of 168.7 kg/ha.

Fluctuations in hay yield are considerably larger in the northern part than in the southern part of the country, due to the greater fluctuations in temperature. The hay yield regression equation predicts these fluctuations, as can be seen when the yields under each of the climate scenarios in the south and the north are compared (Table 4-13).

Table 4-13: Sensitivity of hay yields to temperature variations in the north and south.

Climate Scenario	I Baseline	II Extreme cold	III Cold	IV Warm
	Average (1961-1990)	**Estimated average 1859-1868**	**Average of 10 coldest years 1937-1995**	**Average of 10 warmest years 1937-1995**
Reykjahlíð				
Oct-Apr temperature relative to Scenario I, ºC	0	-1.8	-1.1	+1.6
May-Sept temperature relative to Scenario I, ºC	0	-0.8	-0.6	+1.5
Annual temperature relative to Scenario I, ºC	0	-1.4	-0.8	+1.6
Hay yield from hayfields (%)	100	70	80	135
Sámsstaðir				
Oct-Apr temperature relative to Scenario I, ºC	0	-1.5	-0.9	+1.2
May-Sept temperature relative to Scenario I, ºC	0	-0.5	-0.3	+1.2
Annual temperature relative to Scenario I, ºC	0	-1.1	-0.7	+1.2
Hay yield from hayfields (%)	100	86	92	116

The hay yield sub-model calculates the total amount of hay available for feeding over-wintering livestock, by calculating the hay produced from the hay field and the quantity of hay stored from the previous year. This figure is compared with the amount of hay that is required (calculated from the number and type of livestock and the length of the hay-feeding period). If the hay required exceeds the hay available then further hay calculations for that simulation run cease and the month of simulation failure is recorded. The structure of the hay yield sub-model is given in Figure 4-17.

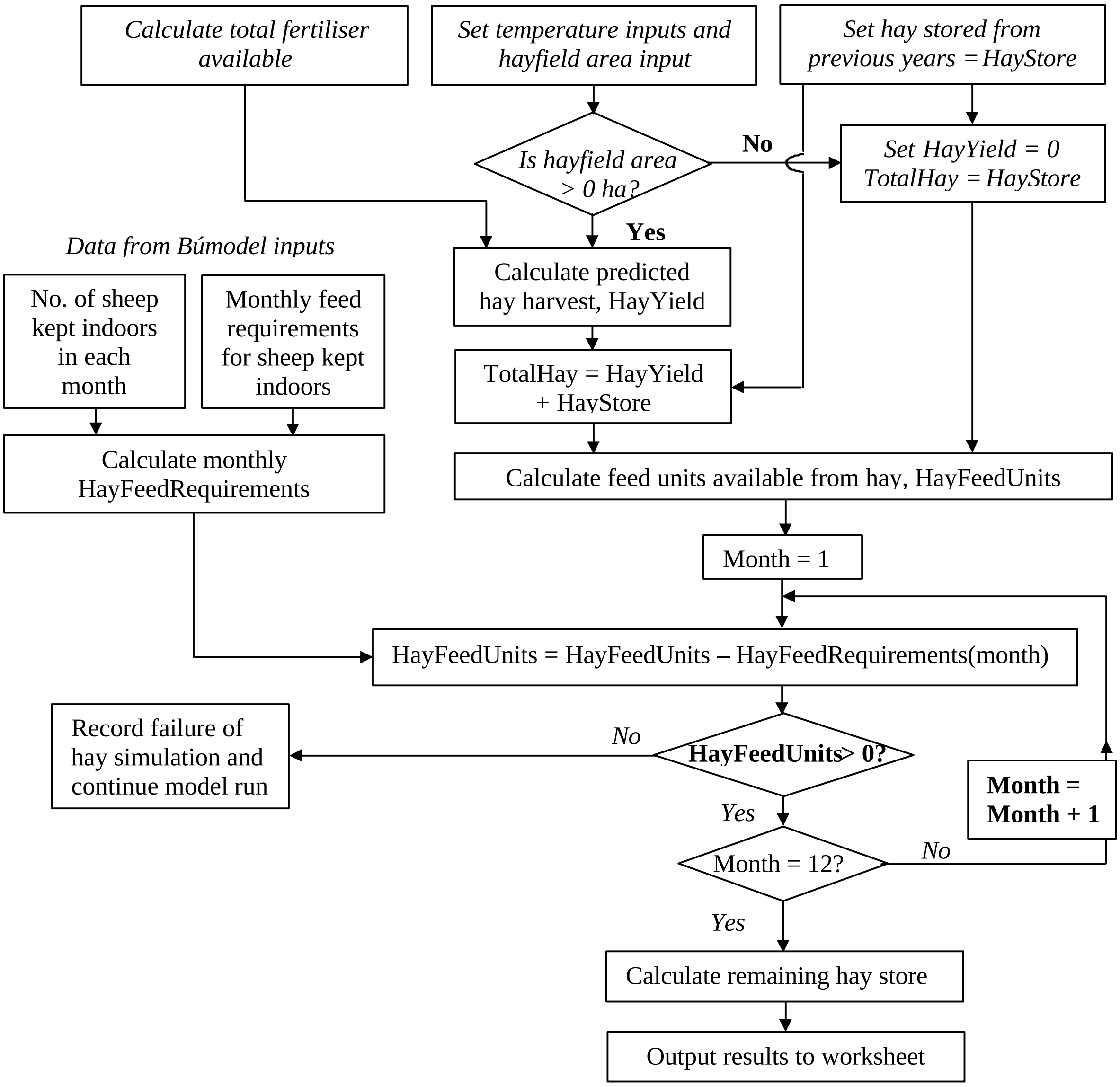


Figure 4-17: Hay yield sub-model structure

4.8 The model interface: spreadsheets and GIS

Environmental simulation models, such as Búmodel, and geographic information systems can be linked by loose or tight coupling (Figure 4-18). Búmodel has been constructed in MS Excel using Visual Basic for Applications code linked to multiple spreadsheets; the model can then be linked to the ArcView geographic information system via shared DBF data files (loose coupling). The vegetation cover is mapped in the GIS; and summarised using a lattice of 25-hectare cells, which all have a unique cell identifier (Cell ID). This summary file is exported to MS Excel, and provides the content of the Pasture Inputs spreadsheet (Figure 4-20). Management and livestock inputs are determined in the Livestock Inputs sheet (Figure 4-19). Both spreadsheets contain drop-down menus that allow the model user to specify the climate scenario, land use type, the number of simulation runs and the ordering of the results spreadsheets.

The program code for Búmodel is contained in Appendix A. A copy of the model can be obtained from the author. After running, Búmodel writes the simulation results to a further set of spreadsheets. In a single simulation run, results are sent to the Pasture Results (botanical composition), Herbage Results (utilisable biomass and sheep density) and Offtake Results spreadsheets (offtake, monthly and cumulative utilisation). When multiple simulation runs are undertaken, the statistical results (the mean, standard deviation, maximum and minimum cell values for each parameter over the set of runs) are recorded in a single spreadsheet, Statistical Results (Figure 4-21). The best and worst runs of the simulation set (based on mean April cumulative utilisation) are recorded in the spreadsheets BestScen and WorstScen, so that the range of possible outcomes (from the same set of input parameters) can be explored. These spreadsheets can then be converted into DBF files and exported into ArcView. The model results are displayed in map form in GIS by joining the DBF file to the shapefile containing the 25-hectare cells using the Cell ID as the common field.

4.9 Summary of the modelling chapters

Chapters 3 and 4 discuss the data requirements of Búmodel and describe the environmental processes (both conceptual and mathematical) on which the model is based. Búmodel operates on a monthly basis over a single year, so processes that operate on a longer time-scale are not explicitly considered in the model. For example, changes in botanical composition could occur as a result of overgrazing, which would be indicated by high levels of biomass utilisation, but this change would occur over the course of several years or more. Although Búmodel has been constructed using the best available environmental information, it must be validated as being fit for its intended purpose before it is accepted as a credible model of the Icelandic grazing system. The process of model validation is described in the following chapter. Búmodel has been constructed using environmental information that has been collected from regions throughout Iceland, so the model should be applicable throughout Iceland, rather than being specific to the two study areas. This assumption is tested in the following chapter.

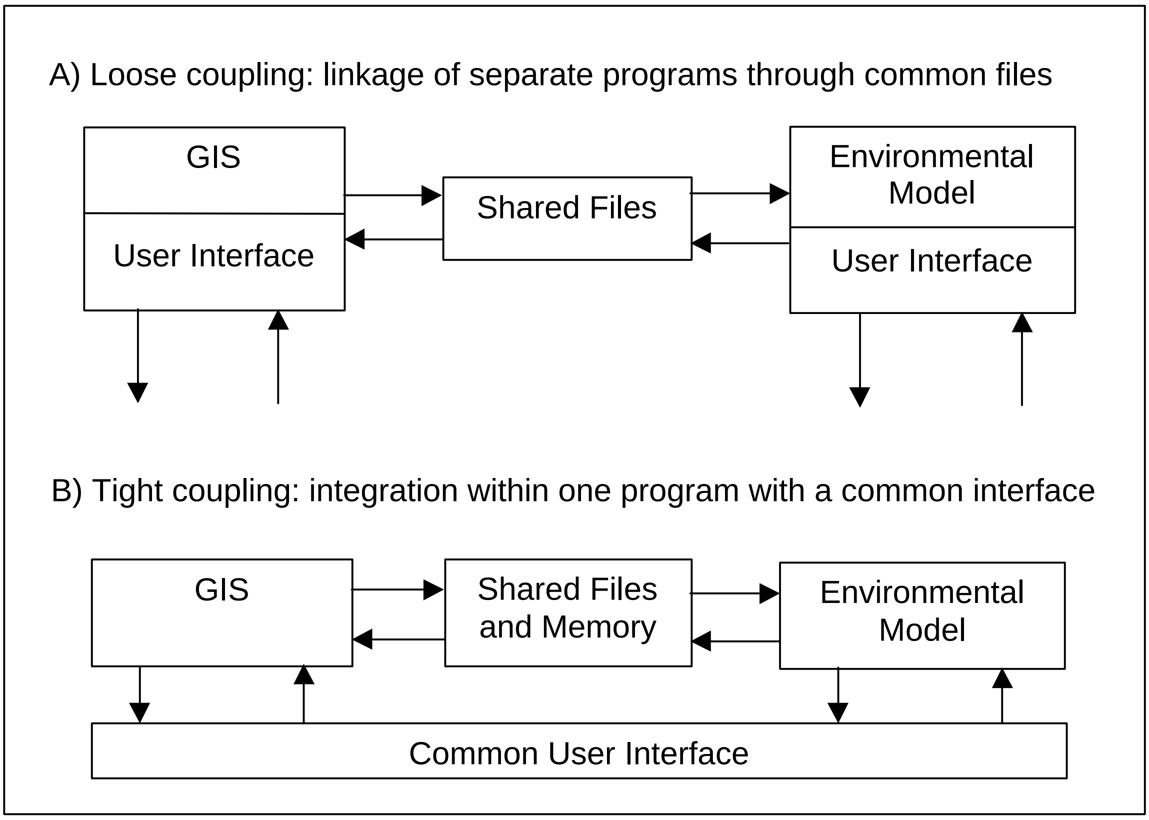
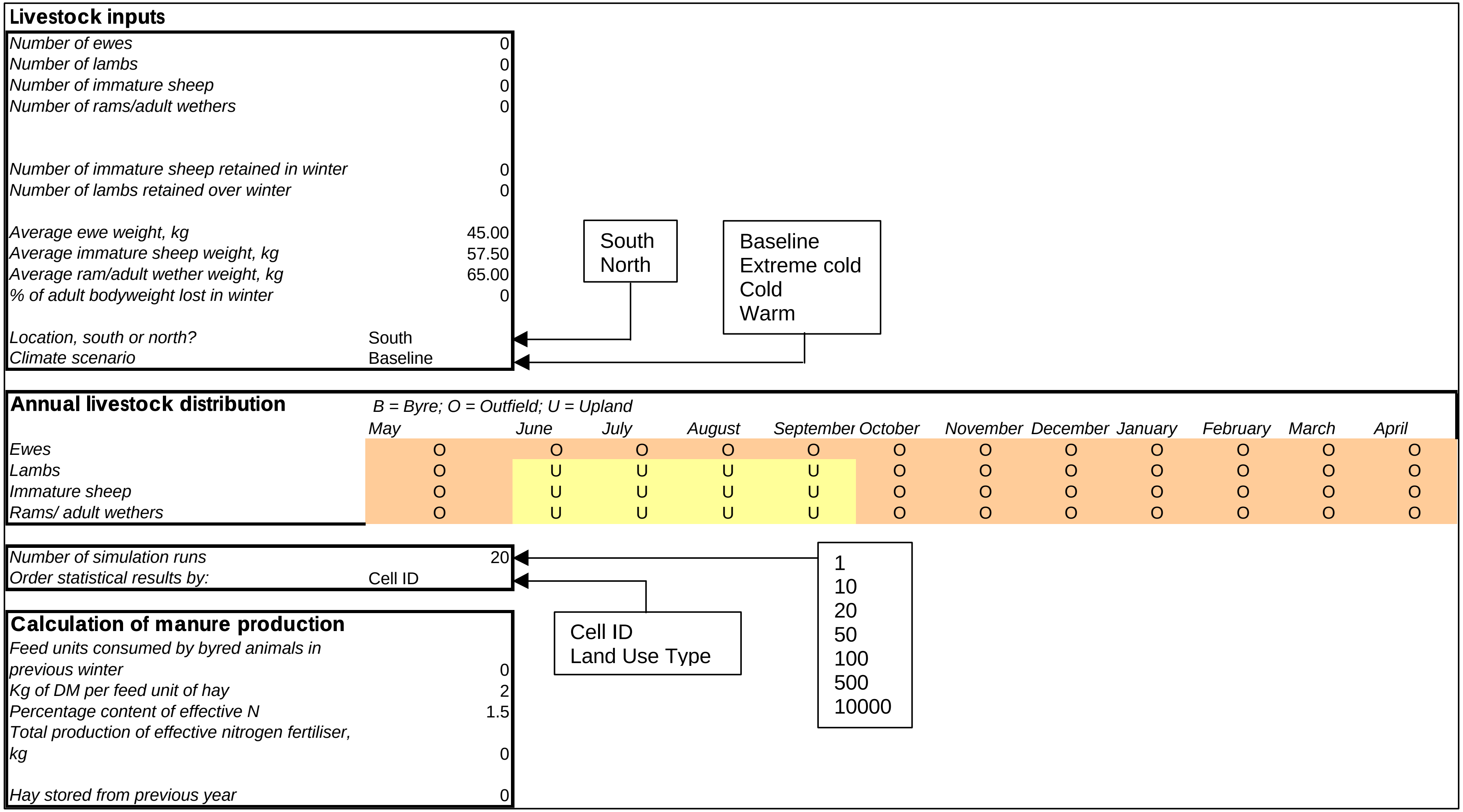


Figure 4-18: Loose and tight coupling of environmental models and GIS (from (Fedra 1993)).



Livestock inputs

Number of ewes	0
Number of lambs	0
Number of immature sheep	0
Number of rams/adult wethers	0
Number of immature sheep retained in winter	0
Number of lambs retained over winter	0
Average ewe weight, kg	45.00
Average immature sheep weight, kg	57.50
Average ram/adult wether weight, kg	65.00
% of adult bodyweight lost in winter	0
Location, south or north?	South
Climate scenario	Baseline

South
North

Baseline
Extreme cold
Cold
Warm

Annual livestock distribution *B = Byre; O = Outfield; U = Upland*

	May	*June*	*July*	*August*	*September*	*October*	*November*	*December*	*January*	*February*	*March*	*April*
Ewes	O	O	O	O	O	O	O	O	O	O	O	O
Lambs	O	U	U	U	U	O	O	O	O	O	O	O
Immature sheep	O	U	U	U	U	O	O	O	O	O	O	O
Rams/ adult wethers	O	U	U	U	U	O	O	O	O	O	O	O

Number of simulation runs	20
Order statistical results by:	Cell ID

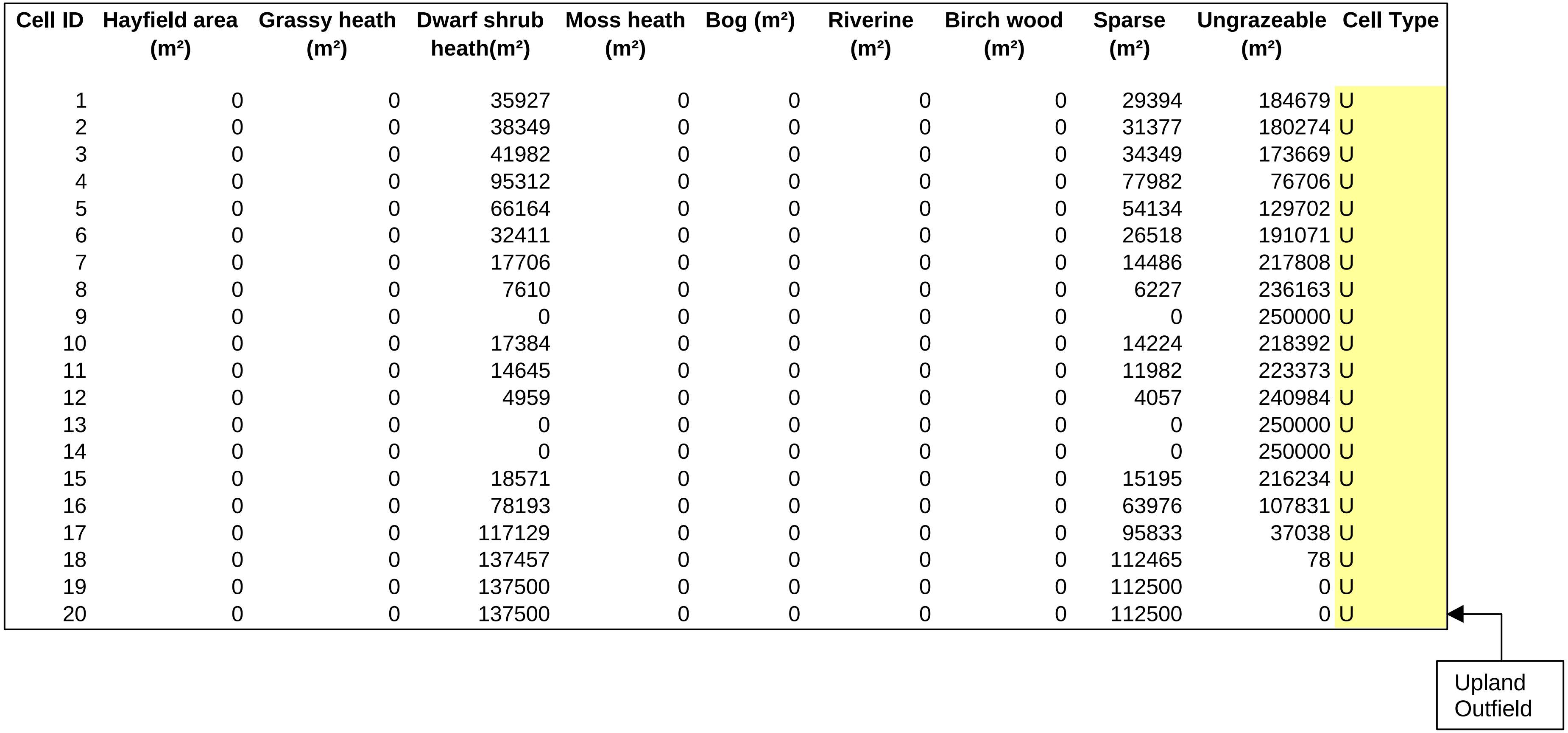
1
10
20
50
100
500
10000

Cell ID
Land Use Type

Calculation of manure production

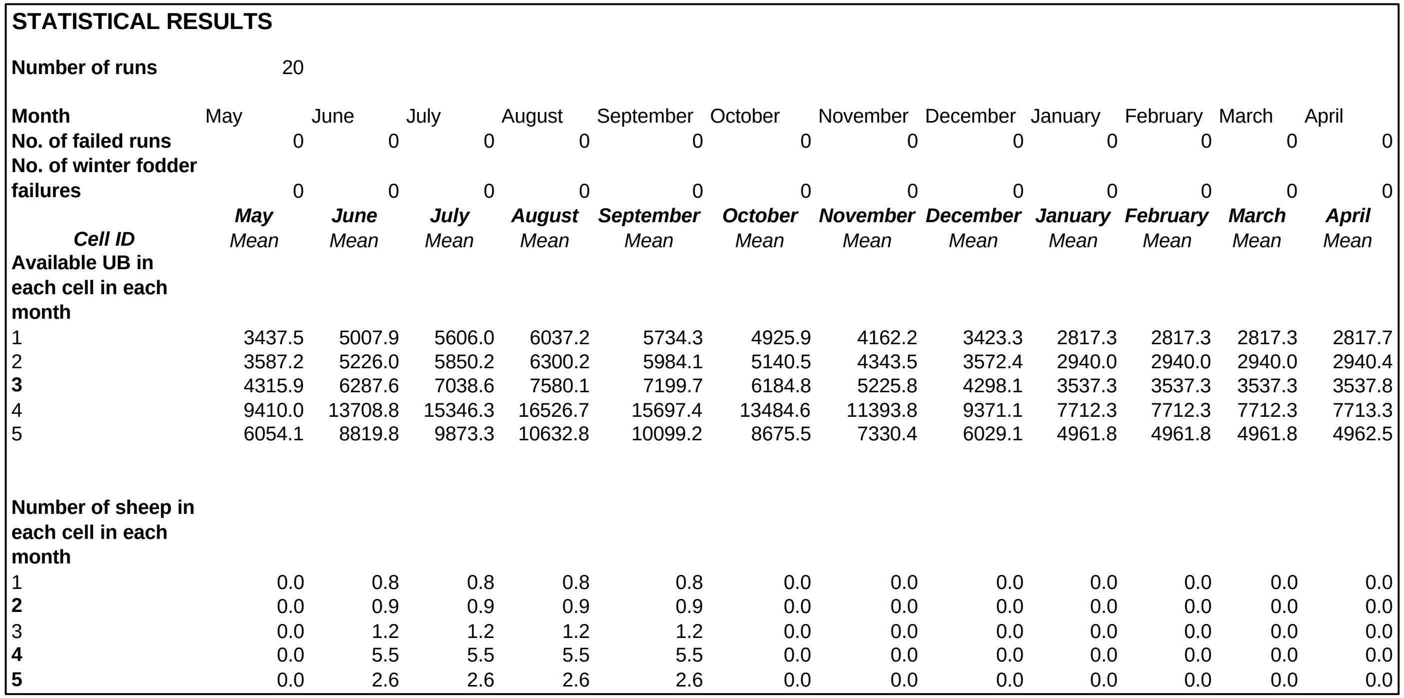
Feed units consumed by byred animals in previous winter	0
Kg of DM per feed unit of hay	2
Percentage content of effective N	1.5
Total production of effective nitrogen fertiliser, kg	0
Hay stored from previous year	0

Figure 4-19: Búmodel livestock inputs user interface



Cell ID	Hayfield area (m²)	Grassy heath (m²)	Dwarf shrub heath(m²)	Moss heath (m²)	Bog (m²)	Riverine (m²)	Birch wood (m²)	Sparse (m²)	Ungrazeable (m²)	Cell Type
1	0	0	35927	0	0	0	0	29394	184679	U
2	0	0	38349	0	0	0	0	31377	180274	U
3	0	0	41982	0	0	0	0	34349	173669	U
4	0	0	95312	0	0	0	0	77982	76706	U
5	0	0	66164	0	0	0	0	54134	129702	U
6	0	0	32411	0	0	0	0	26518	191071	U
7	0	0	17706	0	0	0	0	14486	217808	U
8	0	0	7610	0	0	0	0	6227	236163	U
9	0	0	0	0	0	0	0	0	250000	U
10	0	0	17384	0	0	0	0	14224	218392	U
11	0	0	14645	0	0	0	0	11982	223373	U
12	0	0	4959	0	0	0	0	4057	240984	U
13	0	0	0	0	0	0	0	0	250000	U
14	0	0	0	0	0	0	0	0	250000	U
15	0	0	18571	0	0	0	0	15195	216234	U
16	0	0	78193	0	0	0	0	63976	107831	U
17	0	0	117129	0	0	0	0	95833	37038	U
18	0	0	137457	0	0	0	0	112465	78	U
19	0	0	137500	0	0	0	0	112500	0	U
20	0	0	137500	0	0	0	0	112500	0	U

Figure 4-20: Búmodel vegetation inputs user interface



STATISTICAL RESULTS

Number of runs 20

Month	May	June	July	August	September	October	November	December	January	February	March	April
No. of failed runs	0	0	0	0	0	0	0	0	0	0	0	0
No. of winter fodder failures	0	0	0	0	0	0	0	0	0	0	0	0
	May	***June***	***July***	***August***	***September***	***October***	***November***	***December***	***January***	***February***	***March***	***April***
Cell ID	*Mean*	*Mean*	*Mean*	*Mean*	*Mean*	*Mean*	*Mean*	*Mean*	*Mean*	*Mean*	*Mean*	*Mean*
Available UB in each cell in each month												
1	3437.5	5007.9	5606.0	6037.2	5734.3	4925.9	4162.2	3423.3	2817.3	2817.3	2817.3	2817.7
2	3587.2	5226.0	5850.2	6300.2	5984.1	5140.5	4343.5	3572.4	2940.0	2940.0	2940.0	2940.4
3	4315.9	6287.6	7038.6	7580.1	7199.7	6184.8	5225.8	4298.1	3537.3	3537.3	3537.3	3537.8
4	9410.0	13708.8	15346.3	16526.7	15697.4	13484.6	11393.8	9371.1	7712.3	7712.3	7712.3	7713.3
5	6054.1	8819.8	9873.3	10632.8	10099.2	8675.5	7330.4	6029.1	4961.8	4961.8	4961.8	4962.5
Number of sheep in each cell in each month												
1	0.0	0.8	0.8	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.9	0.9	0.9	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	1.2	1.2	1.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	5.5	5.5	5.5	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	2.6	2.6	2.6	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 4-21: Example of Búmodel output results (note that only a portion of the spreadsheet is shown)

Chapter 5: Model Evaluation: Sensitivity Analysis and Validation

5.1 Introduction

A dynamic environmental model such as Búmodel must be properly tested and validated if it is to be a useful tool for investigation. Model validation should evaluate whether the model as designed can give reasonable predictions and explanations of the system under investigation sufficient for its stated purpose (Rykiel 1996; Deaton and Winebrake 2000). Búmodel was designed to simulate the pre-modern Icelandic grazing system and to investigate the contribution of system management to extensive vegetation and soil degradation. The intention was to model management scenarios in a simplified representation of a real landscape, producing a range of possible outputs from a set of input parameters. There are two resulting variables that it is important for Búmodel to represent as accurately as possible. These primary parameters are the quantity of grazeable vegetation available to livestock at different times of year and how much of this available fodder the livestock consume. From these variables the extent of grazing utilisation in different parts of the grazing area and the potential for vegetation and soil degradation can be assessed.

Sensitivity analyses of the parameters and functions embedded in the model were undertaken. These provide an objective measure of the sensitivity of the model output variables to changes in parameters and functions; they should not necessarily be used to draw any conclusions about the grazing system. Validation of the entire model can only be partial, due to the historical nature of some of the inputs and the lack of suitable data sets against which Búmodel can be tested. However, it is possible to validate those parts of the model that have been parameterised using contemporary Icelandic data. The data set used for validation comes from a grazing experiment undertaken in 1989 in central northern Iceland (Jónsdóttir 1994).

5.2 Structural validation or verification of Búmodel

Structural validation of a model assesses how accurately the model-system infrastructure represents the best understanding of the cause-effect relationships in the real system (Deaton and Winebrake 2000). This process could also be referred to as verification (Jørgensen 1991) and involves checking that system relationships have been accurately translated into computer code. The verification of Búmodel was undertaken during model development. Model verification included checking that Búmodel coped with zero values for certain inputs, that the correct numerical data types were used (i.e. integer or floating point) particularly when very large numbers were involved, and checking input and output values in order to identify possible rounding or summing errors. This process also identified that the modelled landscape was limited to 1000 cells (due to a limitation of Visual Basic), so more extensive landscapes would have to be modelled as two or more discrete areas, given the existing cell size of 25 ha.

The development of Búmodel followed the lead of the Macaulay Institute's Hill Grazing Management Model (Armstrong *et al.* 1997a, 1997b) by developing a conceptual model and using the available information in its parameterisation. This being the case, the structural validation of Búmodel has been embedded in the process of model development from the initial flow diagram, shown in chapter 3.

5.3 Sensitivity analyses

A model sensitivity analysis aims to provide a measure of the sensitivity of the important output variables to changes in parameters, forcing functions or initial values

(Jørgensen 1991). A proper analysis provides insight into the role played by each system element in the overall behaviour of the system and which individual elements, or combination of elements, affect system behaviour most strongly (Deaton and Winebrake 2000). It can also be used to focus future research on those areas of the system that are least understood. In the sensitivity analysis of Búmodel exogenous or input variables (sheep numbers, climatic scenario, distribution) and internal model parameters (livestock body weight, winter weight loss) were tested.

A special Visual Basic MS Excel program (the Sensitivity macro in Appendix A.7) was written for the sensitivity analysis. Búmodel ran within this macro, which allowed the parameter or function under investigation to be incremented while all other input parameters were held constant. The model was run on an idealised landscape of ten 25-hectare cells of uniform vegetation cover. All sensitivity tests on Búmodel were done using a sample set of 20 model runs. A total of 42 MS Excel workbooks were produced, containing the results of 509 model runs of 20 simulations each.

Due to the large amount of data produced, it proved too time consuming to analyse the variation in all parameters in all months. Detailed analyses were carried out on the monthly values of utilisable vegetation biomass, cumulative and monthly utilisation and offtake for September and March, representing the ends of the summer and winter grazing seasons.

5.3.1 Livestock numbers

Both the system and Búmodel are expected to be most sensitive to the stocking rate (numbers per hectare) of livestock grazing the vegetation. All of the pasture vegetation types were run with increasing numbers of ewes (45 kg body weight) under the Baseline climatic scenario. The number of ewes was increased incrementally from a stocking rate of 0.1 ewes/ha (for moss heath and sparsely vegetated land) or 0.4 ewes/ha for the other vegetation types, and remained in the model for a whole year. Stocking with immature sheep or wethers was no different to stocking with lambless ewes apart from the difference in body-weight. If all of the available biomass was consumed during a model simulation then that simulation failed, so that the monthly utilisation, biomass and offtake parameters were set to zero for the remaining months.

The model responses are summarised in graph form. The responses of the moss heath and sparsely vegetated land types are displayed on different graphs to the other vegetation types because different stocking rates were used. Offtake increased linearly with increased stocking (Figure 5-1 a-c); the rate of increase was dependent upon the vegetation type (as bog and dwarf shrub heath have lower feed value they are more heavily grazed than other vegetation types at the same stocking level). Utilisable biomass (UB) in September remained at similar levels under increased stocking until frequent failures of the model runs occurred, when UB declined to low levels. UB in March decreased linearly with increased stocking rate. The graphs of increased cumulative utilisation (CU) for each vegetation type are shown in 5-2 a-g. March CU increases at a greater rate with increased stocking than does September CU. There are also considerable differences between vegetation types: dwarf shrub heath and bog increase at much greater rates than the other vegetation types. Graphs of monthly utilisation over the year are shown in Figures 5-3 a-g. Monthly utilisation is lowest in summer for all vegetation types and then increases during the autumn and winter as the available UB s reduced. This increase is greater at higher stocking levels. The monthly utilisation falls again in April as vegetation growth starts again in the spring.

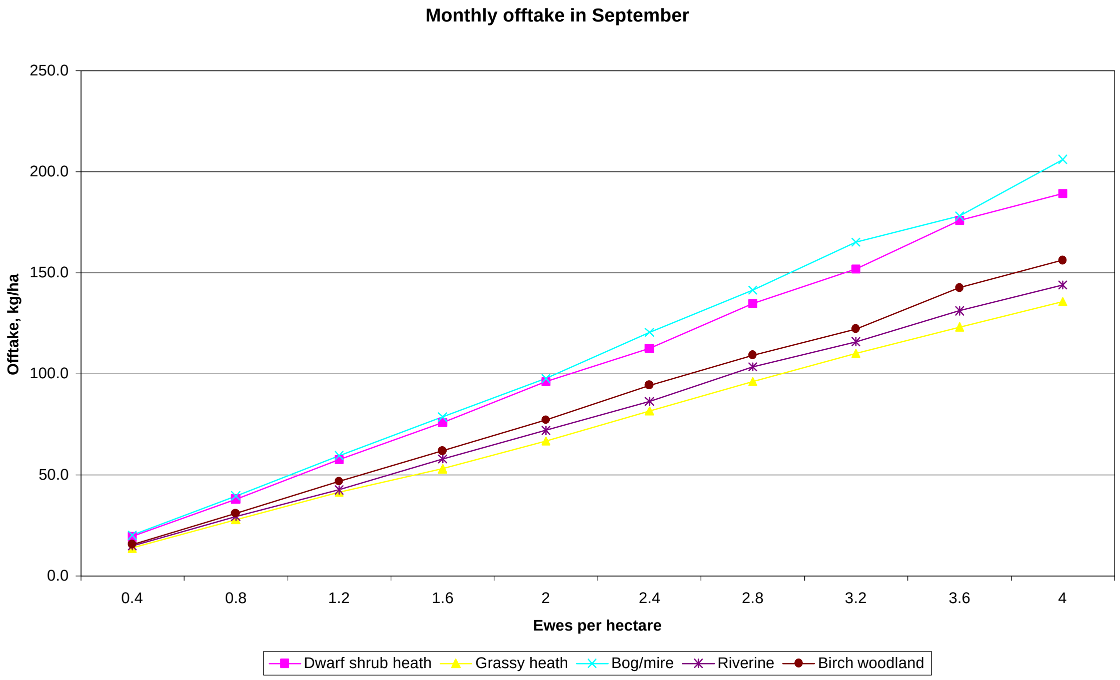


Figure 5-1a: Monthly offtake in September with increased stocking rate (outfield, Baseline climatic scenario)

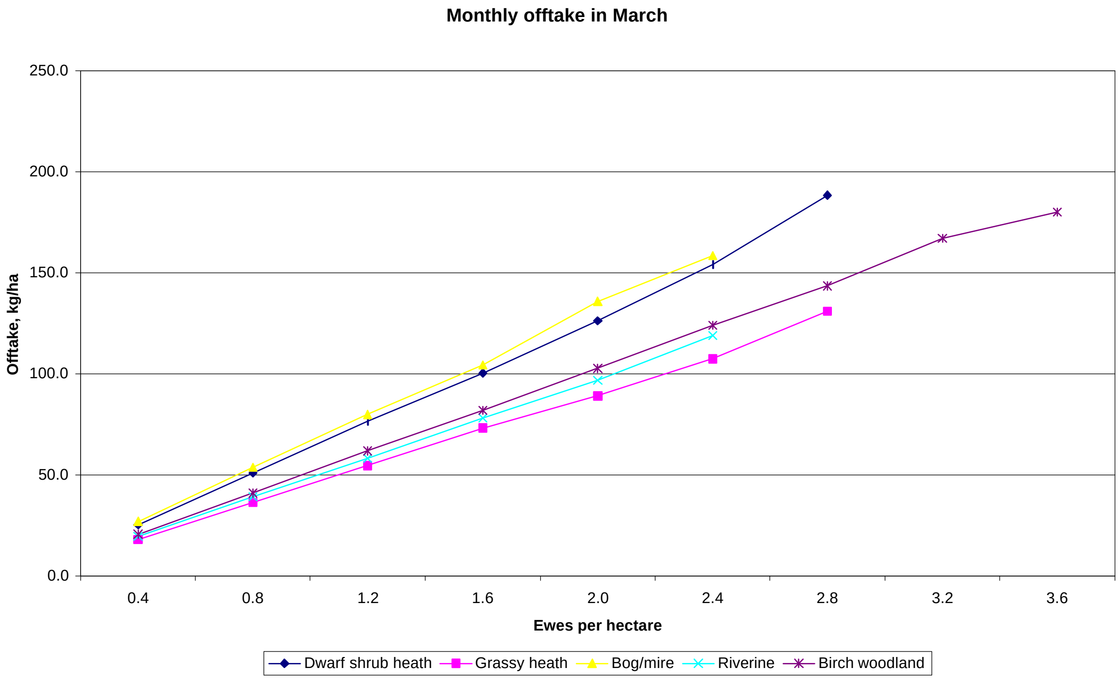


Figure 5-1b: Monthly offtake in March with increased stocking rate (outfield, Baseline climatic scenario)

Figure 5-1c: Monthly offtake in September and March for moss heath and sparsely vegetated land with increased stocking rate (outfield, Baseline climatic scenario)

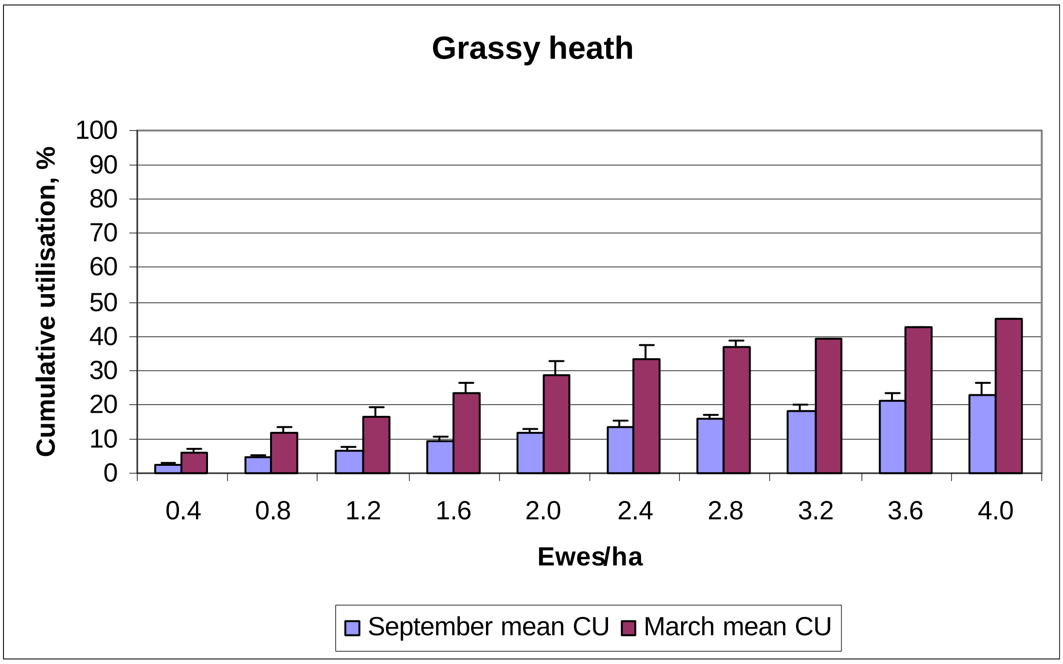


Figure 5-2a: Monthly cumulative utilisation for grassy heath with increased stocking rate (outfield, Baseline climatic scenario)

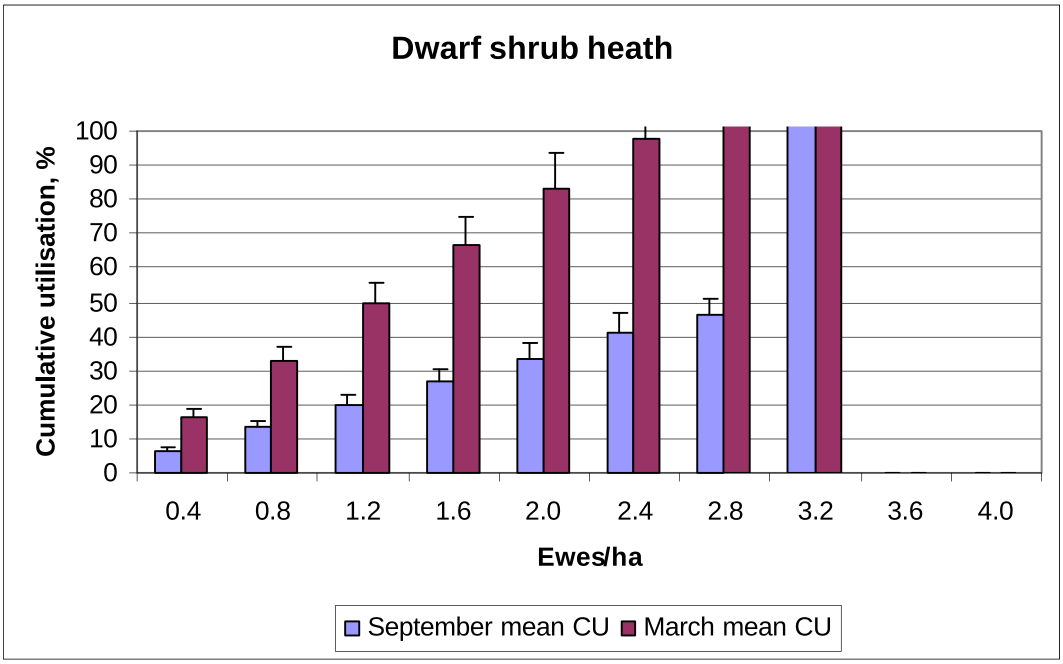


Figure 5-2b: Monthly cumulative utilisation for dwarf shrub heath with increased stocking rate (outfield, Baseline climatic scenario)

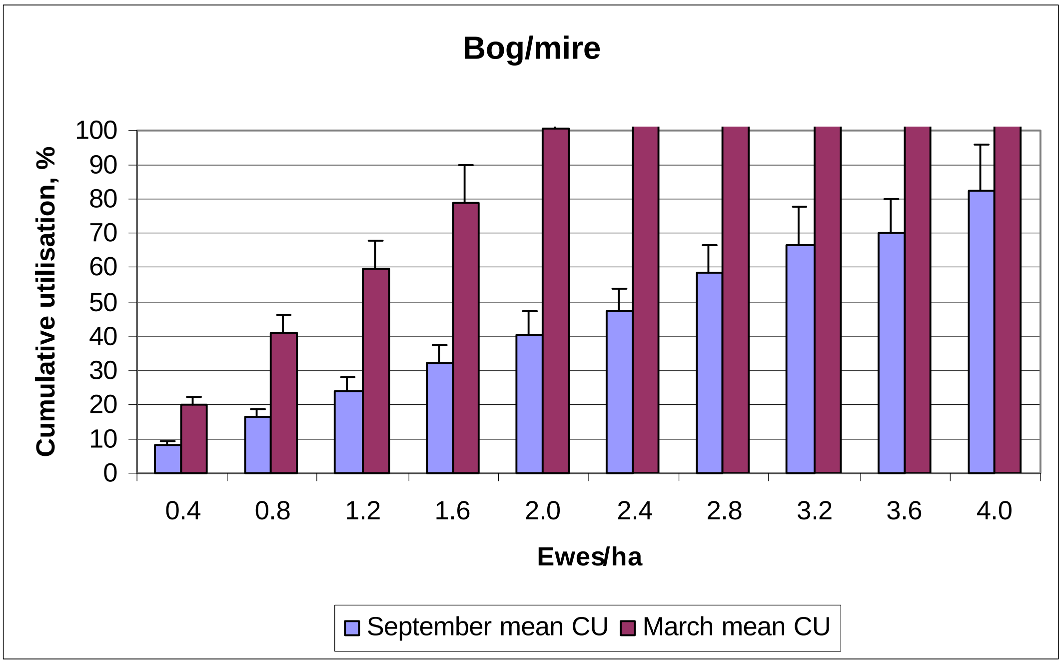


Figure 5-2c: Monthly cumulative utilisation for bog/mire with increased stocking rate (outfield, Baseline climatic scenario)

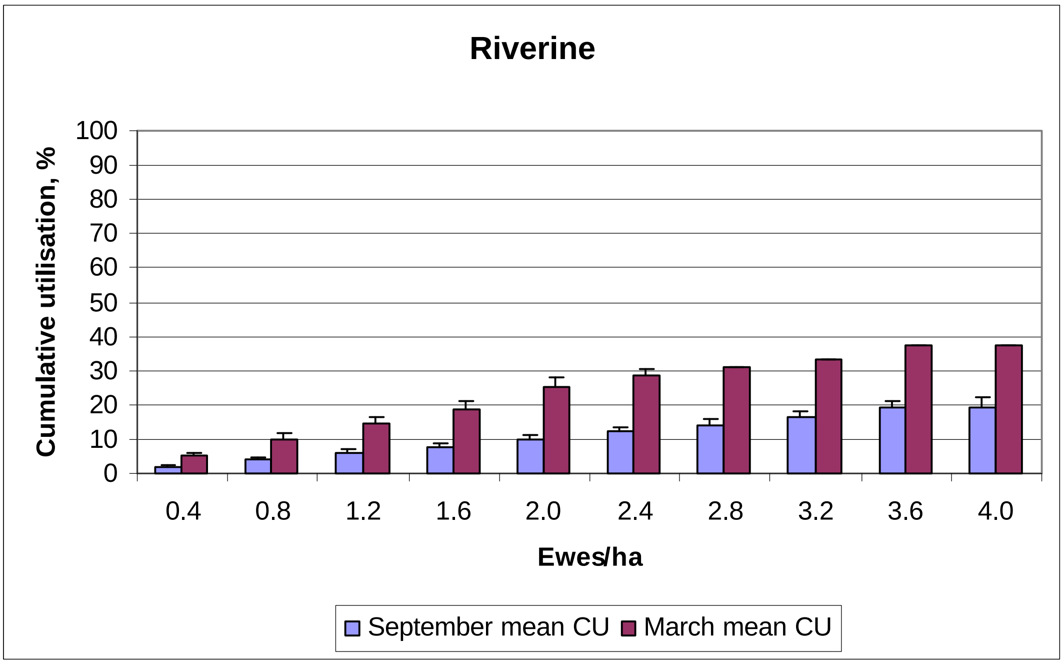


Figure 5-2d: Monthly cumulative utilisation for riverine vegetation type with increased stocking rate (outfield, Baseline climatic scenario)

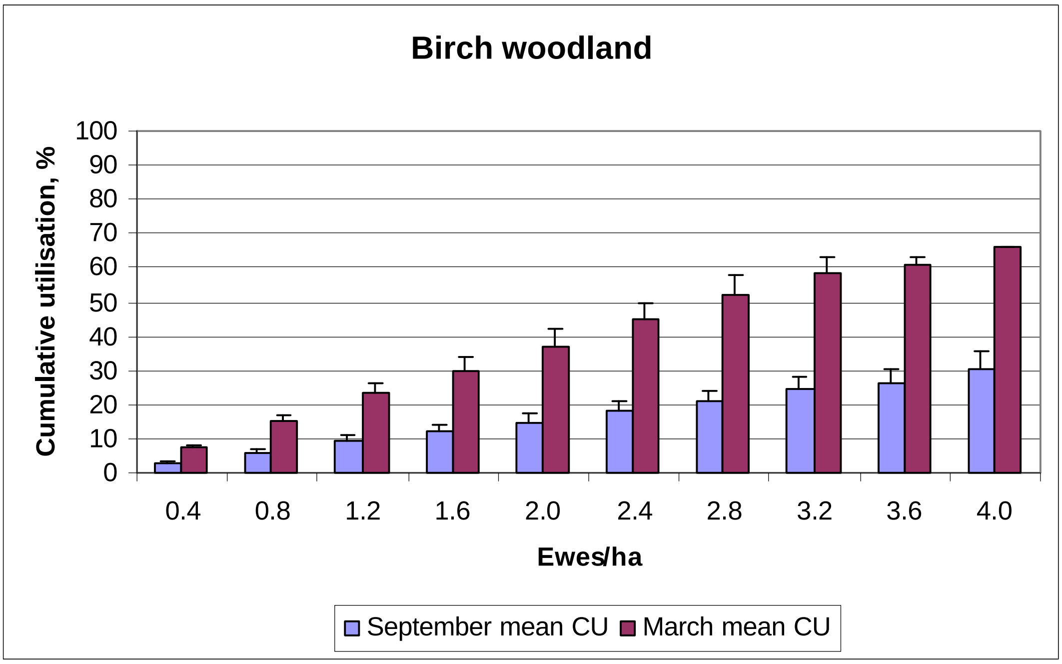


Figure 5-2e: Monthly cumulative utilisation for birch woodland with increased stocking rate (outfield, Baseline climatic scenario)

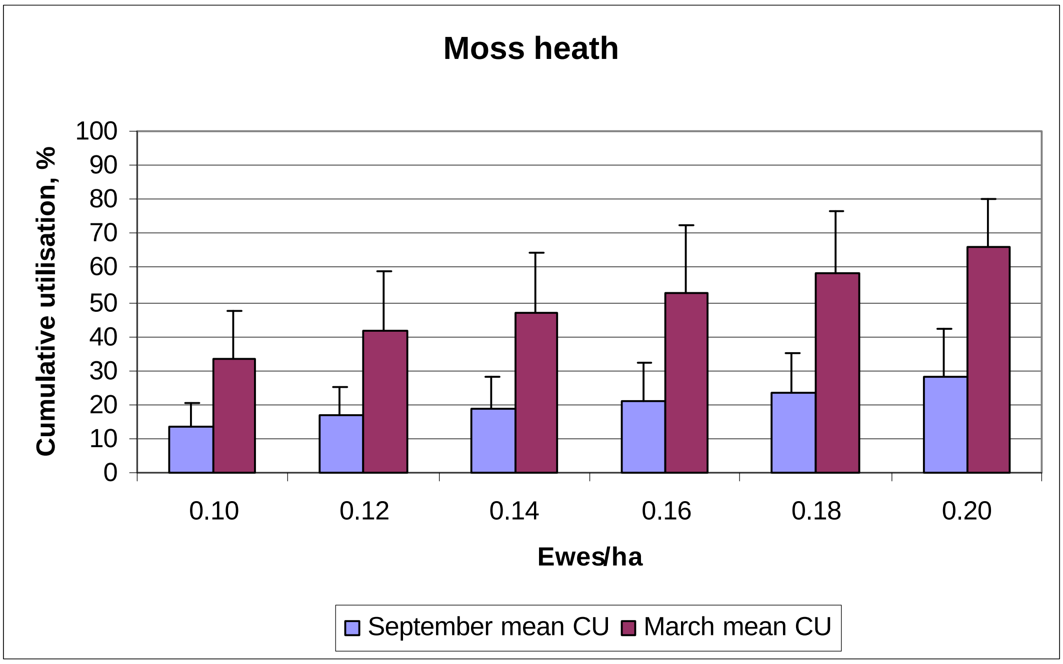


Figure 5-2f: Monthly cumulative utilisation for moss heath with increased stocking rate (outfield, Baseline climatic scenario)

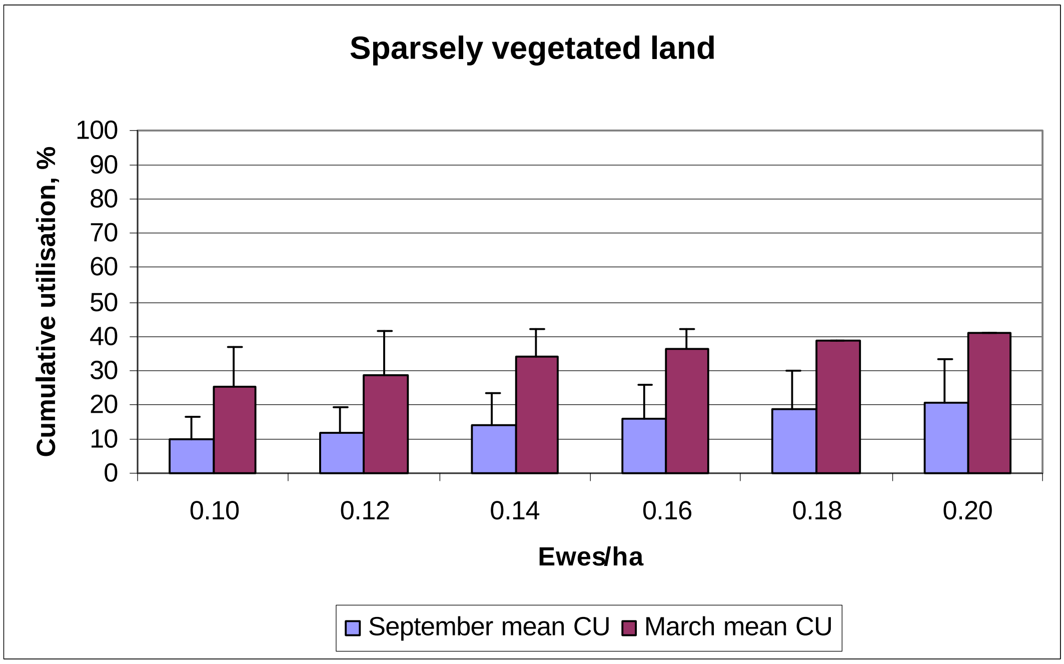


Figure 5-2g: Monthly cumulative utilisation for sparsely vegetated land with increased stocking rate (outfield, Baseline climatic scenario)

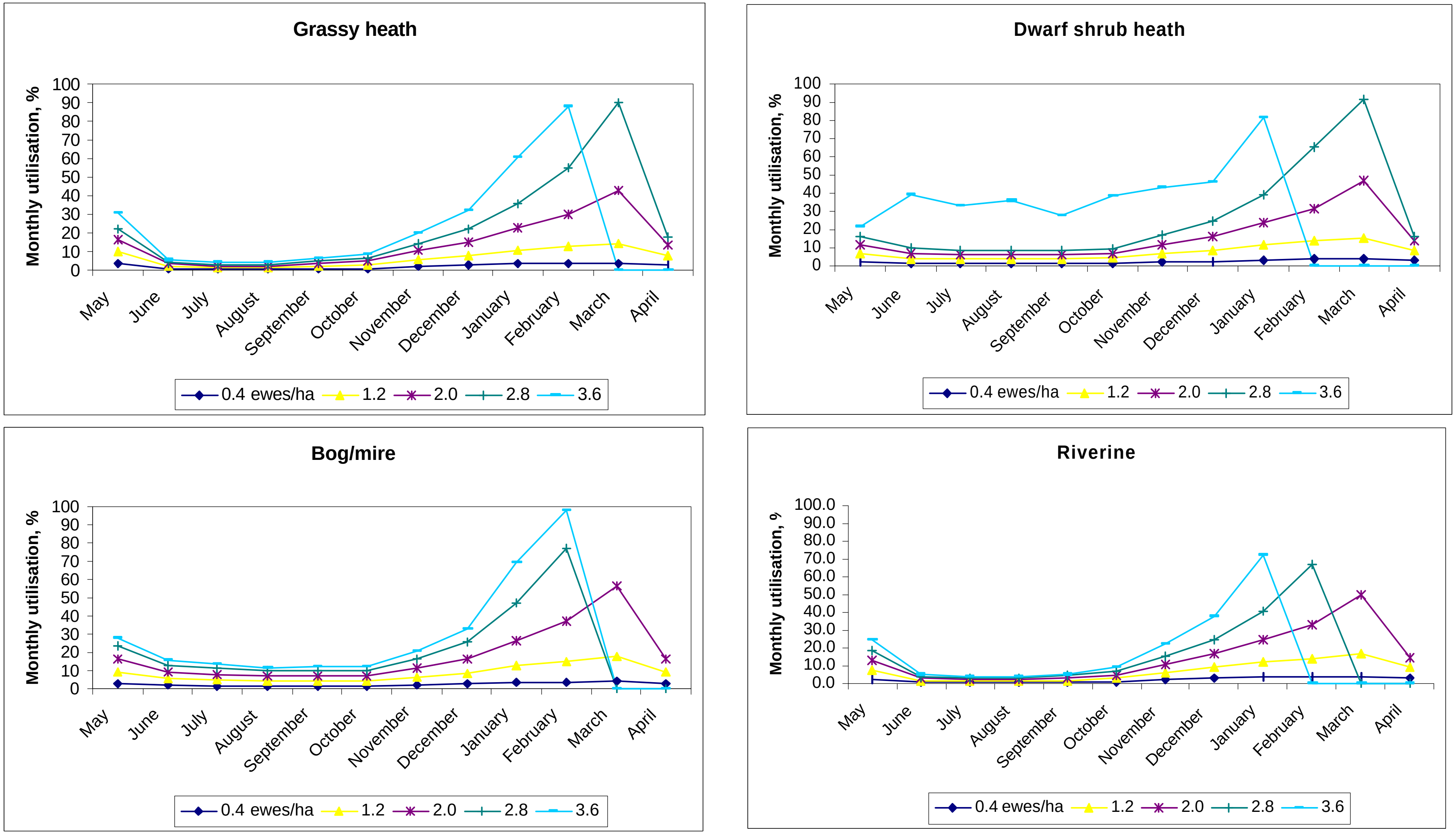


Figure 5-3a: Monthly utilisation under increasing stocking rates

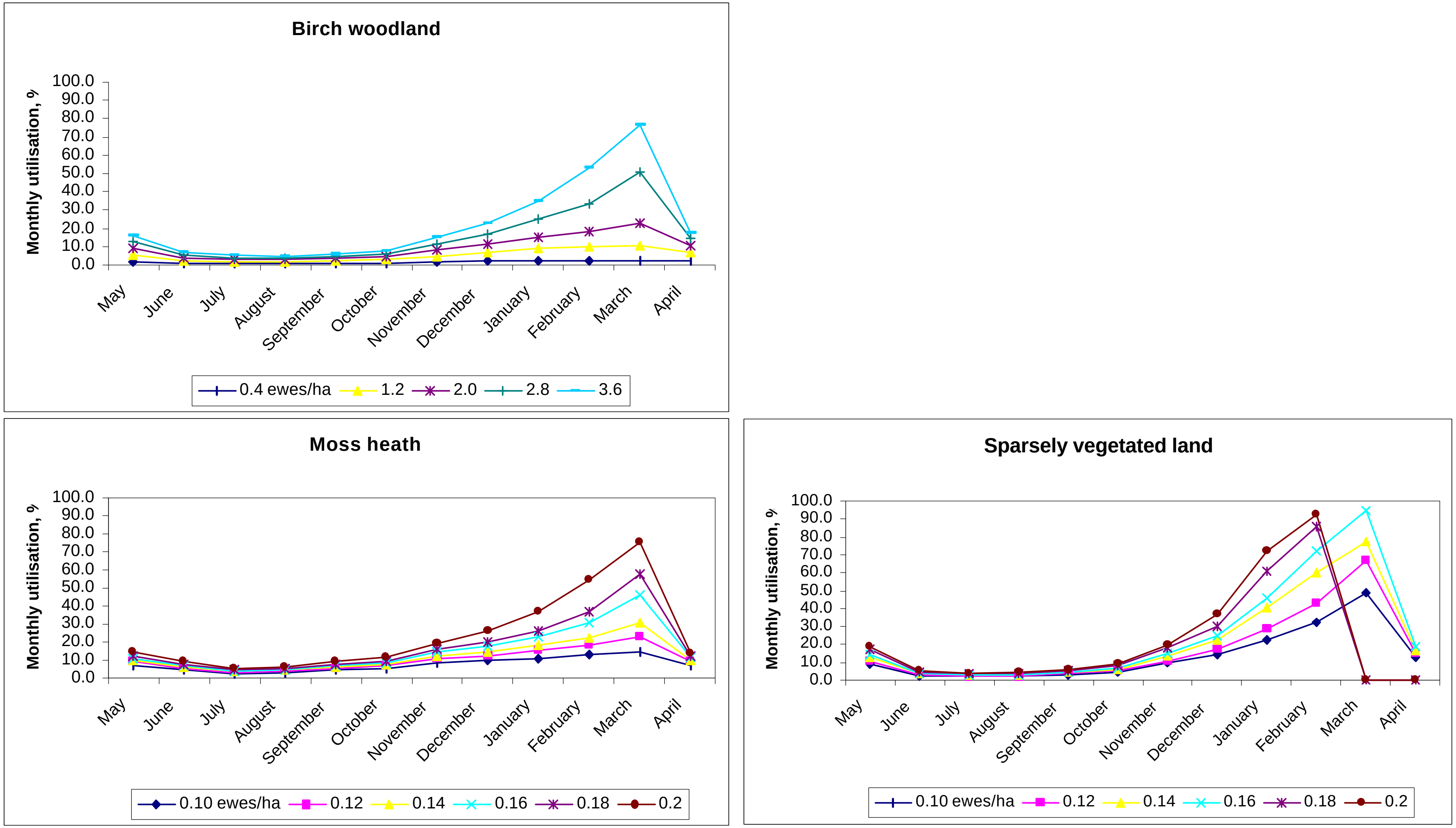


Figure 5-3b: Monthly utilisation under increased stocking rates

Beyond a critical stocking threshold grazing simulation failures start to occur in the later months of the grazing year. If livestock numbers are increased further, failures start to occur earlier and earlier in the year. The stocking rates (to the nearest 0.1 ewes/ha) at which simulation failures start to occur are given in Table 5-1. Unfortunately there seems to be variation in the first failure occurrence within an ‘envelope’ of stocking rates. To obtain a more stable data set would require runs containing more than 1000 simulations, which would be extremely time-consuming, and has therefore not been attempted as part of the sensitivity analysis. The failure threshold values are similar for all vegetation types except for moss heath and sparsely vegetated land, which have much lower thresholds (c. 0.15 ewes/ha compared to 2.0 ewes/ha), and birch woodland, which has a slightly higher threshold (2.8 ewes/ha). Búmodel simulation results at stocking rates higher than the critical threshold are unreliable and cannot be validated against real-life data sets.

Table 5-1: Stocking rate failure thresholds for Búmodel vegetation types under the Baseline climate scenario

	Stocking rates above which simulation failures start occurring						
Scenario	Grassy heath	Dwarf shrub heath	Bog	Riverine vegetation	Birch woodland	Moss heath	Sparsely vegetated land
Baseline	2.0	2.0	2.0	2.0	2.8	0.18	0.12

The cumulative utilisation values for September and March (at stocking rates of 0.1 ewes/ha for sparsely vegetated land and moss heath, and rates of 0.4 and 2.0 ewes/ha for the remaining vegetation types) will be used as benchmark values for the other sensitivity tests. The March monthly utilisation values will also be compared to assess how close the simulations are to failure. It is expected that modification of input parameters and functions will affect these values, which can then be compared against the benchmark values.

5.3.2 Climatic scenarios

Simulation runs were done on all vegetation types for the remaining climatic scenarios: Cold, Extreme Cold and Warm. Cumulative utilisation increases under the cold and extreme cold scenarios, relative to the benchmark, and decreases under the warm scenario (Figure 5-4 a-b). There was more variation in the response of the different vegetation types under the extreme cold scenario (for example, grassy heath CU increased by 142% compared to a 48% increase in the dwarf shrub heath CU), than in either the cold or warm scenario. The failure threshold is closer to 2.0 ewes/ha in the colder scenarios as illustrated by the monthly utilisation rates (Figure 5-5 a-b). In some cases (grassy heath, dwarf shrub heath, bog) all simulations have failed in the extreme cold scenario at a stocking rate of 2.0 ewes/ha.

5.3.3 Livestock distribution

Búmodel was tested to see the impact of varying livestock distribution upon grazing capacity, in terms of land-use category and the months of usage. Land-use category (upland rather than outfield) had a small effect upon cumulative utilisation values, with an increase of up to 10% above benchmark values across all vegetation categories. March monthly utilisation was similar to that of the benchmark value (Figure 5-5 a-b).

The impact of the length of the grazing season was also examined (Figure 5-6), for grassy heath (outfield, Baseline climatic scenario) at a stocking rate of 2.0 ewes/ha. Cumulative utilisation declined linearly as the length of the grazing season was reduced. This rate of change was similar for both September and March, a drop in cumulative utilisation of 2.3-2.5% for every month. March monthly utilisation was similar for the runs when grazing was initiated between May and October. If grazing was initiated post-October, then March monthly utilisation declined linearly (Figure 5-7).

Change in September cumulative utilisation under different climate scenarios (0.4 ewes/ha)

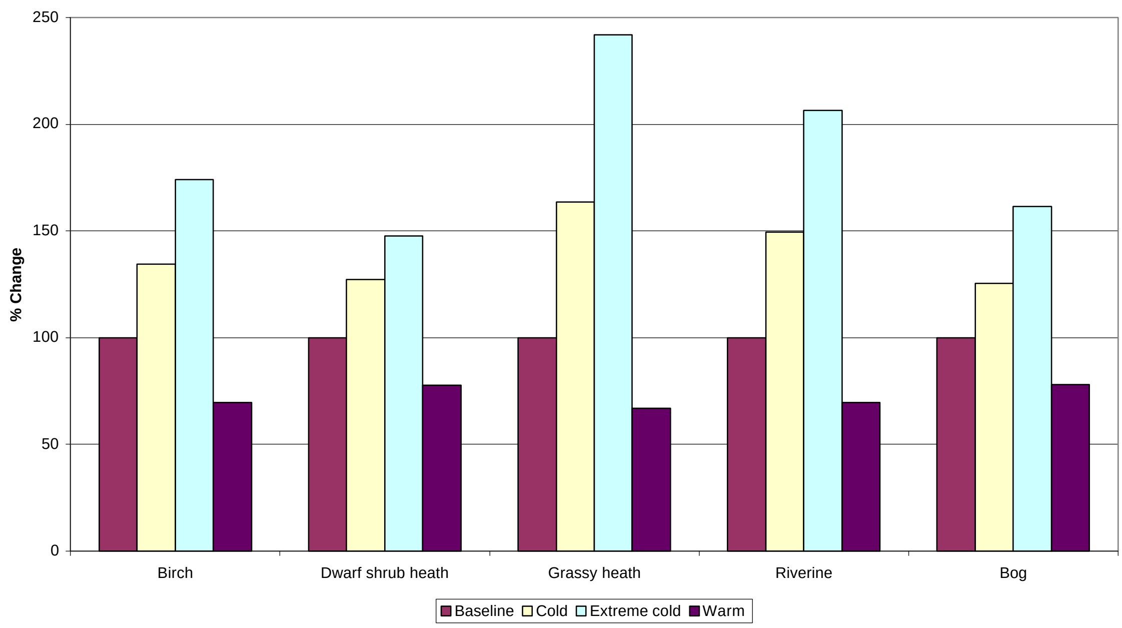


Figure 5-4a: Relative change in September cumulative utilisation under different climate scenarios (0.4 ewes/ha)

Change in September cumulative utilisation across different climate scenarios (0.1 ewes/ha)

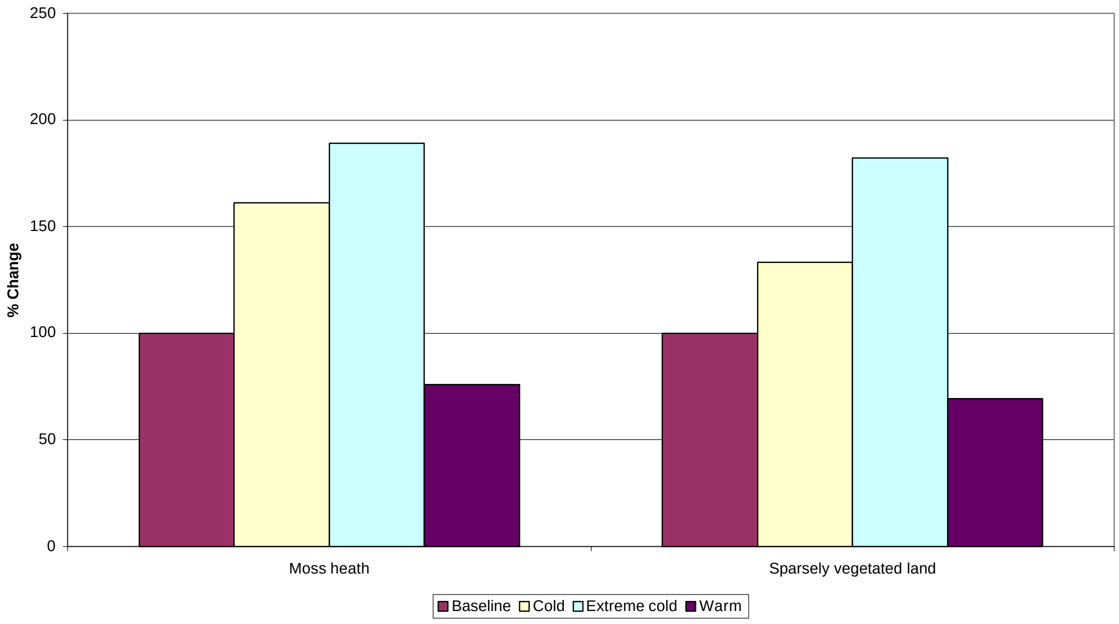


Figure 5-4b: Relative change in September cumulative utilisation under different climate scenarios (0.1 ewes/ha)

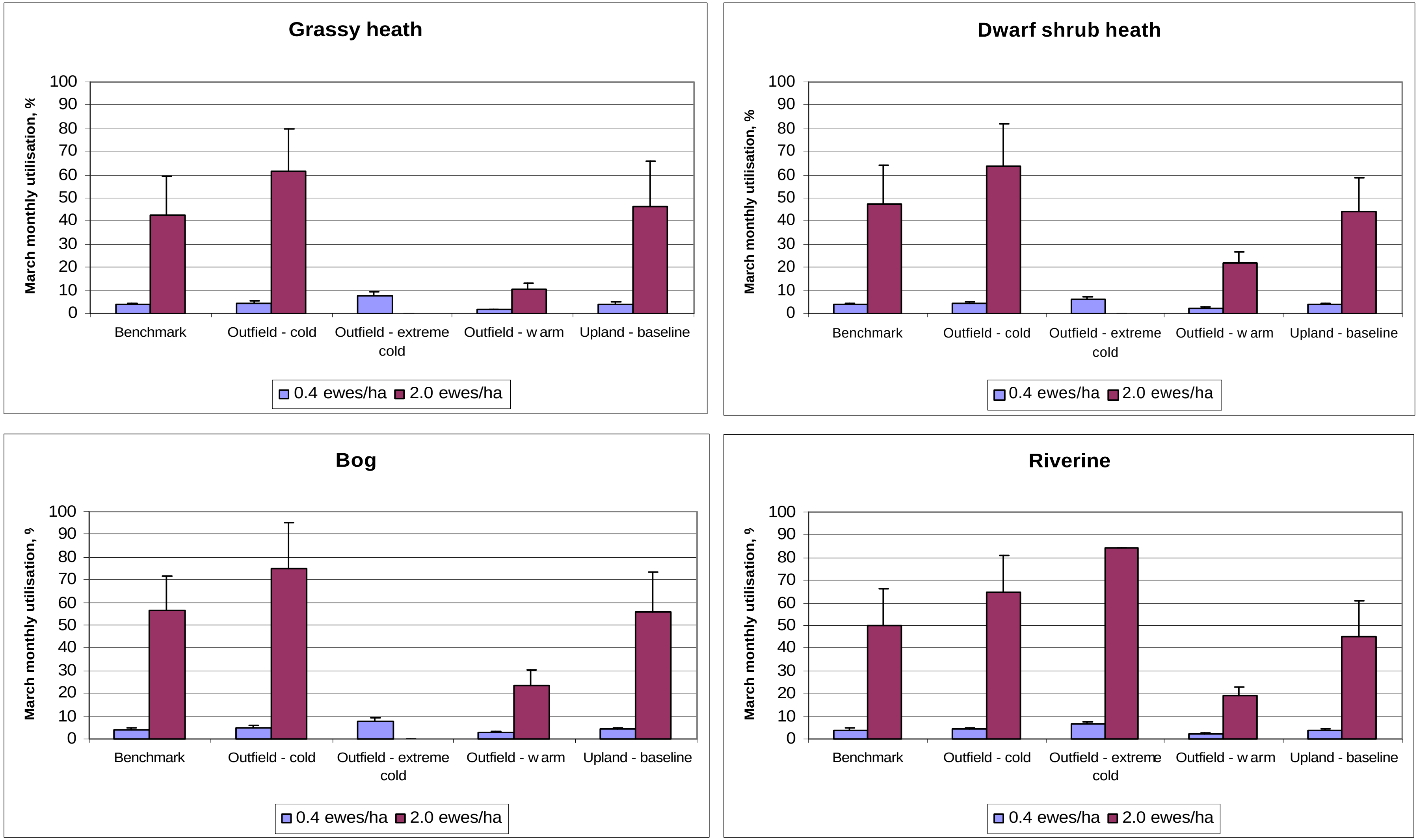


Figure 5-5a: March monthly utilisation for different climate scenarios and landuse types

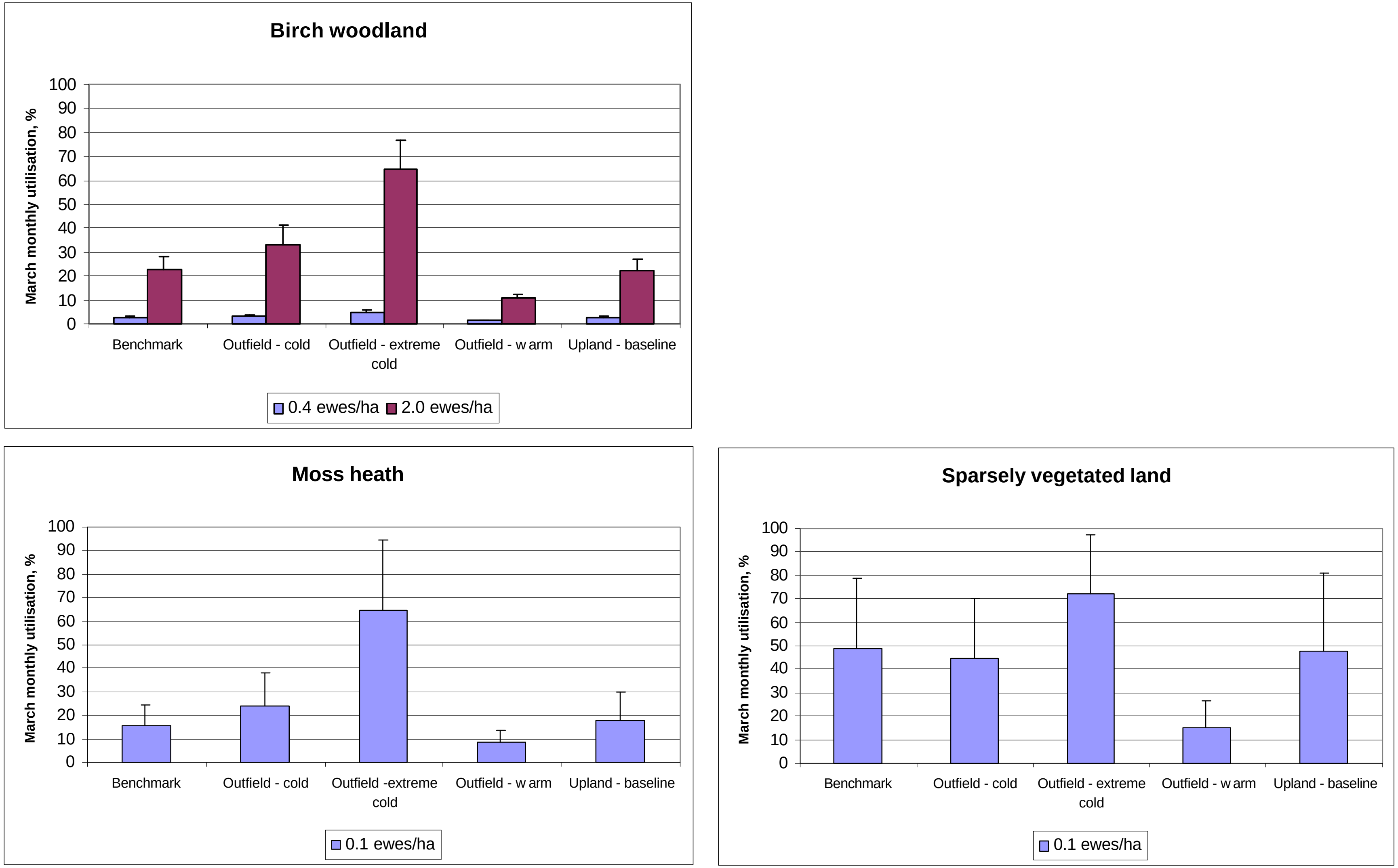


Figure 5-5b: March monthly utilisation for different climate scenarios and landuse types

5.3.4 Lambing rates

A scenario with ewes but no lambs was compared with a scenario with equal numbers of lambs and ewes, a scenario with twice as many ewes as there were lambs, and one with twice as many lambs as ewes. All lambs were retained over the winter. Only grassy heath was simulated in this sensitivity test, under the baseline climatic scenario. Only the results from the 0.4 ewes/ha stocking level are given here, as the 2.0 ewes/ha rate was higher than the failure threshold and the results from that simulation are therefore unreliable. Cumulative utilisation was considerably increased with additional lambs in the system (Table 5-2), and this difference increased during the year.

Table 5-2: Comparison of utilisation with different lambing rates

	No lambs	**Lambs = ewes/2**	**Lambs = ewes**	**Lambs = ewes*2**
September cumulative utilisation, %	2.3 ±0.4	3.2 ±0.5	4.0 ±0.5	5.4 ±0.6
Change from September benchmark	0 %	39 %	75 %	136 %
March cumulative utilisation, %	5.7 ±1.1	9.8 ±1.8	13.7 ±2.3	20.5 ±3.1
Change from March benchmark	0 %	71 %	141 %	260 %
March monthly utilisation	3.5 ±1.0	8.5 ±2.3	15.0 ±4.1	34.1 ±10.4

5.3.5 Livestock body weight

Using a stocking rate of 2.0 ewes/ha on grassy heath (outfield, Baseline climatic scenario) the average body weight of a ewe was increased incrementally from 25 kg to 65 kg. The increase in cumulative utilisation was linear for both September and March (Figure 5-8), but the rate of increase was greater in March (1.9% for every 5kg increase) than in September (0.8% increase for every 5kg). March monthly utilisation values are approaching 100% above a bodyweight of 55kg, indicating imminent simulation failure (Figure 5-9).

Búmodel includes a component that allows the sheep to lose up to 40% of their body weight over the winter (October – April). Using a stocking rate of 2.0 ewes/ha on grassy heath, this produces a reduction in offtake of 0.667 kg/ha for every 1% reduction in bodyweight. This reduction also lowers the March cumulative utilisation value. This impact is small, from 27.4 ±3.3 % with zero weight loss, to 25.2 ±3.5 % with 40% weight loss.

5.3.6 Discussion of the sensitivity analysis

Stocking rate and climatic scenario have the greatest effect upon the model outputs. Offtake is higher with greater numbers of livestock, increasing utilisation of the available biomass. The climatic scenarios affect both the quantity of the utilisable biomass and the feed requirements of livestock, thus having a dual impact upon utilisation. Less utilisable biomass is produced under the cooler climate scenarios, but the feed requirements of livestock are increased, and vice versa under the warm climate scenario.

Moss heath and sparsely vegetated land are the most sensitive vegetation types in the model. These vegetation types can only support livestock at very low stocking levels (generally less than 0.16 ewes/ha), due to their very low levels of utilisable biomass. Dwarf shrub heath and bog vegetation are the most sensitive to stocking rate, but grassy heath and riverine vegetation appear to be the most responsive to climatic scenario.

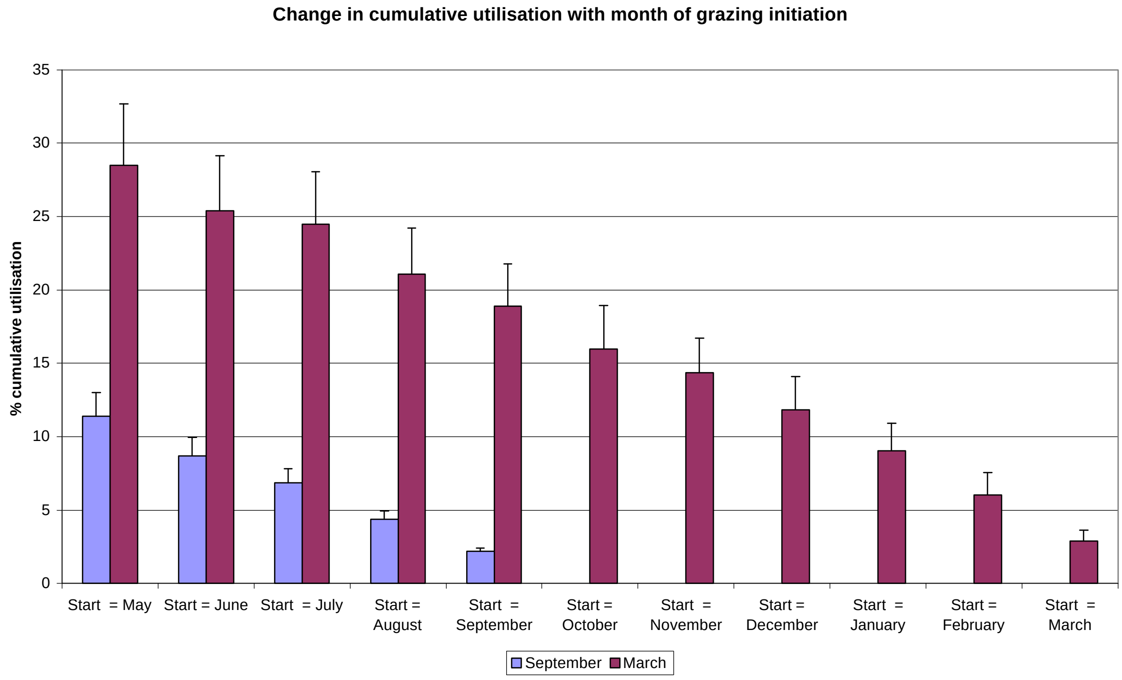


Figure 5-6: Change in cumulative utilisation with month of grazing initiation (Grassy heath vegetation type, outfield, Baseline climatic scenario).

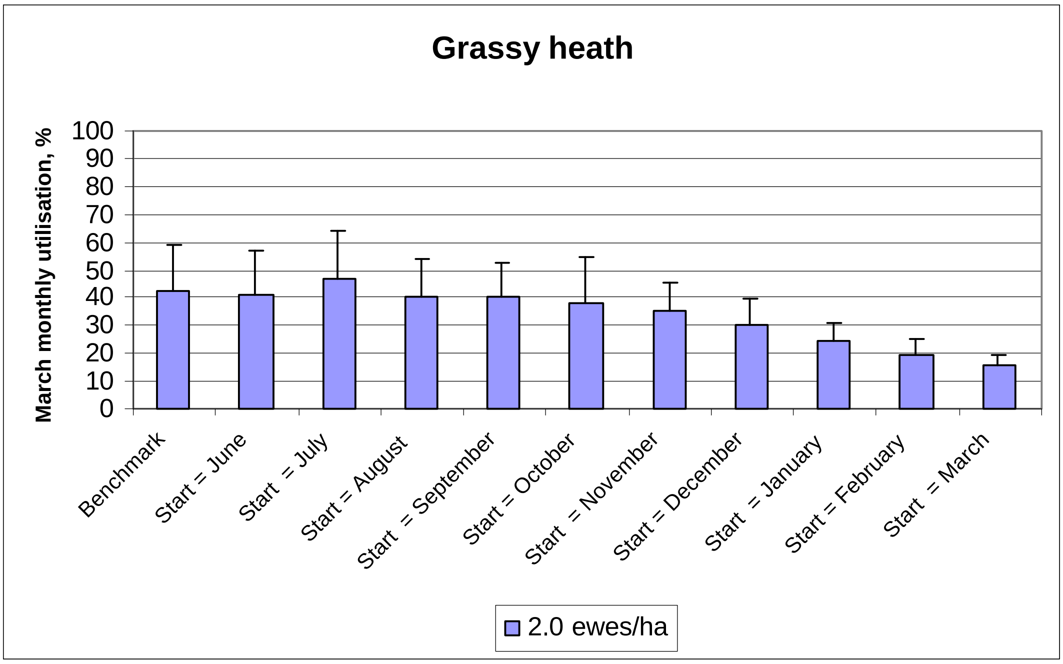


Figure 5-7: Change in March monthly utilisation with month of grazing initiation (Grassy heath vegetation type, outfield, Baseline climatic scenario).

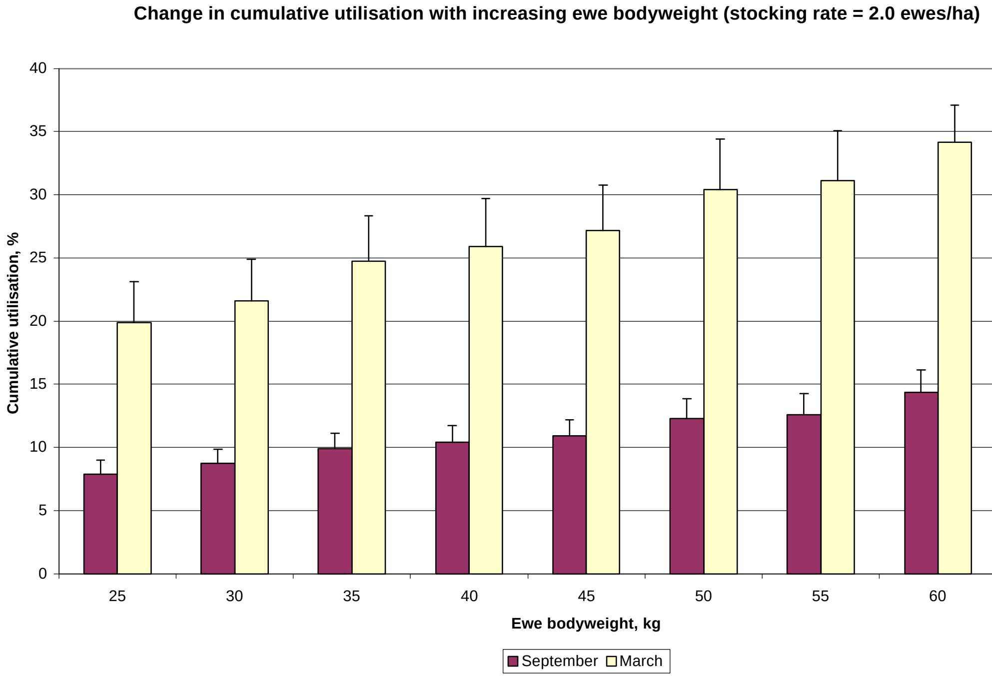


Figure 5-8 Cumulative utilisation with increasing ewe bodyweight

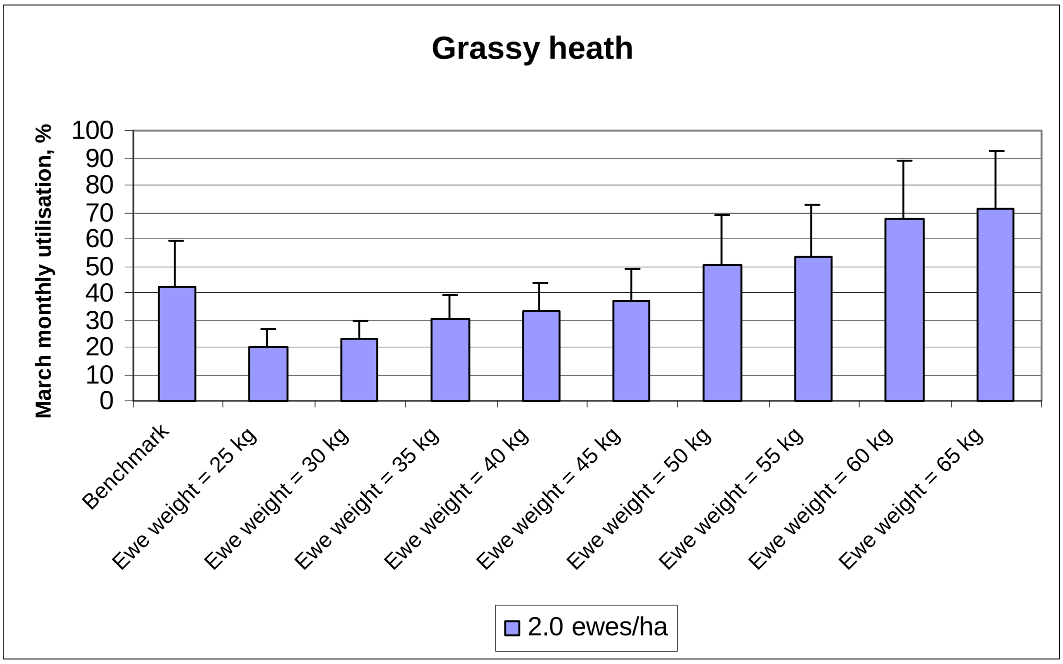


Figure 5-9: March monthly utilisation with increasing bodyweight

Of the other model parameters that were examined, the land use category, lambing rates and bodyweight parameters affect the feed requirements of livestock. The length of the grazing season affects the total amount of biomass that is consumed: as less utilisable biomass has been consumed by the start of winter (when no new biomass is being added to the system) there is more available for grazing in later months, thus reducing the March monthly utilisation value. The impact of the different parameters upon cumulative utilisation is summarised in Table 5-3.

The spatial sensitivity of the model was tested using landscape models of 1, 5, 10, 25 and 50 cells. Búmodel does not exhibit spatial sensitivity (i.e. the results do not change significantly with increasing area) except for very small areas (less than 5 cells). This is probably due to the fact that the chosen cell size (25 hectares) was reasonably large: a previous version of the model which used a cell size of one hectare exhibited spatial sensitivity at the lower end of the spatial scale.

Table 5-3: Summary of relative impact of different parameters upon the September cumulative utilisation rate

	0.4 ewes/ha					**0.1 ewes/ha**	
Scenario	Grassy heath	Dwarf shrub heath	Bog	Riverine vegetation	Birch woodland	Moss heath	Sparsely vegetated land
Benchmark (Outfield, Baseline climatic scenario)	0	0	0	0	0	0	0
Outfield - Cold	+63	+27	+26	+50	+34	+61	+33
Outfield-Extreme cold	+142	+48	+61	+107	+74	+89	+82
Outfield-Warm	-33	-22	-22	-30	-30	-24	-71
Upland - Baseline	+10	+9	+7	+4	+9	+11	0
Lambs = ewes/2 (outfield, Baseline)	+39	-	-	-	-	-	-
Lambs = ewes (outfield, Baseline)	+75	-	-	-	-	-	-
Lambs = ewes*2 (outfield, Baseline)	+136	-	-	-	-	-	-

It should be restated that Búmodel results should not be relied upon once extensive failures start occurring in the grazing simulations. These simulations are operating beyond the limits of the data that was used to parameterise the model, and there is no way of validating the results produced in this way. It should also be noted that grazing damage can occur below these failure thresholds, and land can be considered unsuitable for grazing, even though not all of the utilisable biomass has been consumed.

5.4 Validation against existing, independent data sets

Predictive validation of Búmodel was undertaken using published experimental data from a highland range in northern central Iceland (Magnússon and Magnússon 1992; Jónsdóttir 1994). The experiment took place between July and September 1989 at Auðkúluheiði, (location shown in Figure 4-5), where grazing experiments have been carried out since 1975. The purpose of the experiment was to measure vegetation and animal performance, 'in order to determine the carrying capacity and optimum stocking rate of the highland range in Iceland' (Jónsdóttir 1994: 1).

The experimental site is approximately 470m above sea level and is a hummocky heath with mosses, dwarf shrubs and grasses. A botanical survey of the site was undertaken in 1987 (Magnússon and Magnússon 1992), which is summarised in Table 5-4. Three plots, with light (L), medium (M) and heavy (H) grazing pressures, were used in the experiment. The same stocking rate of 0.28 ewes/ha was used in each plot, but differences in biomass due to previous stocking treatments created the different grazing pressures.

The summer of 1989 at the experimental site was reported as cold and wet. The nearest meteorological record comes from Hveravellir, 36km to the south at 600m a.s.l. The monthly temperature readings were adjusted, using a lapse rate of 0.6 ºC/100m, so that they were comparable to those of Reykjahlíð, the station used in formulating the northern climatic scenarios in Búmodel. This adjusted temperature curve did not match any of the climatic scenarios very well, but the mean annual temperature (0.4 ºC) was close to that of the cold scenario (0.6 ºC), so the cold scenario and northern location were used in the model simulations.

Table 5-4: **Average vegetation cover (%) and dominant species in the experimental grazing plots at Auðkúluheiði in 1987 (Magnússon and Magnússon 1992).**

Plant type	**Light**	**Medium**	**Heavy**	**Dominant species**
Grasses	2.0	2.5	3.0	*Festuca richardsonii*
Sedges and rushes	6.5	7.5	8.9	*Carex bigelowii, C. rupestris, Kobresia myosuroides*
Dicot herbs	10.8	12.1	14.2	*Armeria maritima, Bistorta vivipara, Silene acaulis, Thalictrum alpinum, Dryas octopetala*
Shrubs	22.7	16.6	10.3	*Betula nana, Empetrum hermafroditum, Salix callicarpaea, S. herbacea, S. phylicifolia, Vaccinium uliginosum*
Bryophytes	53.2	49.4	38.2	*Racomitrium lanuginosum, R. erocoides, Drepanocladus uncinatus, Polytrichum spp.*
Lichens	14.8	17.5	15.4	*Cetraria islandica, Cladina arbuscula, Ochrolechia frigida, Stereocaulon spp.*
Vascular plant cover	42.7	39.8	37.5	
Bryophyte and lichen cover	68.0	66.8	53.5	
Total vegetation cover	111.7	106.6	91.0	
Bare ground	14.2	8.8	10.1	

The experimental plots were represented in Búmodel using a combination of dwarf shrub heath, moss heath and bare ground, as deduced from the coverage of plant types and the botanical species composition. The vegetated area in L was estimated as being composed of 3:1 dwarf shrub heath to moss heath, that in M as 2:1, and the vegetated area in H as being composed of equal areas of dwarf shrub heath and moss heath.

Table 5-5: Area, stocking numbers and weights for each plot

Plot	Area, ha	Ewes	Initial weight of ewes, kg	Lambs	Initial weight of lambs, kg
Light	54	15	59.2 ± 6.27	29	14.9 ± 2.37
Medium	36	10	59.8 ± 4.86	20	14.8 ± 3.16
Heavy	18	5	59.3 ± 4.22	10	14.6 ± 1.51

Ewes with twin lambs were assigned to each plot (Table 5-5). The lambs were born in mid-late May, as opposed to Búmodel's assigned lambing date of 1st May. The model therefore over-estimates lamb weights at the beginning of the experiment (+ 3.4-3.7 kg), but correctly estimates the lamb weights at the end of the experiment. This is because the equation used to estimate lamb growth in Búmodel is based upon historical data, when growth rates were slower than those achievable with modern farming methods. The mean ewe body weight also increased by up to 2 kg during the experiment, but this minor increase is not represented in Búmodel.

Búmodel was initialised with the parameters previously mentioned (sheep numbers, sheep live weights, climate scenario, vegetation area and composition) for each of the three grazing pressures. The Auðkúluheiði experiment ran from 13th July to 13th September so the livestock distribution sub-model was set up so that the sheep grazed the upland in these months only. A run of 20 simulations was undertaken for each grazing experiment. Results given in Jónsdóttir's thesis allow utilisable biomass and dry matter intake (a proxy for offtake) values from the experiment and Búmodel to be compared. It is important that Búmodel predicts these two parameters correctly so that the grazing utilisation can be assessed.

Due to the structure of Búmodel it was not possible to predict utilisable biomass for the same days as the experimental measurements were taken. The experimental versus the predicted biomass values are shown in Figures 5-10 – 5-12. In general the observed mean biomass values fall within ±1 standard deviation of the predicted mean biomass. Even when the observed values fall outside the range of standard deviation, they still fall (with one exception) within the predicted maximum and minimum values. Essentially the model predictions fit the observed biomass values well because the variability built into the model is supposed to produce a range of results, and the observed values fall within that range.

The mismatch between the predicted and observed biomass in the L plot in early July seems to be related to grazing management in previous years (Jónsdóttir 1994), resulting in large amounts of standing biomass being carried through from the previous year's growth. Búmodel does not accommodate such situations in the present version, but it would be useful to allow this type of situation to be included in future versions of the model.

In all three plots the model overestimates biomass in the later part of the experiment. This may be due to the reported wet weather in the summer of 1989 affecting growth (precipitation has not been factored into Búmodel); or it may be because Auðkúluheiði, being at high elevation and experiencing a relatively 'continental' climate, has a short growing season, whereas Búmodel was built using data from mainly lowland sites, with longer growing seasons. If the growing season is over by early September, then there is no replacement of the green biomass removed by the sheep. This is an omission that ought to be rectified in subsequent versions of the model.

Dry matter intake (grams of dry matter consumed per head of livestock per day) was taken as a proxy for offtake (kilograms of dry matter removed per month). In the experiment this was measured over three periods (13th –31st July, 1st-21st August, and 22nd August-13th September) for livestock on the Light and Heavy plots. These measurements were compared to the corresponding mean offtake per head per day for the months of July, August and September (Figure 5-13). It can be seen that the model predicts dry matter intake well, as the observed mean value falls within one standard deviation of the model mean value for all but one of the periods. Búmodel also correctly predicts the August peak, and the lower intake on the lightly grazed plot. T-tests comparing the observed and predicted values found no significant difference between the two data sets on both the Light (T-value = 0.15, p = 0.893, df =2) and the Heavy plots (T-value = 1.22, p = 0.347, df = 2). (However it should be noted that the size of the sample was very small).

The monthly cumulative utilisation values predicted by Búmodel are given in Table 5-6. Given the high proportion of dwarf shrub heath in the experimental area, it would appear that all three plots are at risk of being overgrazed (as the September cumulative utilisation values are above the threshold value of 15%. This is supported by Jónsdóttir, who concluded that stocking was too high in both the M and H plots, and that the optimum stocking rate was closer to that in plot L. She also suggested that grazing on the experimental area started too early in the summer of 1989, reducing the length of productive grazing in the later part of the grazing season.

Table 5-6: Búmodel predicted cumulative utilisation, %, on the experimental plots

	July	August	September
Light	9.0 ± 1.5	18.6 ± 2.9	26.4 ± 4.2
Medium	10.4 ± 2.5	21.7 ± 5.1	30.8 ± 7.3
Heavy	12.5 ± 2.3	25.8 ± 4.7	36.5 ± 6.5

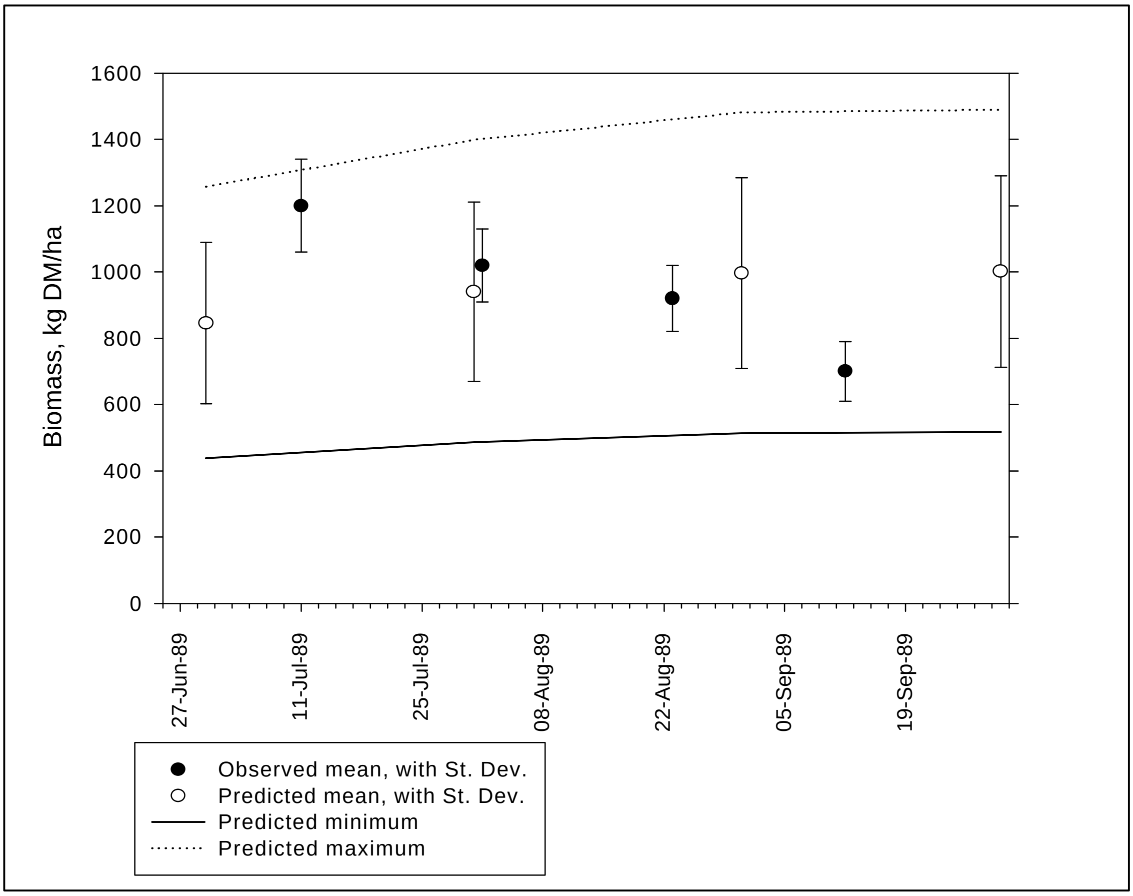


Figure 5-10: Observed vs. Búmodel predicted utilisable biomass on the Light grazed plot

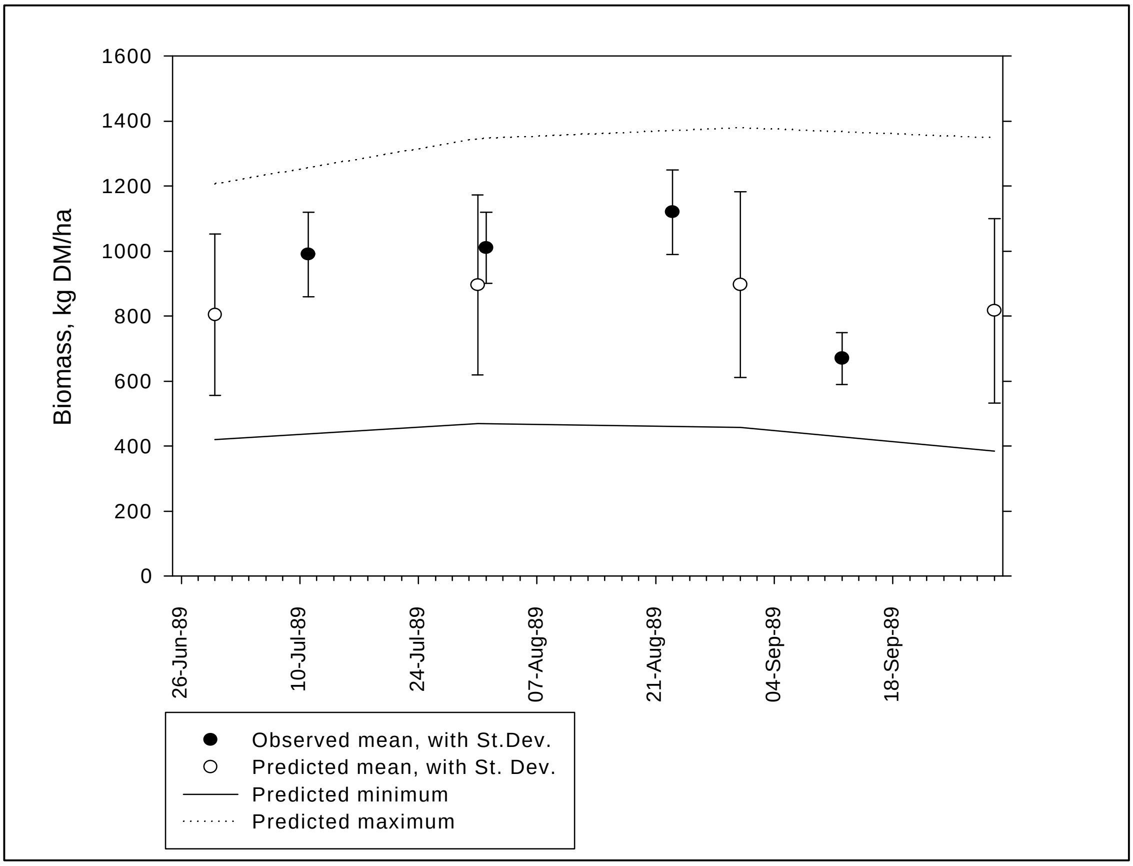


Figure 5-11: Observed vs. Búmodel predicted utilisable biomass on the Medium grazed plot

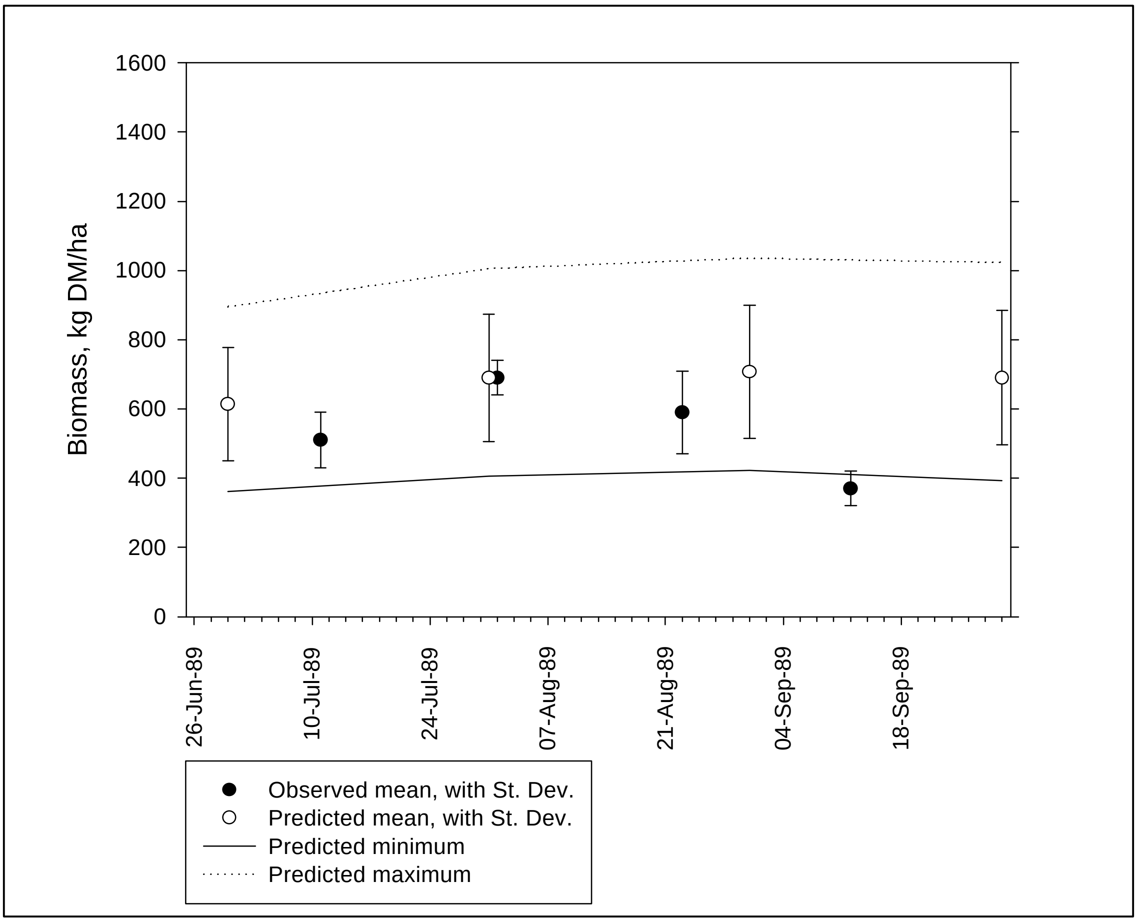


Figure 5-12: Observed vs. Búmodel predicted utilisable biomass on the Heavy grazed plot

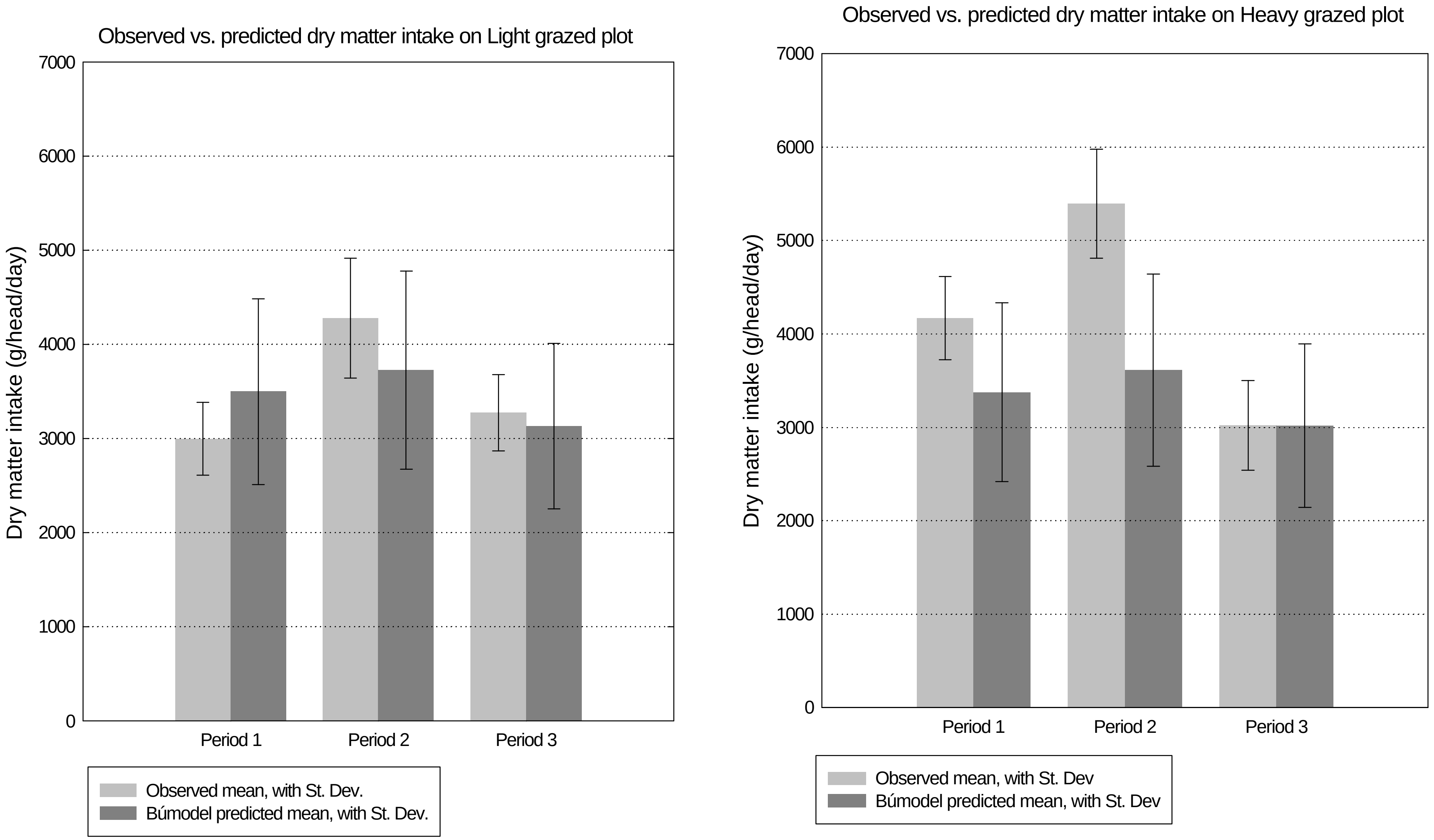


Figure 5-13: Observed vs. Búmodel predicted dry matter intake on the Light and Heavy grazed plots

5.5 Discussion and conclusions

The validation process for Búmodel has consisted of sensitivity analyses of the main parameters and a test of the model's ability to simulate a real-life grazing experiment. 'Face validation', where 'knowledgeable people are asked if the model and its behaviour are reasonable' (Rykiel 1996: 235), has also been undertaken through discussion with Icelandic agricultural experts (Ólafur Arnalds, Ólafur Dýrmundsson, Borgþór Magnússon), who were satisfied with the model structure and data. Model validation is an important part of the model building process, as it builds model credibility and presents potential users with information with which they can evaluate the model (Bart 1995).

Sargent (1984) in Rykiel (1996) describes three areas that need to be tested before it can be stated that a model has been validated: operational validity, conceptual validity and data validity. Operational validation tests how well the model mimics the real-life system, regardless of the mechanisms built into the model. According to the Auðkúluheiði grazing test, Búmodel mimics the Icelandic grazing system well, with the observed mean values of utilisable biomass and dry matter intake falling within one standard deviation of the predicted mean values. Extensive statistical tests were not possible because of differences in the model and the observed measurement dates, and the unavailability of the complete observational data-set. Nevertheless, visual comparisons demonstrate a good match between the observed and predicted results. The sensitivity analysis also demonstrated that the model responded in a realistic way to changing parameters such as livestock numbers and climatic scenarios.

Conceptual validation provides a ‘scientifically acceptable explanation of the cause-effect relationships included in the model [and/or] justification is given for using simplifications of known processes’ (Rykiel 1996: 234). This has been covered in the development of Búmodel by using known ecological relationships in the model, which have been derived from the published scientific literature. There are some areas that could be improved in future versions of Búmodel. The main omission from the list of system inputs is previous grazing management, which has been subsumed in vegetation and bare ground cover. At present there is not enough quantified information about how management affects growth and vegetation composition in subsequent years. It seems from the Auðkúluheiði experiment that the amount of ungrazed biomass remaining from the previous year may be the most visible effect of management, but this can be complicated by climatic interactions (warm spring or autumn temperatures might prolong the growing season, or frost or heavy precipitation might accelerate vegetation senescence and decay). The livestock fodder requirements sub-model also represents a simplification of known processes. Fodder intake has been restricted to the level required to maintain bodily functions: no account is taken of the additional fodder required for weight gain except in the case of lambs. It has been assumed that there are no restrictions on livestock fulfilling their fodder requirements except in the absence of vegetation, at which point the simulation fails. This is a much simpler approach than that taken by the HGMM model (Armstrong *et al.* 1997b), which involves bite weights, bite rates and maximum grazing times in the calculation of offtake. Nevertheless, Búmodel predicted offtake (as dry matter intake) correctly in the case of the Auðkúluheiði grazing experiment.

Data validation certifies the standard of the data and that the data has been correctly interpreted. Icelandic data has been used to construct and calibrate the model in preference to other sources. This has come from scientifically published sources and parameter ranges have been incorporated into the model where they are available. Contact with Icelandic experts provided informal checks upon the quality of some of the data sources. In particular further information on the feed unit value of different vegetation types (Thorsteinsson 1980c) would be useful, as no descriptive statistics are provided, whereas common sense indicates that a range of values are possible. The data was retained, as that part of the model was vital, and no alternative sources (covering all vegetation communities) were available. Where several sources of information were available, for example utilisable biomass yields, sources which were presented in a scientifically rigorous manner (giving dates of collection, means and standard deviations) were preferred to those which gave single seasonal values.

Efforts have also been made to ensure that the spatial and temporal scale of the data used was consistent within the model, and that spurious precision was avoided. Spatial data was resolved to the vegetation community scale (approximately 1-100 hectares); time-dependent data was resolved to the monthly scale. In the case of the vegetation palatability sub-model, this resulted in ostensibly ‘better’ quantified data on plant digestibility being omitted in favour of more subjective palatability classes, because consistent data on digestibility was not available across all of the Búmodel vegetation types.

The validation process tests the ability of the model to meet criteria that make it acceptable for use within a given context. In the case of Búmodel, the model must predict the range of possible utilisation values in a grazed area given vegetation, livestock and management inputs. The intended context is that of pre-modern (approximately 1000 – 1900 AD) mainland Iceland under a range of typical climate conditions. Búmodel has been validated for this purpose and context. Sensitivity tests have established that the model is most sensitive to the stocking rate and the climatic scenario, and that the vegetation types show a range of sensitivities to these parameters. The model results should not be relied upon when very high stocking rates are applied (resulting in a high rate of simulation failure). Further validation (against observed data-sets) is recommended if the model is applied in areas where the temperature regime and/or growth conditions are markedly different from the mainland (for example, the central interior, or the north-west peninsular). Neither has the model been validated for unusual environmental conditions, for example the impact of volcanic eruptions or unseasonable cold weather upon vegetation growth have not been taken into account.

Chapter 6: Model application to study areas

6.1 Introduction

Búmodel was used to investigate historical grazing management in the two study areas, Vestur-Eyjafjallahreppur and Hofstaðir estate, during the early 18th century. This exercise was intended to demonstrate the application of the model in an historical context. The past vegetation cover was reconstructed using palaeo-environmental data and relevant ecological relationships. Information on livestock numbers and management was taken from the 1709-1714 farm census, Jarðabók (Magnússon and Vídalín 1913-1990). This can be cross-referenced with the 1703 livestock survey (Vésteinsson, *pers. comm.*).

The model scenarios provide an analysis of the impacts of different management strategies under four climatic scenarios in the early eighteenth century. The scenarios are modelled at a range of scales, from the individual farm estate to the community. Twenty model iterations were undertaken for each investigative scenario. The range of results reflect the range of responses to the same set of environmental and management inputs. Simple descriptive statistics (mean, standard deviation, minimum and maximum cell values) were generated for the set of iterations, together with the individual worst and best runs from each set (based upon mean April cumulative utilisation across all cells).

6.2 Modelling results for Hofstaðir estate

6.2.1 Vegetation reconstruction for 1712

The contemporary vegetation of Hofstaðir, mapped according to the Búmodel vegetation categories and based upon the published vegetation map (RALA/Icelandic

Survey Department 1982a), is shown in Figure 6-1. Fieldwork in 2000 and 2001 indicated that the vegetation map was not entirely accurate (section 3.2.1.2), possibly due to vegetation changes since the survey period in 1974, or the method of vegetation mapping (using aerial photographs) (Guðbergsson 1980). There was confusion between dwarf shrub heath and poor grassy heath in some areas, and no distinction between highly productive grassland/riverine vegetation beside the Laxá and the drier grassland on the valley slopes. These inaccuracies could have serious consequences for the accurate prediction of vegetation biomass production and utilisation in Búmodel if the vegetation map was used without ground truthing by fieldwork.

The reconstructed vegetation cover for Hofstaðir is shown in Figure 6-2. It has been extrapolated from the contemporary vegetation map and fieldwork survey, based upon successional principles. It was assumed that there was less vegetation degradation three centuries ago and that drainage and exposure were the primary influences upon vegetation cover. The extensive areas of cultivated land shown in Figure 6-1 would not have existed in 1712, and the tún (hay meadow) area near the farmstead would have been much smaller at that time. Dwarf shrub heath would have been restricted to higher and more exposed areas. Although pollen coring has taken place in the region the analytical results are not yet available.

The assumed vegetation cover in 1712

The tún was small (4.5 ha) and located beside the farmstead. Riverine, or wet meadow vegetation, extended in a narrow strip along the banks of the Laxá and there were patches of birch woodland and grassy heath on the river islands. Grassy heath also covered the valley slopes, extending down to the riverbank along the southern section of the Laxá's course. The vegetation along the Sortulækur stream, which formed the eastern boundary of the estate, was assumed to be a mixture of bog and grassy heath. The upland plateau area was covered by dwarf shrub heath, with moss/lichen heath on ground above 300m. Eroded areas, classified as sparsely vegetated land, were assumed to have the same location and extent as they do today (Simpson *et al.*, in press), but there is no information to support either their presence or their absence. The areas of each vegetation class in the 1712 vegetation reconstruction are given in Table 6-1. The farm estate was covered by 78 Búmodel 25 ha cells.

Table 6-1: Areas of Búmodel communities in the 1712 Hofstaðir estate reconstruction

Búmodel vegetation community	Area (hectares)
Hayfield	4.5
Grassy heath	215.6
Dwarf shrub heath	810.3
Moss heath	265.6
Bog	124.4
Riverine vegetation	31.7
Birch woodland	14.1
Sparsely vegetated land	10.4

6.2.2 Farm census information for the early 18th century

The earlier livestock survey was compiled in June 1703 (Vésteinsson *pers. comm.*), and the farms surrounding Mývatn were surveyed for Jarðabók in August 1712 (translated by Ragnar Edvardsson). As the surveys were both undertaken in the summer before the autumn slaughter the livestock counts are comparable. In 1703 the householder at Hofstaðir was one Halldór, but by 1712 the tenancy had changed hands and was shared equally between two tenant households, one headed by Þórlákur Sigmundsson and the other Marteinn Sigmundsson (relationship unknown). The landowner was a woman called Steinunn Jónsdóttir, who had inherited the farm from her brother in Reykjahlíð (one of the church farms in the hreppur). In 1712 the value of the farm was forty ‘hundreds’, the highest valuation in the hreppur. The rent for the farm was 160 álnir, to

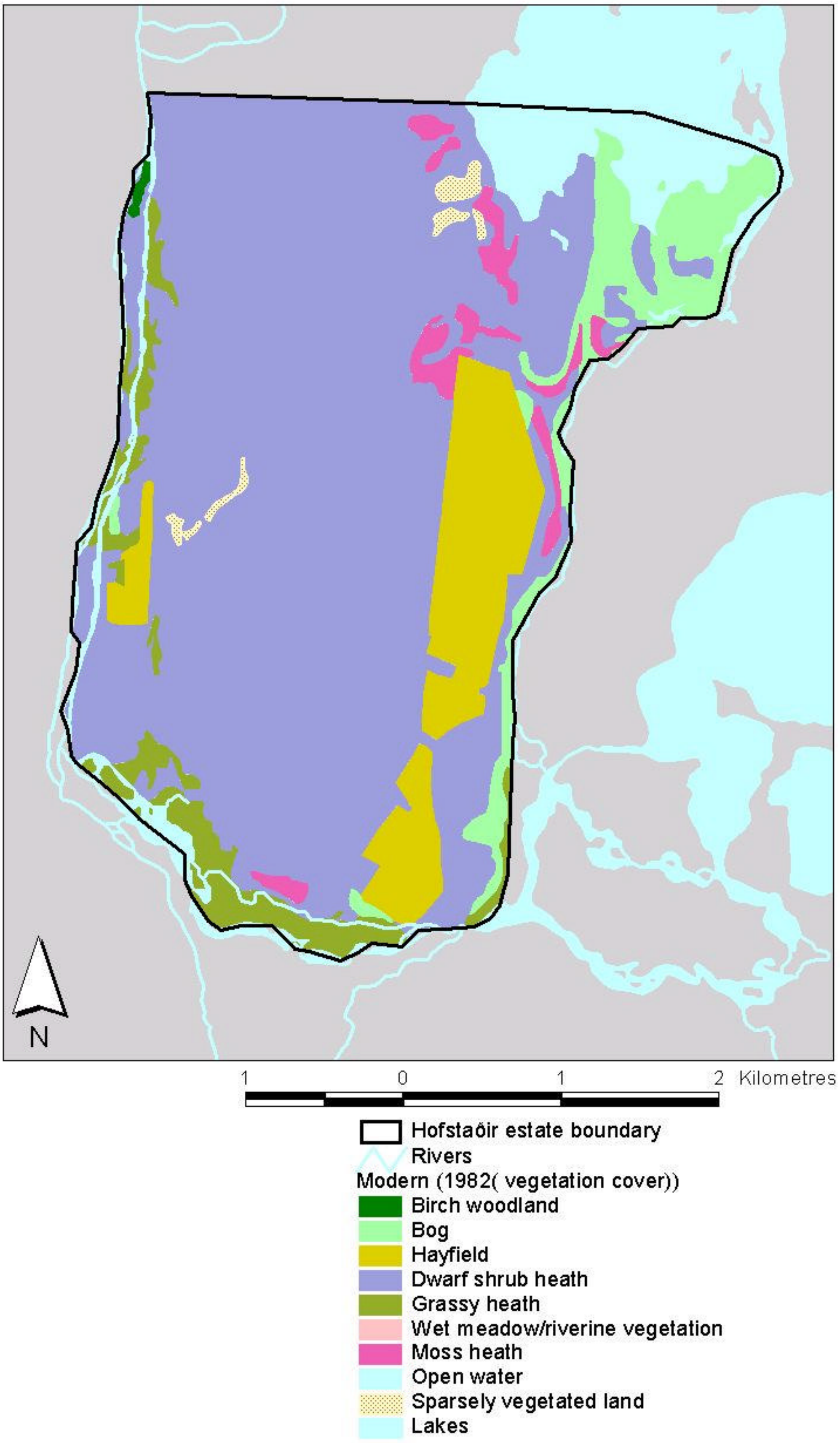


Figure 6-1: 1982 vegetation map of the Hofstaðir estate derived from aerial photographs

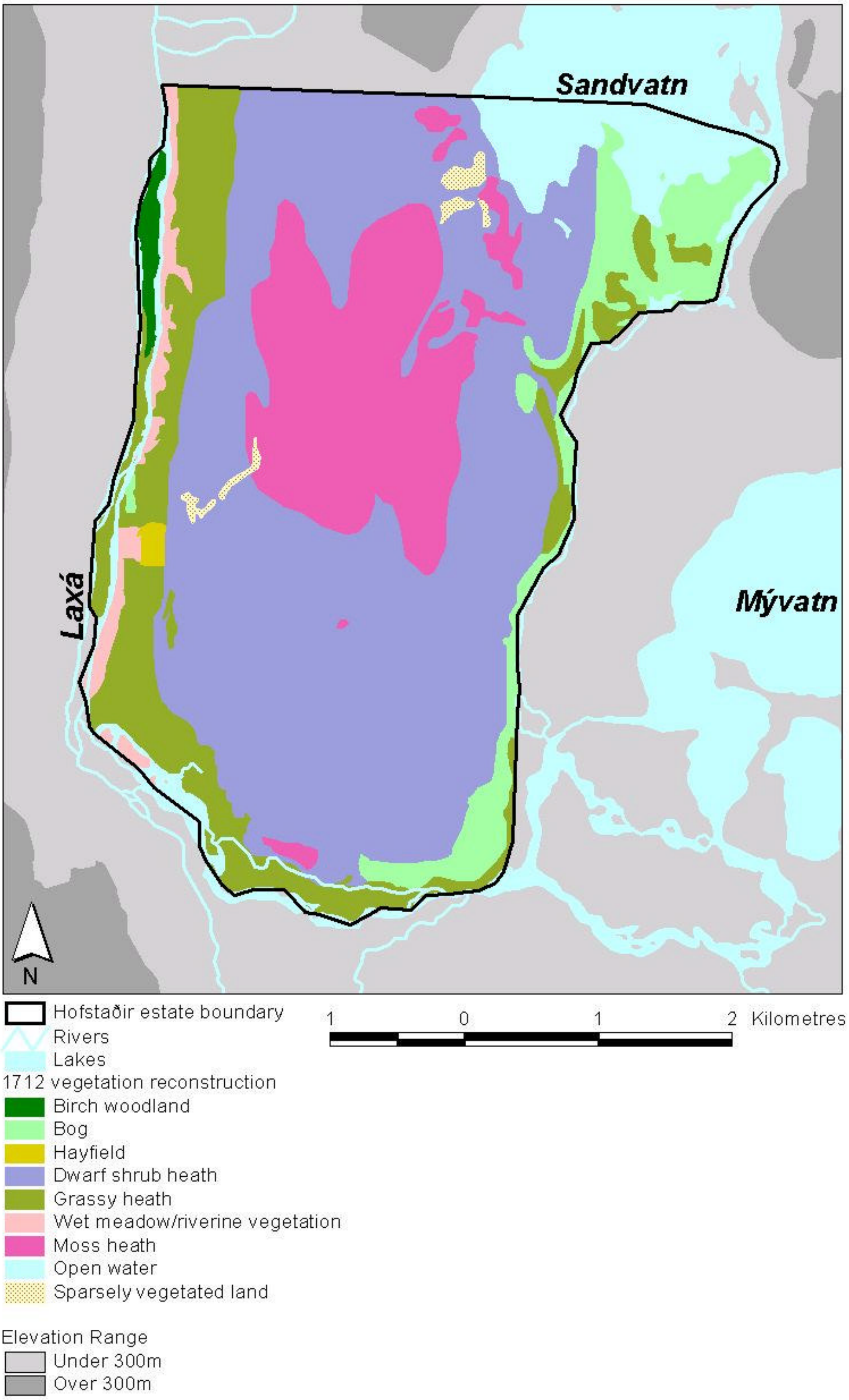


Figure 6-2: 1712 vegetation reconstruction for Búmodel

be paid in fish of equivalent value. The cattle rent was paid in butter. The numbers of livestock kept by each household are shown in Table 6-2. In 1703 Hofstaðir ranked fourteenth of the farms in the hreppur in terms of the number of livestock kept, but by 1712 it ranked sixth.

Table 6-2: Numbers of livestock at Hofstaðir, 1712

	Number of livestock	
Livestock type	*1703 Household*	*1712 Total in 2 households*
Cows	3*	4
Milk ewes	19	55
Lambs	18	25
Wethers	25	34
Goats	5	4
Horses	2	5
Total	**72**	**127**

* Also 2 calves.

In the commentary of Jarðabók the pasture at Hofstaðir is described as good, with sheep being able to survive without much extra hay during the winter. The horses were sent away from the estate in winter to Mývatnsöræfi (an area to the south-west of the lake) and left to graze without supervision. The Jarðabók record notes that there was sufficient dwarf birch and willow for fuel and for bulking out hay supplies but no further details are given.

6.2.3 Hay scenario runs

The calculation of hay production in Búmodel depends upon the area of hayfield, the climate scenario and the amount of fertiliser applied. The bulk of the fertiliser came from the cattle dung that accumulated in the byre in the previous winter. This in turn depended upon the length of the winter feeding period and the quantities of fodder that were consumed. 2944 feed units would have been required for the four cows recorded at Hofstaðir, if they were kept indoors from October to May, which would have produced

88.32 kg of effective nitrogen fertiliser. This equates to 19.54 kg ha^{-1} (assuming that hay contains 1.5% of effective nitrogen), which is relatively low. In contrast, Bergþórsson *et al.* (1987) describe farms in the early 20th century as applying the equivalent of 45 kg ha^{-1} in manure. This figure might include manure from livestock other than cattle, household waste or fuel ash. Figure 6-3 shows the impact of different climate scenarios and fertiliser applications upon predicted hay production. Hay production is given in 'cow-months', as a dairy cow is estimated to require 180.15 kg of hay per month when fed indoors over winter (based on 1 cow: 6 ewes). The use of 'cow-months' allows the assessment of the impact of different hay management strategies and climate scenarios upon the farm's ability to support its livestock. The increase in predicted hay production between the 19.5 kg/ha fertiliser input and the 45 kg/ha input was between 26% (warm scenario) and 42% (extreme cold scenario).

The cultivated hayfield at Hofstaðir was capable of supporting the reported cattle numbers from October to May under all climate scenarios, even if the hayfield area was reduced to 3.5 ha (but no smaller). A variable number of ewes could be supported in addition to the cattle, depending upon the climate scenario and fertiliser regime (Figure 6-4). Under the extreme cold scenario and low fertiliser input, 42 ewes could be supported on hay for a single month. In contrast, under the warm scenario with high fertiliser input, 283 ewes could be supported for a single month, or approximately all of Hofstaðir's sheep flock could be supported for 2½ months.

It is probable that additional fodder could be gathered from the outfield, in order to feed winter-grazing livestock in periods of harsh weather. If this was gathered from the richly vegetated areas on the banks of the Laxá near the farmstead, then one hectare could provide approximately 1285 ± 539 kg (assuming 70% harvesting efficiency at the

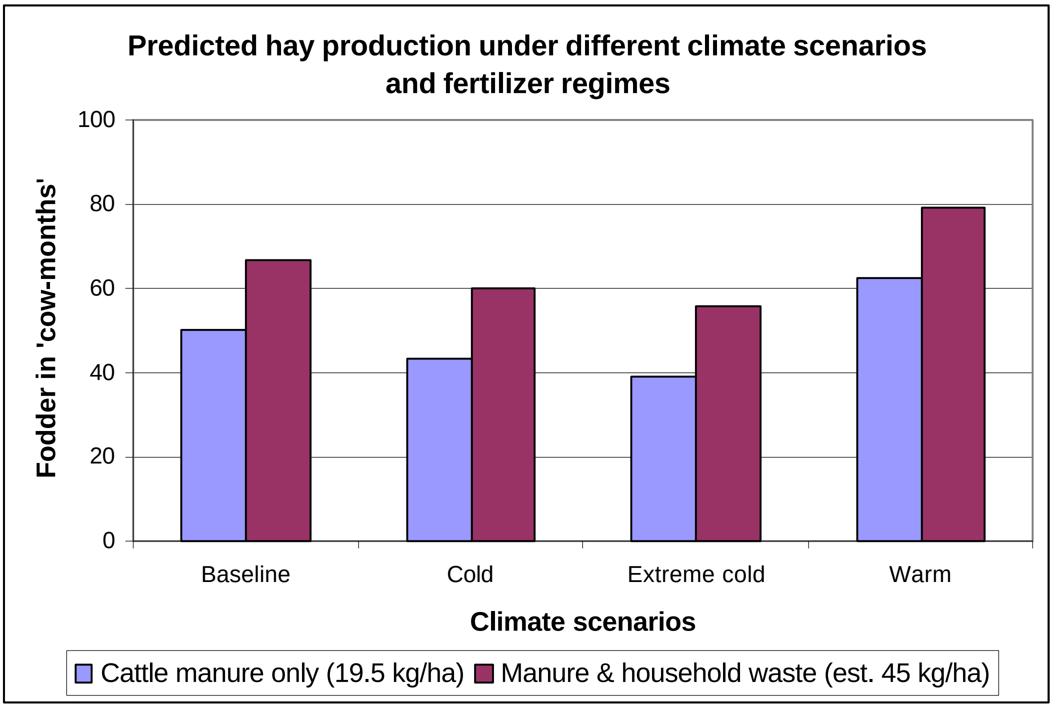


Figure 6-3: Predicted hay production under different climate scenarios and fertiliser inputs at Hofstaðir in 1712 (1 'cow-month' = 180.15 kg of hay)

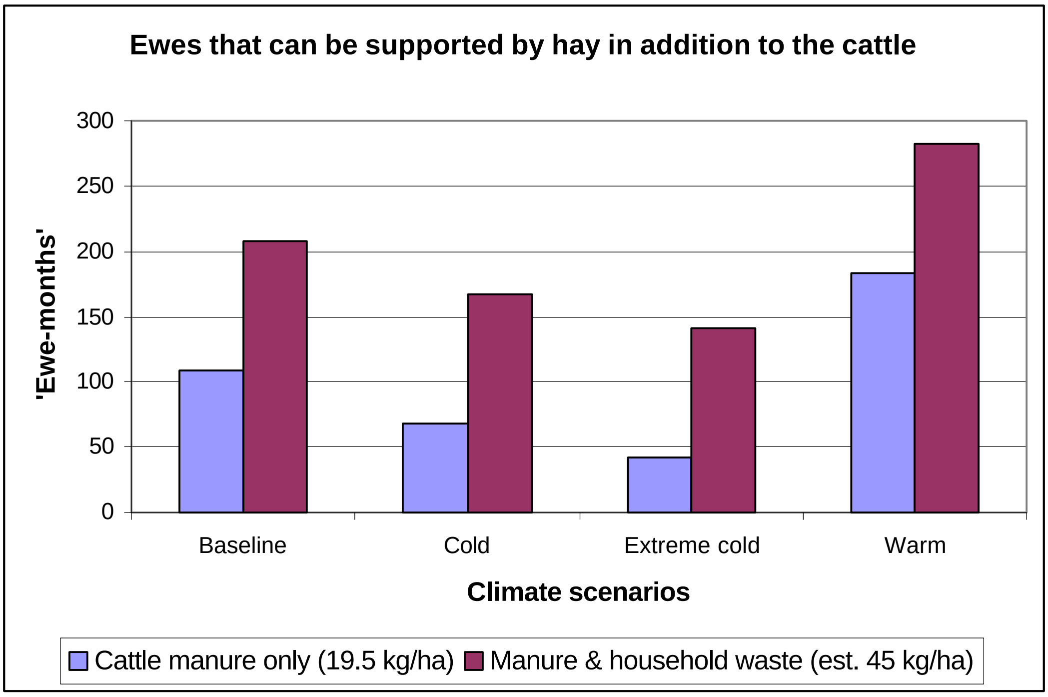


Figure 6-4: Number of ewes that can be supported by hay feeding in addition to cattle at Hofstaðir in 1712 (1 'ewe-month' = 30.025 kg of hay).

end of July). This would provide enough fodder to feed 43 ± 18 ewes for one month (all climate scenarios). This harvesting would be labour intensive and it is probable that the harvested vegetation made lower quality fodder than the cultivated tún vegetation. If this vegetation was taken from the wet meadow on the banks of the Laxá on a rotational basis then the risk of degradation was small. Higher risks were attached to the practice of hrísrif (where birch and willow scrub was grubbed out by the roots for livestock fodder (Dýrmundsson, *pers. comm.*)) but it is not known whether this was practiced at Hofstaðir.

6.2.4 Grazing scenario runs

Summer and winter grazing must be looked at together when it seems probable, as in the case of Hofstaðir, that the same area was used at all times of year. The most extreme summer usage would involve grazing all of the farm's livestock on the farm estate, although it is likely that at least some of the livestock were grazed on the common land south of Mývatn during the summer months. According to the available information, the cattle would have been kept indoors over winter and fed hay, the sheep were grazed out of doors with a little hay feeding when weather conditions prevented grazing, and the horses were grazed at a remote location away from the farm estate. The livestock numbers for Hofstaðir in 1712 were recorded at the end of August, and it is unclear whether the numbers given refer to the summer herd, or the reduced winter herd. Twenty five lambs compared to fifty five milk ewes seems a high number to retain over winter, but a relatively low number, when compared to the expected fertility rate of c.70% (which would give thirty nine lambs). For the initial set of runs, it is assumed that the numbers given in Jarðabók are constant throughout the year. The impact of varying livestock numbers will be investigated in later runs.

It seems that the vegetation on the Hofstaðir estate was capable of supporting the recorded livestock numbers grazing throughout the year without risk of vegetation damage, in all but the coldest climate scenario (Figure 6-5). The distribution of sheep in summer and winter is shown in Figure 6-6. There was little difference in distribution between climate scenarios. Under the extreme cold scenario, an average of two cells had April cumulative utilisation figures of over 15%, which put them at risk of grazing damage, particularly as these cells were dominated by dwarf shrub heath. In the worst case run thirteen cells, or 17 % of the estate area, was at risk of grazing damage.

However, these runs assume that the whole estate was grazeable during the winter months (October-April). The occurrence of persistent snow and ice cover would actually have prevented grazing on large areas of the estate. In winter the dominant wind direction is from the south, and southern facing or exposed areas would have had only a very thin or non-existent snow-cover. The snow layer would have been thickest and most persistent in densely vegetated areas, for example on the western facing slopes of the Laxá valley. Winter snow cover puts additional grazing pressure on the land that is still grazeable (Figure 6-7). Mann-Whitney non-parametric tests demonstrated a significant increase in cumulative utilisation under all climate scenarios ($p < 0.05$). There is a risk of grazing damage under both the cold (7 cells) and extreme cold (15 cells) scenarios in the worst case runs, and even in the best case runs 5 cells are at risk of grazing damage under the extreme cold scenario. The 40% cumulative utilisation threshold was not exceeded under any of the scenario runs. Levels of monthly utilisation in March were examined to investigate the relative impact of winter grazing. The maximum level of monthly utilisation did not exceed 7%, even under the extreme

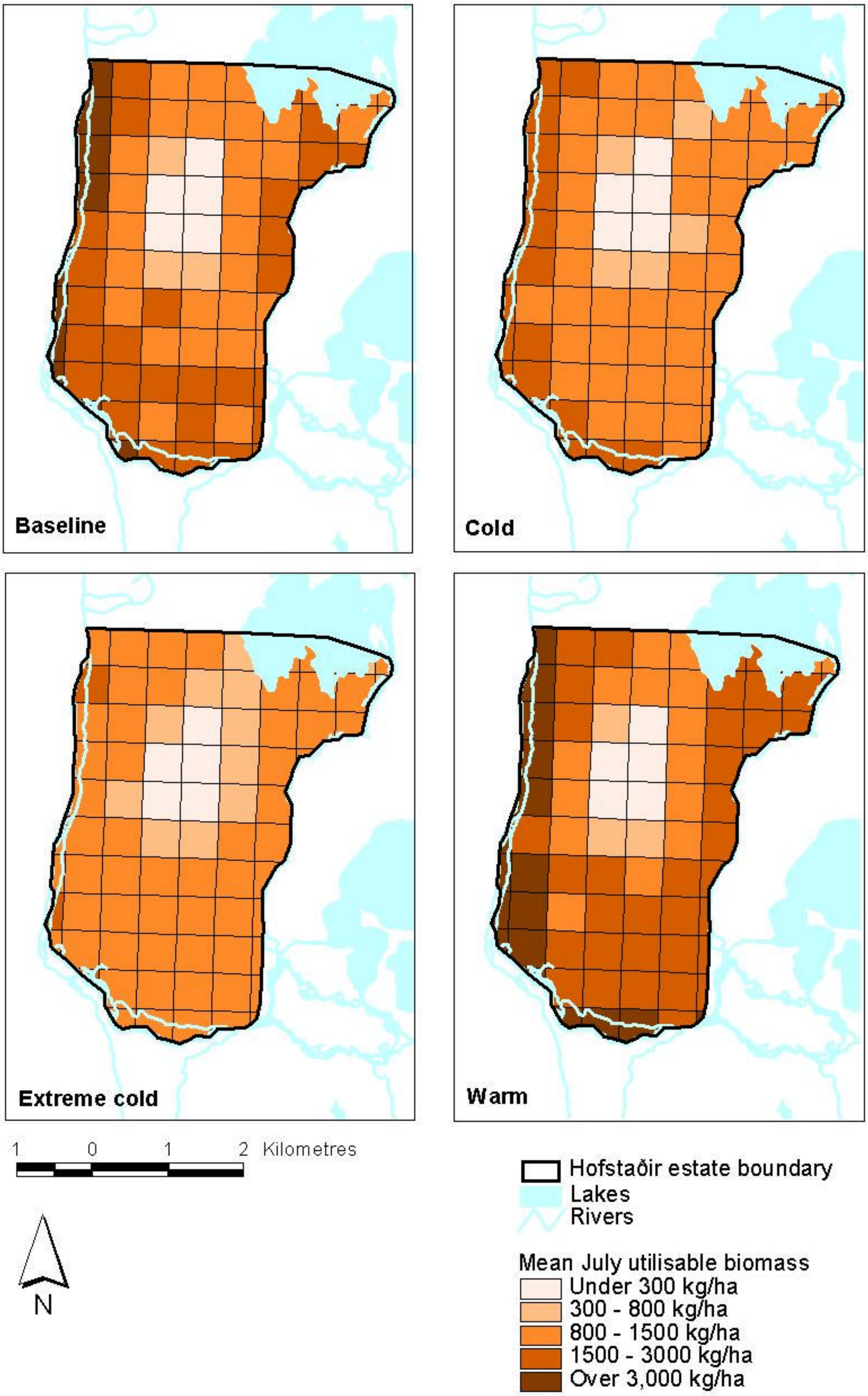


Figure 6-5: Mean July utilisable biomass on the Hofstaðir estate under the four climatic scenarios

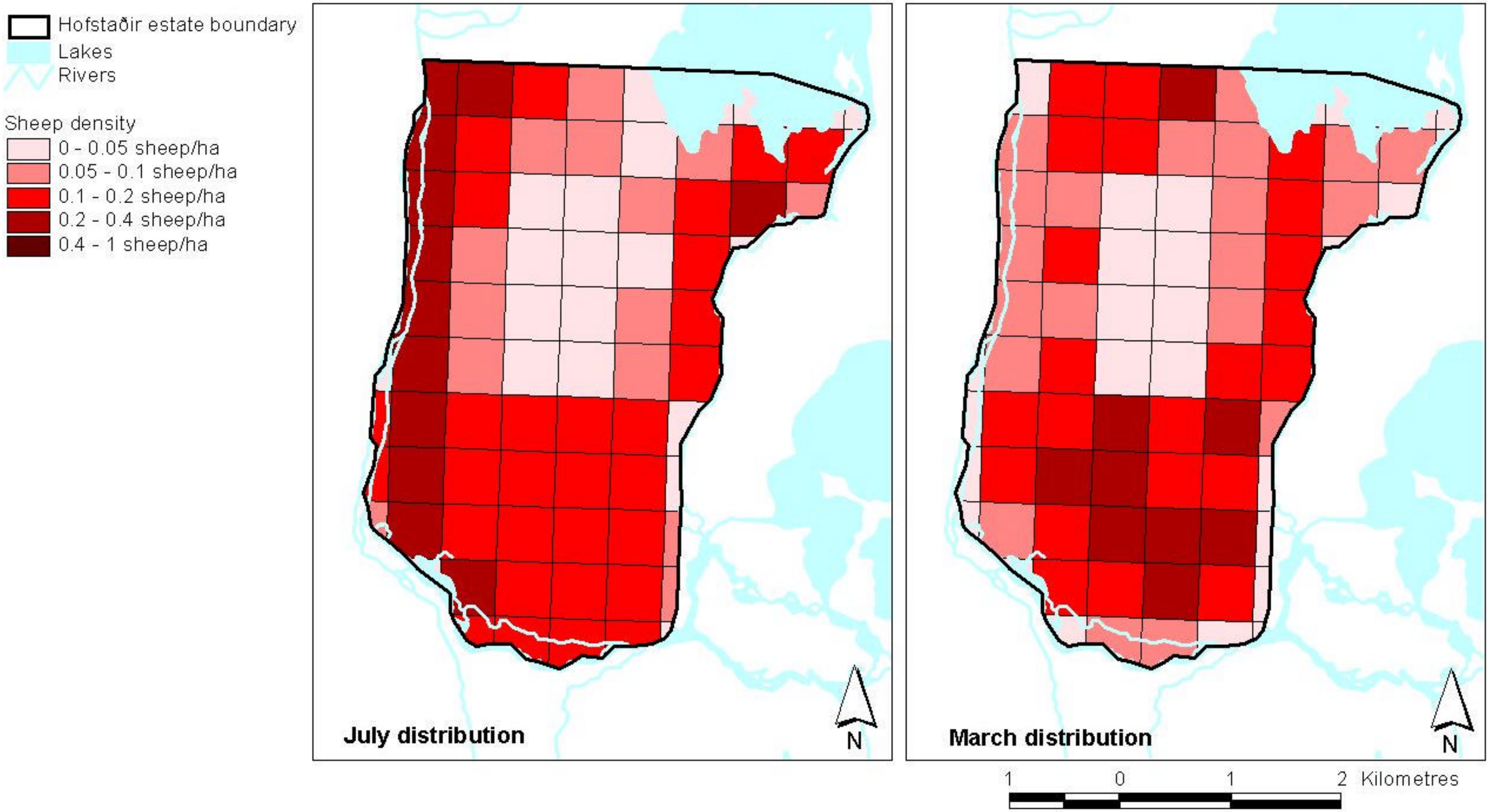


Figure 6-6: Sheep distribution in summer and winter under the baseline climate scenario (Assuming no winter snow cover)

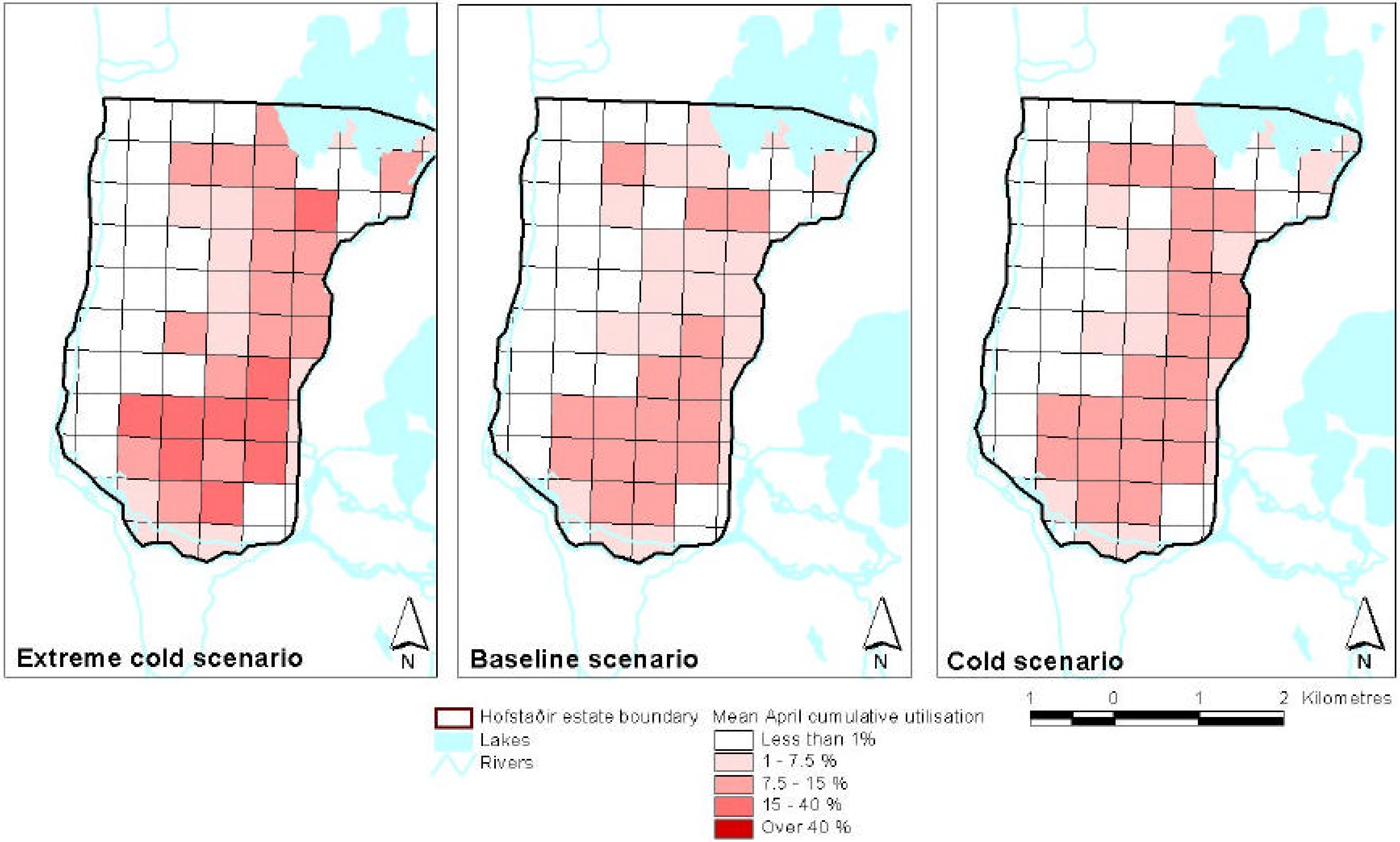


Figure 6-7: Mean April cumulative utilisation with snow cover on sheltered slopes

cold scenario, indicating that the chances of vegetation degradation due to grazing alone were small.

If snow and ice cover continued into May and June there would be additional pressure upon the ice-free pastures. It is difficult to assess the cumulative impact of this type of scenario as Búmodel only runs for twelve months. Neither is it possible to factor in the effect of snow/ice cover in delaying the growing season or as ‘winter-kill’. It is only possible to state that there is a significant increase in the cumulative utilisation ($p < 0.005$ Mann-Whitney test) on the grazeable pastures when snow cover remains until summer than when it does not.

The impact of increasing the reported livestock numbers by 25% was examined. There was no risk of grazing damage during the summer months, and all cells were well below the 15% cumulative utilisation threshold. In the winter, with the valley vegetation ungrazeable due to snow cover, there was an increased risk of grazing damage under the cold (up to 12 cells) and extreme cold (up to 20 cells) climate scenarios.

Management strategies, such as reducing the numbers of livestock by slaughtering in autumn, and increasing hay feeding of livestock in winter, reduce the risk of grazing damage. If the number of reported lambs in 1712 is halved from 25 to 13 at the end of September in an extremely cold year, with persistent snow cover, then 6 cells have a April cumulative utilisation above 15% in the worst case run. If the number of wethers is also reduced by 30% from 34 to 24, then only 3 cells are at risk of grazing damage in the worst case run. If reduced livestock numbers are combined with additional feeding using fodder from the outfield (all sheep fed for one winter month), then no cells have a cumulative utilisation > 15% even in the worst case run. It is estimated that 3.2 ha of outfield meadow would need to be harvested for fodder in order to feed this sheep flock for one month in such a scenario (using the previous outfield fodder production estimate).

6.2.5 Summary of modelling results for Hofstaðir estate

The potential for grazing at Hofstaðir has been investigated using Búmodel and a reconstructed vegetation cover for 1712. It appears that the estate could support its livestock throughout the year whilst avoiding undue land degradation. Prolonged snow cover might place additional stress on the winter grazing area but it was possible to mitigate this by supplementary feeding of livestock with fodder from the hayfield and/or the outfield pastures.

6.3 Modelling results for Vestur-Eyjafjallahreppur

6.3.1 Vegetation reconstruction for 1709

The landscape reconstruction for Vestur-Eyjafjallahreppur is principally based upon the reconstruction for 1750 in Simpson *et al.* (2001) (Figure 6-8). Fieldwork observations and place names also contributed to the reconstruction. It was necessary to adapt the 1750 map to take account of the Búmodel vegetation classification and changes in the Markarfljót channel in the 18th century (Haraldsson 1981) (Figure 6-9).

Large areas of the hreppur were inaccessible to grazing, either because they were covered by unstable river gravels or they were very steep. There were also large areas in the lowland and upland that were only sparsely vegetated, due to the action of water or aeolian erosion. Much of the lowland pasture area was covered with wet meadow (assumed to be an equal mixture of Búmodel riverine and bog communities), with areas of bog vegetation. The lowland slopes up to 300m were covered with grassy heath beside the streams, dwarf shrub heath on the dry, exposed areas between streams, or moss heath on old lava flows. There was also an extensive area of rich dwarf shrub heath in the Langanes area in the northern part of the hreppur, between Markarfljót and Eyjafjallajökull (based upon fieldwork observations). Between 300m and 700m the vegetation cover was assumed to be dwarf shrub heath, except for the area of Trollamýri (mýri meaning mire) which was assumed to be bog. There was little vegetation cover above 700m, which was therefore classified as sparsely vegetated land. The assumption of declining vegetation cover with altitude has been retained from the 1750 reconstruction (Figure 6-9).

The hayfield areas can be estimated from the yields given in the 1709 farm census of the hreppur (Table 6-4). However, because the locations of some of the farms listed in 1709 are unknown, or may have changed, it is not possible to precisely site the hayfield areas in the lowland. The unknown locations are estimated from the known locations of farms that are contiguous in the Jarðabók record, and from additional information given by Sveinbjarnardóttir (1992). They are all located on the low-lying wet meadow or bog areas, so the precise location of the hayfields should not make much difference to the distribution of livestock. The areas of the Búmodel vegetation classes are given in Table 6-3.

Table 6-3: Areas of Búmodel communities in the 1709 Vestur-Eyjafjallahreppur landscape reconstruction (based on a lattice of 25 ha cells covering the area)

Búmodel vegetation community	Area (hectares)
Hayfield	285
Grassy heath	1,666
Dwarf shrub heath	1,704
Moss heath	205
Bog	4,302
Riverine	3,526
Sparsely vegetated land	15,354
Inaccessible to grazing	5,358

6.3.2 Farm census information for the early 18th century

The livestock survey of Vestur-Eyjafjallahreppur was conducted in June 1703, and the Jarðabók farm census was taken in December 1709.Therefore they should be used carefully as some livestock numbers (particularly of lambs) are not directly comparable. Fifty working farms are listed in the 1709 census, of which 39 can be located on modern maps, although the locations of the farmsteads are known to have shifted over time in response to river and coastal erosion (Sveinbjarnardóttir 1992). The numbers of livestock on each farm are shown in Figure 6-10a & 6-10b. Twenty-two farms are listed in the 1703 survey, although two of those actually group together seven farms in the 1709 survey (the Fit and Sandar groups), and one farm appears to have been abandoned in the intervening period (Brúnir). The numbers of livestock on the surveyed farms are shown in Figure 6-11, and a comparison of the change in total livestock numbers from 1703 to 1709 is shown in Figure 6-12.

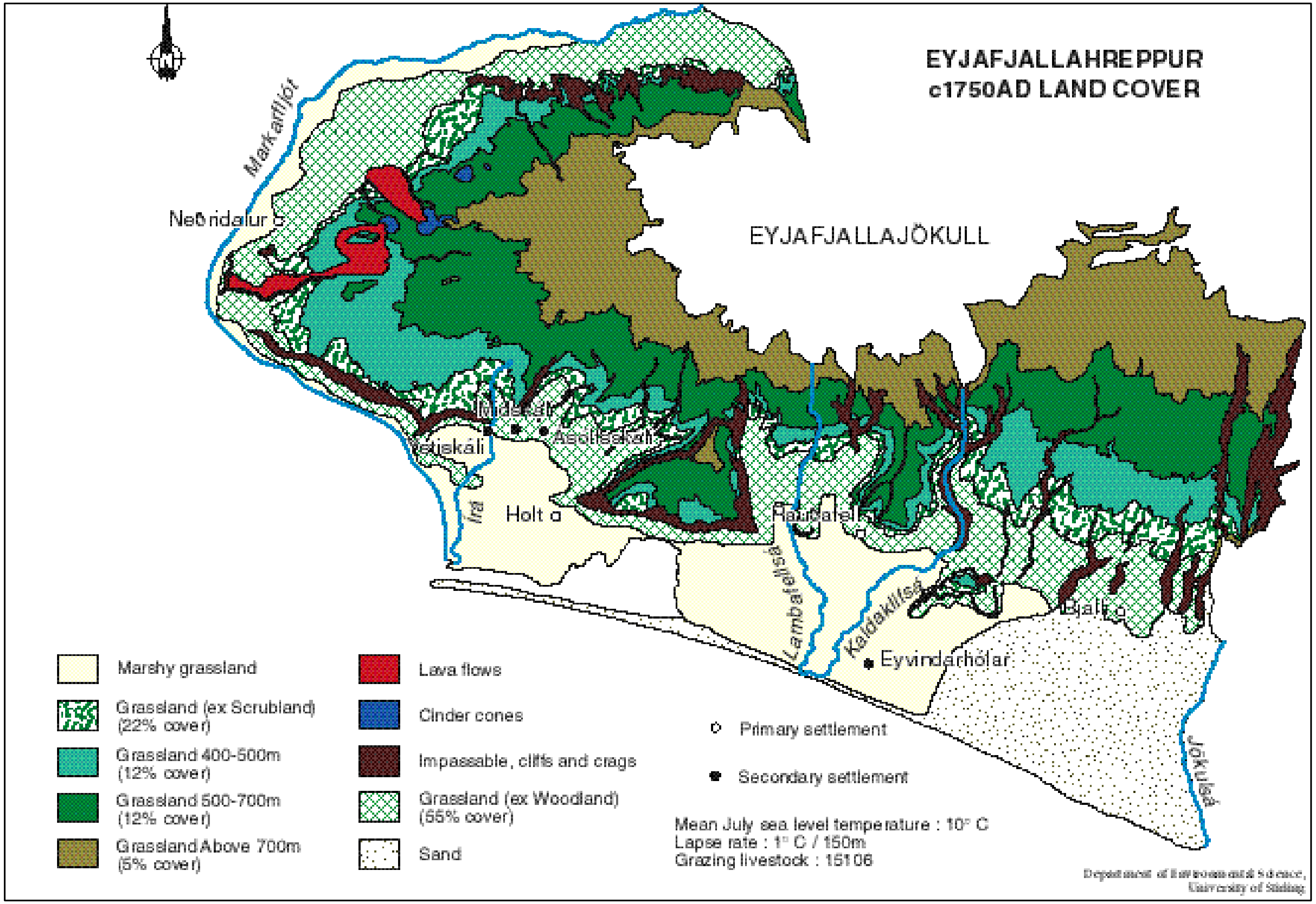


Figure 6-8: Vegetation reconstruction for 1750 AD (from Simpson *et al.* 2001)

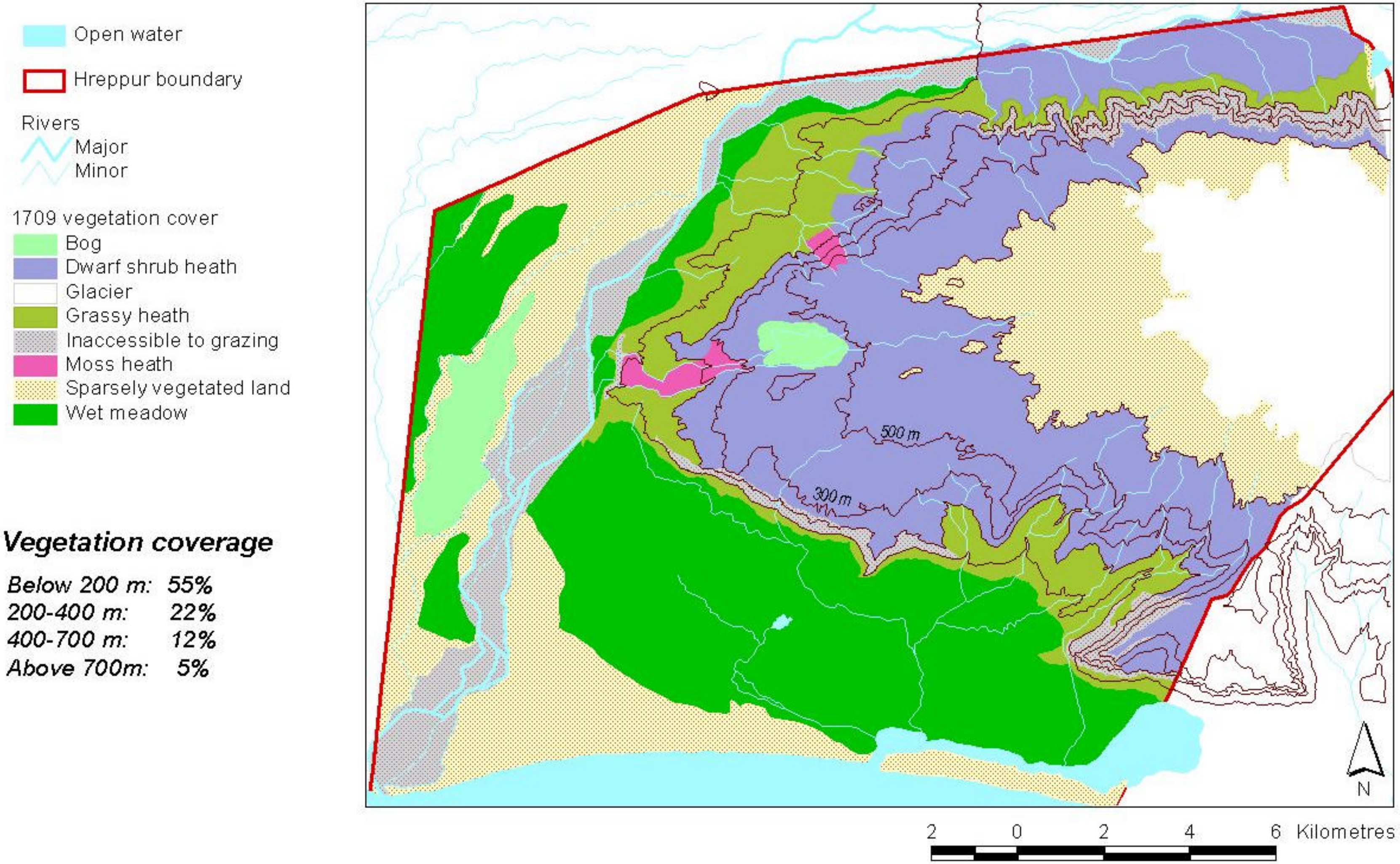


Figure 6-9: Búmodel vegetation reconstruction for 1709 AD

Table 6-4: Estimated hayfield area of farms in Vestur-Eyjafjallahreppur, based on hay yields from Jarðabók and Baseline climate scenario. (Hayfield area would be adjusted by ±20% under the extreme cold or warm climate scenarios).

Farm name	*Cattle*	*Horses*	*Yearling cow*	*Lambs*	*Estimated hay production, kg*	*Estimated hayfield area, ha*
Varmahlið	9	0	1	0	12,709	4.8
Ormskot	9	0	0	0	11,438	4.3
Vallnatún	33	0	0	0	41,940	15.8
Gerðakot	17	0	0	0	21,606	8.1
Holt	28	3	0	0	39,399	14.8
Hallnahóll	7	0	0	0	8,896	3.4
Einarskot	12	0	0	0	15,251	5.7
Harde-vollur	8	0	0	0	10,167	3.8
Brenna	14	0	0	0	17,793	6.7
Efstakot	10	0	0	0	12,709	4.8
Efstagrund	7	0	0	0	8,896	3.4
Ásólfsskáli	17	0	0	0	21,606	8.1
Skálakot	10	0	0	0	12,709	4.8
Moldnúpur	10	0	0	0	12,709	4.8
Björnskot	6	0	0	0	7,626	2.9
Rimhús	9	0	0	0	11,438	4.3
Miðskáli	18	0	0	0	22,877	8.6
Ystiskáli	26	0	0	0	33,044	12.5
Aurgata	5	0	1	0	7,626	2.9
Núpur	23	5	0	56	57,279	21.6
Hvammur	9	0	0	0	11,438	4.3
Efre hooll	12	0	0	0	15,251	5.7
Sijdre hooll	11	0	0	0	13,980	5.3
Efraholt	20	0	0	0	25,418	9.6
Vesturholt	12	0	0	0	15,251	5.7
Nýibær	8	1	0	12	16,087	6.1
Sauðhusvöllur	6	1	0	0	8,896	3.4
Fit	6	1	0	12	13,545	5.1
Fitarmýri	14	0	0	0	17,793	6.7
Fornusandar	8	0	0	0	10,167	3.8
Helgusandar	5	1	0	12	12,274	4.6
Helgubaer	4	0	0	0	5,084	1.9
Steckiartuned	5	0	0	0	6,355	2.4
Rotinn	3	1	0	10	8,957	3.4
Seljaland	10	3	0	30	28,143	10.6
Tjarnir	4	0	0	0	5,084	1.9
Hamragarðar	3	1	0	12	9,732	3.7
Neðridalur	11	2	0	27	26,981	10.2
Stóridalur	7	2	0	30	23,060	8.7
Krókfen	3	1	0	12	9,732	3.7
Dals-kot	2	1	0	0	3,813	1.4
Olafshus	4	1	0	12	11,003	4.1
Borgareyrar	2	0	0	0	2,542	1.0
Dalssel	3	0	0	0	3,813	1.4
Steinmoðarbær	3	0	0	0	3,813	1.4
Murnavollur	3	0	0	0	3,813	1.4
Eyvindarholt	10	0	0	0	12,709	4.8
Syðstamörk	6	0	0	0	7,626	2.9
Miðmörk	5	1	0	0	7,626	2.9
Stóramörk	16	1	0	20	29,353	11.1

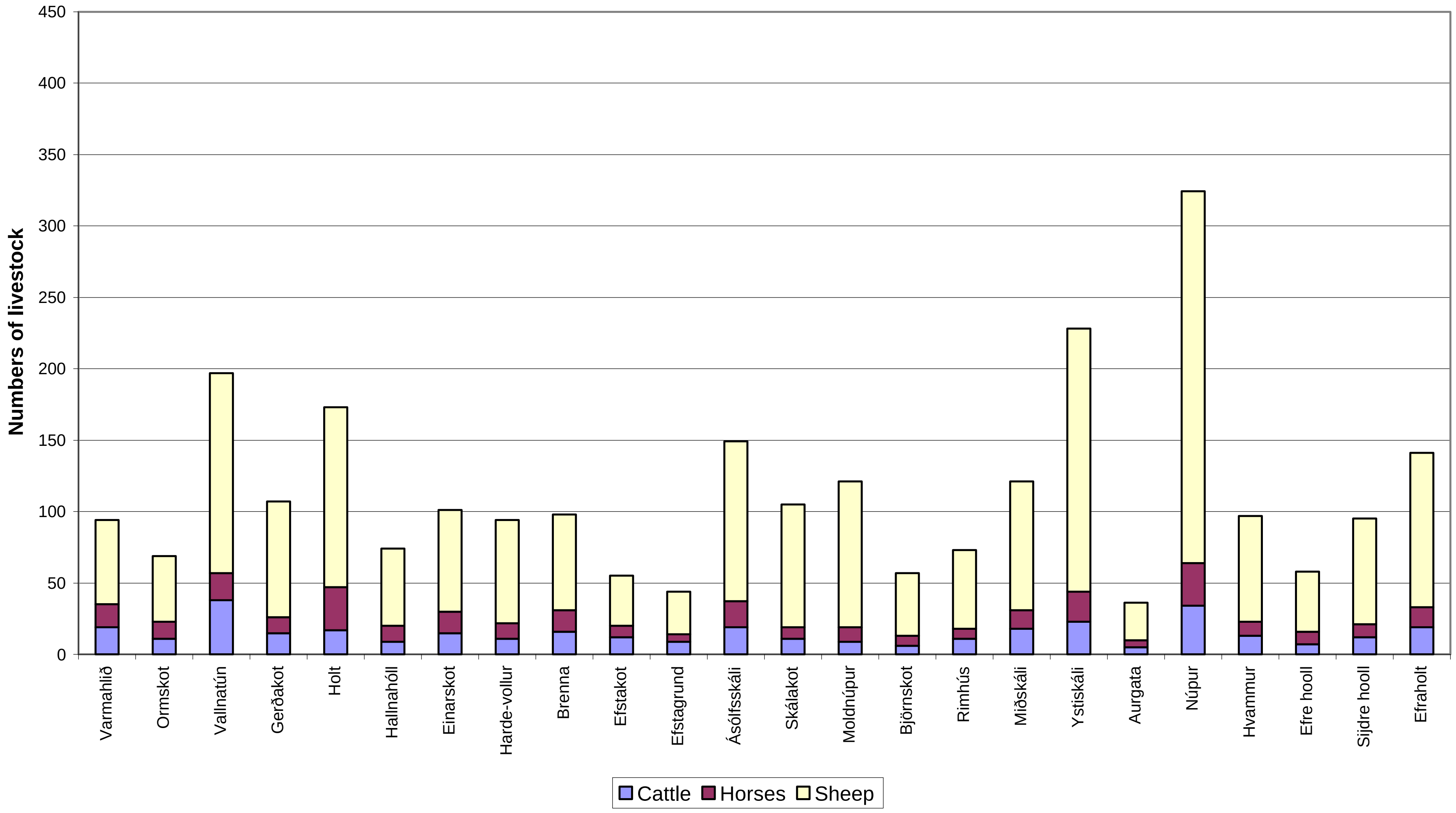


Figure 6-10a: 1709 livestock census (southern area)

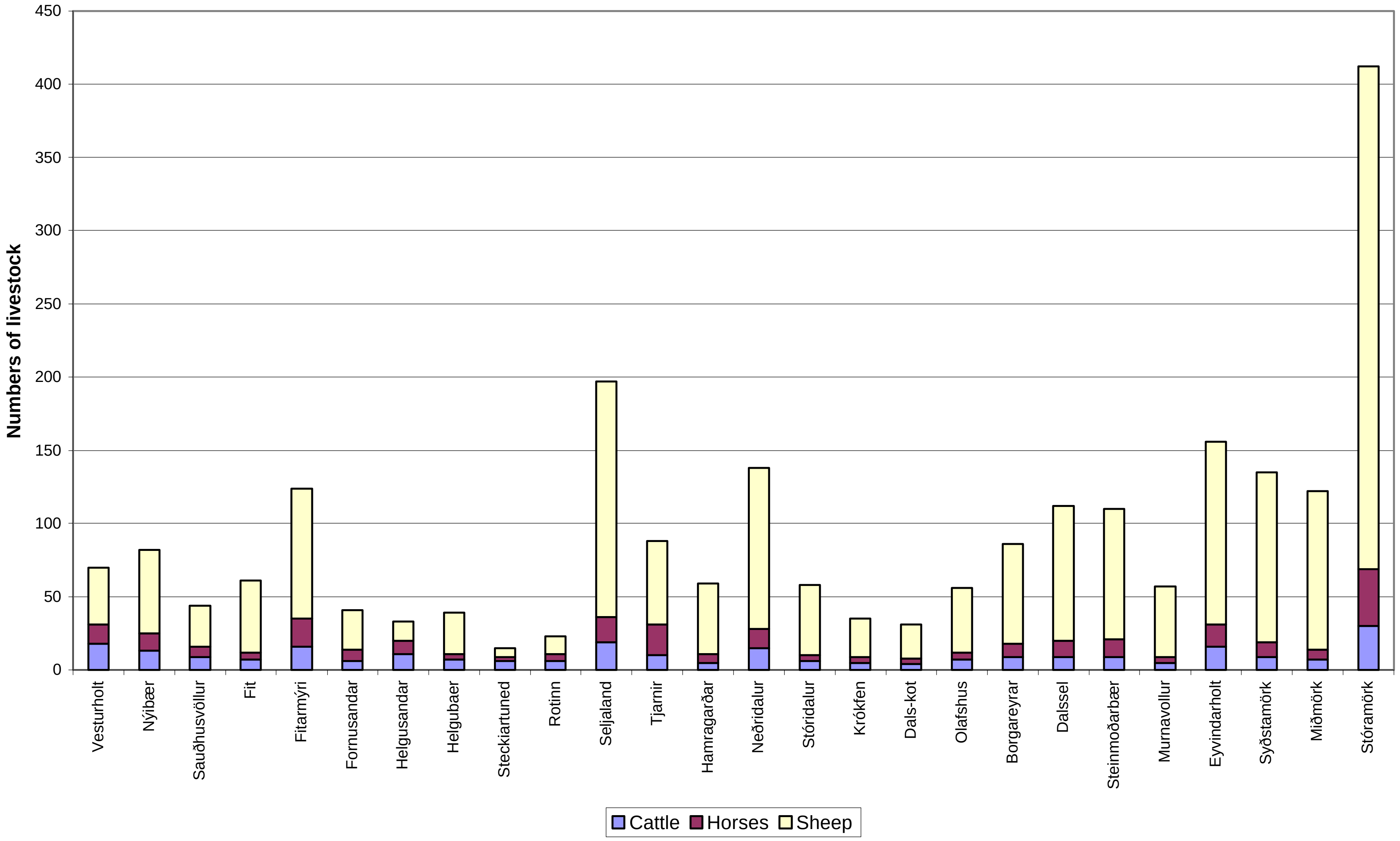


Figure 6-10b: 1709 livestock census (northern area)

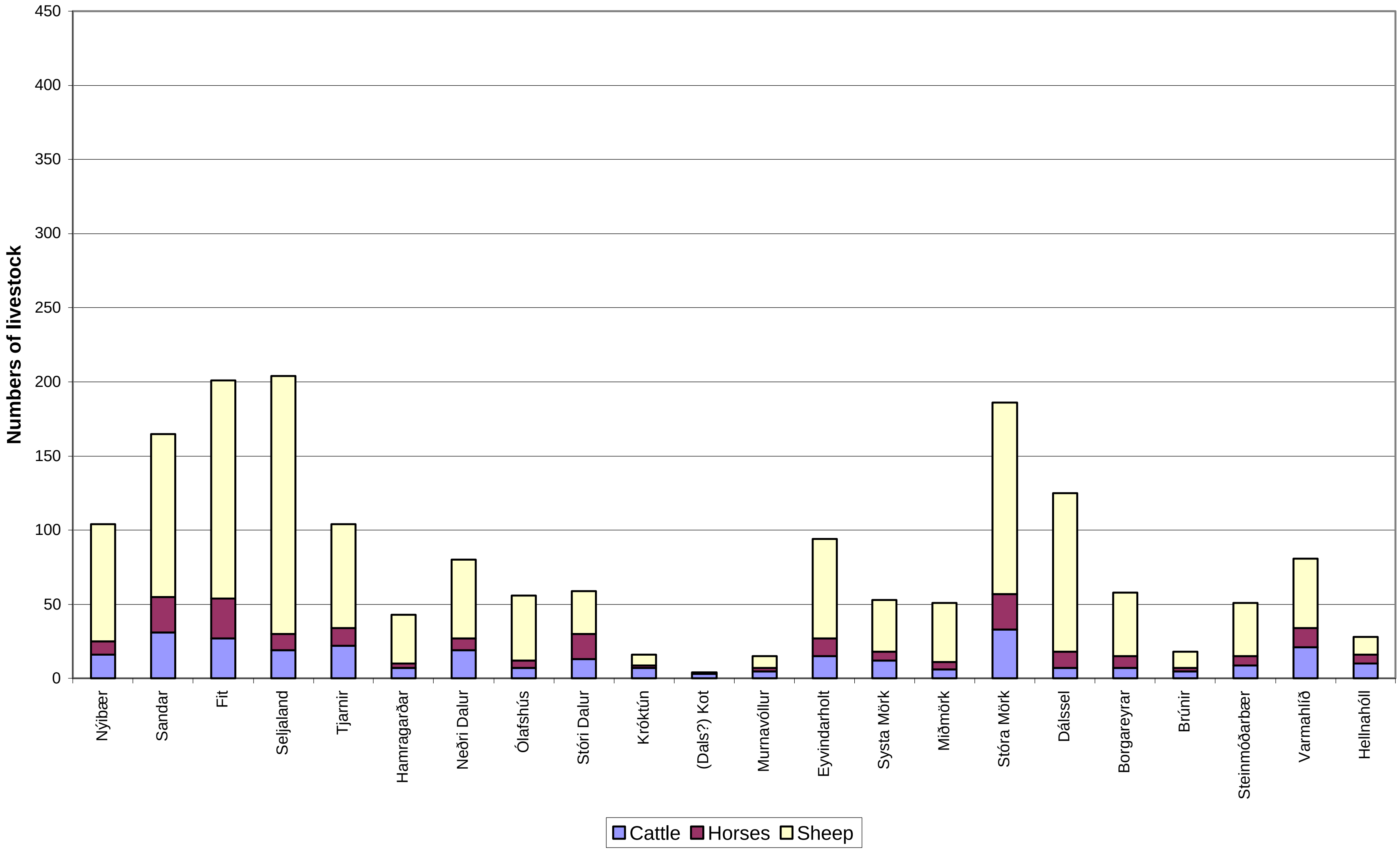


Figure 6-11: 1703 livestock survey

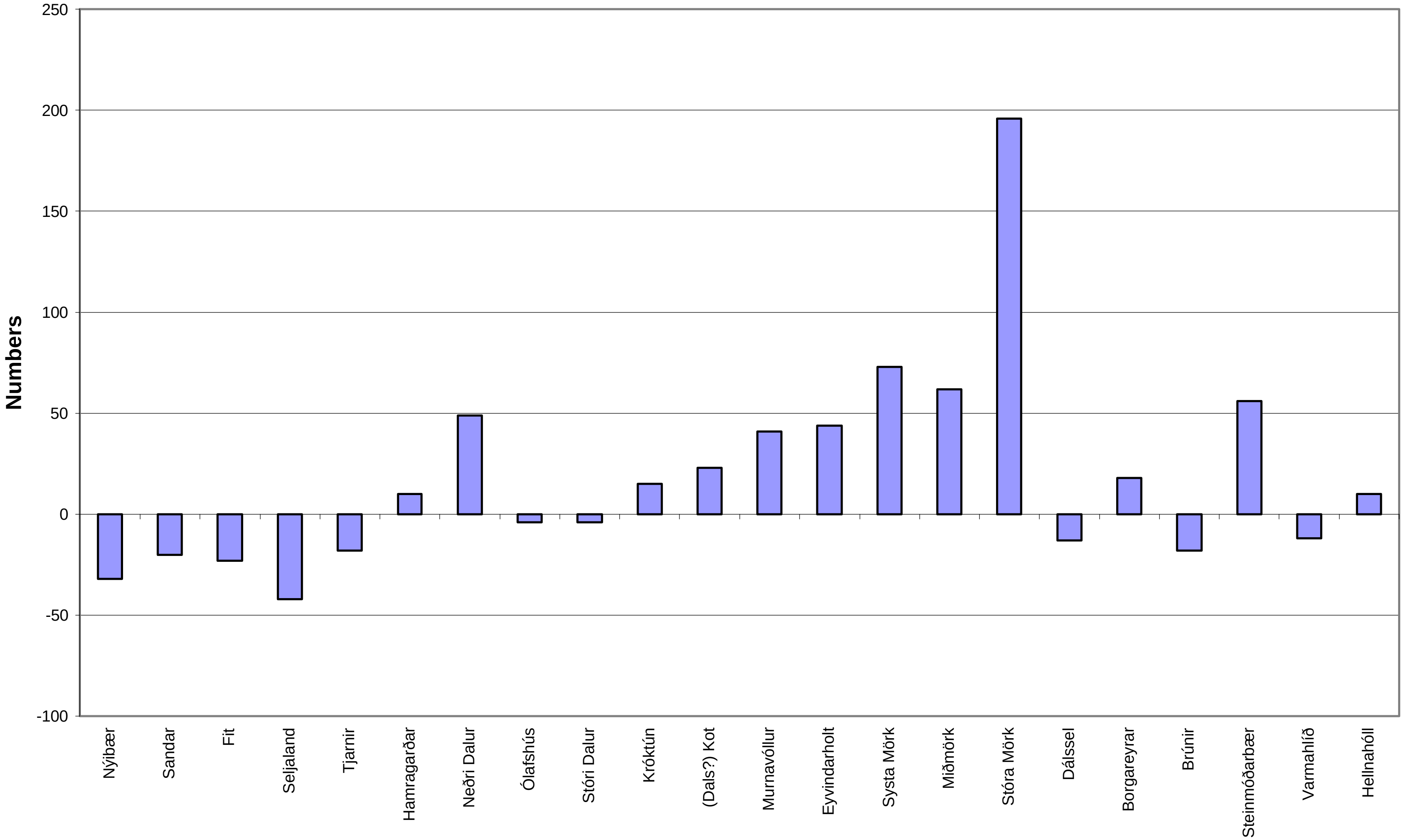


Figure 6-12: Difference in total livestock numbers 1703-1709 on farms reported in both surveys

There were seventy one farmers in the hreppur, as many farms supported two or more households. Twenty six landowners had interests in farms in Vestur-Eyjafjallahreppur (several landowners might have shares in a single farm). These included the churches at Holt and Stóridalur, four individual priests, a sheriff, the Crown and individual private landowners. Most of the landowners appear to live in the local region, although there are mentions of owners living in other parts of Iceland. Some farmers had part ownership of farms but were tenants on other properties, and five farmers retained farming stakes at two or three different farms. The farm valuations and rents are shown in Table 6-5. The farms with the highest values are Ásólfskáli, Stóramörk and Stóridalur at 60 hundreds, Holt and Seljaland at 50 hundreds, and Núpur and Ystiskáli at 40 hundreds. Farms that do not have values are outliers of other farms. Holt and Moldnúpur were occupied by their owners, and therefore no land or cattle-rent values are given in Jarðabók.

There appears to be a difference in the 1709 census reporting between the eastern and western halves of the hreppur, particularly of the numbers of lambs. In the eastern half, from Varmahlið to Efre Hollt, 664 lambs are recorded, compared to 738 ewes, whereas in the western half (from Vesturholt to Storamörk), 186 lambs are recorded, compared with 1081 ewes. Lamb numbers are 90% of ewe numbers in the east, but only 17% in the west. Although the census was recorded in December, these percentages resemble those that might be expected before and after the autumn slaughter (Aðalsteinsson states that a replacement rate of 16% is needed to maintain herd size). This discrepancy might be due to misreporting by the farmers, conflicting methods of data collection, or subsequent misinterpretation. The impact of increasing the number of lambs in the western half to 90% of the ewe numbers will be investigated in the model simulations.

Table 6-5: Farm valuation and rental value, Vestur-Eyjafjallahreppur 1709 (Magnússon and Vídalín 1913-1990)

Farm	Value, hundreds	Rent, alnir	Leigukúgildi, alnir
Ásólfsskáli	60	190	4.5
Aurgata		50	1
Björnskot		60	1.5
Borgareyrar	2.5	60	1
Brenna		240	3
Dals-kot	2.5	40	1
Dalssel	5	50	1
Efraholt	6	120	5
Efre hooll	3	60	3
Efstagrund		50	2
Efstakot		120	2
Einarskot		120	2
Eyvindarholt	15	140	2
Fit	10	60	1.5
Fitarmýri	15	90	2.5
Fornusandar	5	60	1
Gerðakot	12	120	3
Hallnahóll		60	2
Hamragarðar	8	40	1
Harde-vollur		60	2
Helgubaer	3.5	40	1
Helgusandar	3.5	40	1
Holt	50		
Hvammur	20	140	5
Krókfen	2.5	60	0
Miðmörk	12	0	0
Miðskáli	30	114	4
Moldnúpur			
Murnavollur	2.5	60	1
Neðridalur	20	140	4.5
Núpur	40	270	8
Nýibær	10	60	3
Olafshus	2.5	60	1
Ormskot	10	120	2
Rimhús		60	1.5
Rotinn	3	20	1
Sauðhusvöllur	10	60	2.5
Seljaland	50	170	4
Sijdre hooll	3	60	2
Skálakot		120	2
Steckiartuned	5	60	1
Steinmoðarbær	5	60	1
Stóramörk	60	230	3
Stóridalur	60	80	2
Syðstamörk	20	130	1
Tjarnir	10	100	3
Vallnatún	30	240	6
Varmahlið	12	180.5	3
Vesturholt	12	180	4
Ystiskáli	40	180	4

6.3.3 Hay scenario runs

According to Jarðabók, there was sufficient hay from the hay fields to feed 562 cattle over the winter, although there were 623 cattle in the hreppur, 429 of which were dairy cattle. The hay available was not distributed evenly between farms. The winter hay required for the cattle on each farm was compared with the hay yield reported for each farm in Jarðabók (Table 6-4). Eighteen farms had a hay balance or surplus; this included five of the seven highest valued farms, but also a number of smaller ‘cottage’ farms, for example Rotinn and Hamragarðar. Holt, Núpur and Stóridalur had the largest hay surpluses (>10,000 kg). The remaining farms would have been dependent upon fodder harvested from the wet meadow areas of the outfield and upon winter grazing. The outfield could provide a harvest of 1,775 ± 504 kg/ha (assuming 70% harvesting efficiency) in a baseline scenario year. If a winter feeding period of six months is assumed, then it would have been necessary to harvest hay from 74.2 ha of the outfield in order to supply the fodder needs of the remaining cattle. Fodder for any of the other livestock would have required additional harvesting from the outfield. The extensive use of seaweed for winter fodder is unlikely because the coast of Eyjafjallahreppur is very exposed and little is blown onshore.

6.3.4 Hreppur grazing simulations

The communal use of the rangeland in summer and the lowland pastures in winter were investigated. It was not possible to investigate the use of winter grazing of individual farms across the whole hreppur because the early 18th century farm boundaries are unknown. The location of some farms is also unclear: if this matter were resolved it might be possible to apply spatial analyses such as Theissen polygons, weighted according to farm herd size or rental value. A hreppur-wide investigation was not possible so the impact of different grazing practices in the outfield was investigated in detail on a small, relatively self-contained area consisting of four farms in the north of the hreppur.

6.3.5 Rangeland grazing simulations

The communal rangeland is assumed to extend from the 300m contour to the edge of the Eyjafjallajökull glacier. This division of the highland and lowland is based on that made by Bergþórsson *et al.* (1987) (Figure 1-3). The rangeland is also assumed to include the Langanes area (100-300m) which did not have any permanent farms, possibly due to its northern aspect. The rangeland covers 13,900 ha in total, of which approximately 1,900 ha are inaccessible to grazing. This area is covered by 556 25 ha Búmodel cells.

It is assumed that the lambs, yearling sheep and wethers grazed the rangeland during the summer months. The first set of simulations used the numbers of livestock recorded in 1709: 850 lambs, 229 yearling sheep and 952 wethers, grazing from June to September. The results of modelling utilisable biomass are presented in Figure 6-13. The quantity of utilisable biomass is much reduced under extremely cold conditions, from a cell average of 482±134 kg/ha under baseline conditions to 281±80 kg/ha. The cell average under warm conditions is 579±161 kg/ha. The cells with relatively high quantities of utilisable biomass are concentrated in the low-lying Langanes region in the north, the Trollamýri mire in the western part of the rangeland, and the cells along the edge of the upland/lowland boundary. Sheep grazing is concentrated in these areas throughout the summer (Figure 6-14).

The difference that climate makes to the cumulative utilisation is illustrated by Figure 6-15. The numbers given are the mean values of 20 simulation runs. There are some cells that have cumulative utilisation rates greater than 15% under all the climate scenarios. The numbers of vulnerable cells are low under the baseline and warm scenarios (8 and 7 cells out of 556), and are concentrated on areas of boggy vegetation, which can support such grazing levels without too much damage. Under the cold and extreme cold scenarios however, the number of cells vulnerable to over grazing increases considerably (65 and 97 cells respectively), and are distributed in areas of dwarf shrub heath, which is vulnerable to grazing damage above the 15% threshold.

Increasing the number of lambs to 1637 (so that lamb numbers are 90% of ewe numbers in both parts of the hreppur) increases the number of cells that are vulnerable to over grazing. This increase has a greater impact under the extremely cold climate scenario (Figure 6-16): 227 cells have cumulative utilisation >15% (representing 40% of the rangeland area), and 9 cells are above the 40% threshold.

Increasing the grazing season by a month also increases the level of cumulative utilisation so that there is a considerable increase in the area that is vulnerable to over-grazing. If the grazing season runs from May to September, the number of cells vulnerable to overgrazing under the extreme cold scenario increases to 348 (63% of the grazing area), and to 72 cells (13%) under the baseline scenario. An increasing number of cells are grazed beyond the 40% threshold (62 in the extreme cold scenario and 5 in the baseline scenario). If sheep were allowed to graze the rangeland in May in an extremely cold year, monthly utilisation of the available utilisable biomass could be up to 40% in individual cells. Even under the baseline climate scenario, monthly utilisation figures could reach 17% of the available biomass. Such heavy grazing early in the growing season would greatly increase the risk of degradation. Extending the grazing season into the autumn (from June to October) also increases the number of vulnerable cells (322 under the extreme cold scenario and 68 under the baseline scenario), but not as much as spring grazing (Mann-Whitney 1-tail test significant at $p<0.0005$). The impact of the different grazing regimes in terms of vulnerability to over-grazing is summarised in Figure 6-17.

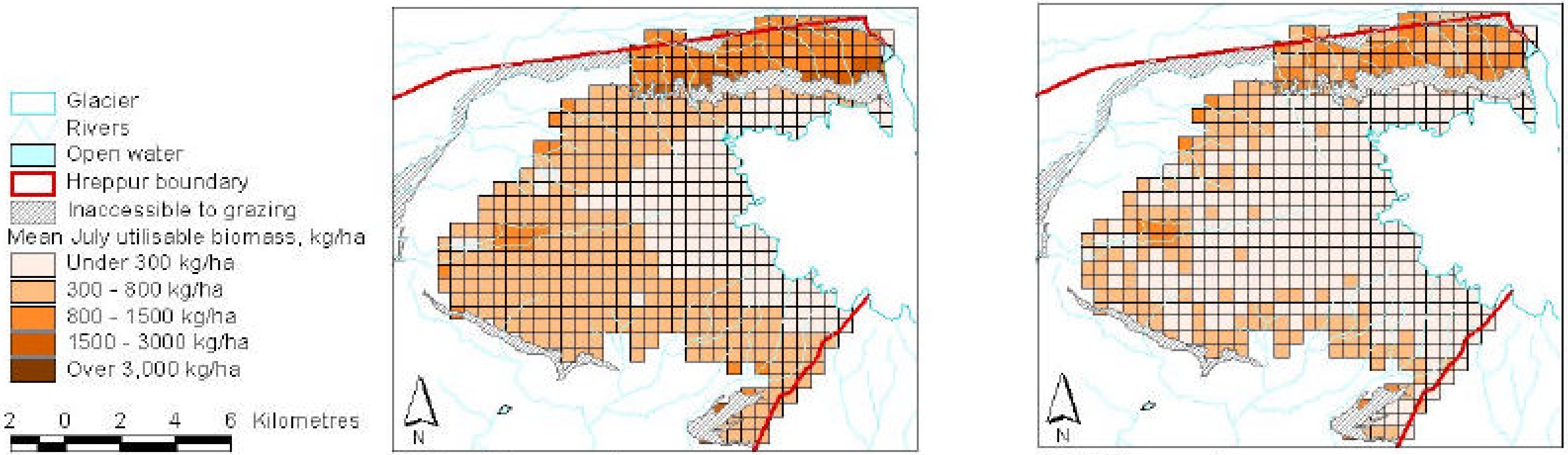
6.3.6 Outfield grazing runs

The hreppur outfield area is assumed to be all the land below 300m elevation. Of the 18,500 hectares in the outfield zone, 3445 hectares are assumed to be inaccessible to grazing (being either open water or unstable river deposits). This area is covered by 740 25 ha Búmodel cells.

Only one grazing regime was modelled for this region. Ewes, cattle and horses were grazed on the lowland throughout the summer (June-September), the cattle were fed indoors over winter while the entire sheep flock, the horses and non-dairy cattle grazed outside on the lowland during the winter months (October – May). Numbers are given in Table 6-6. Hayfield areas are left ungrazed.

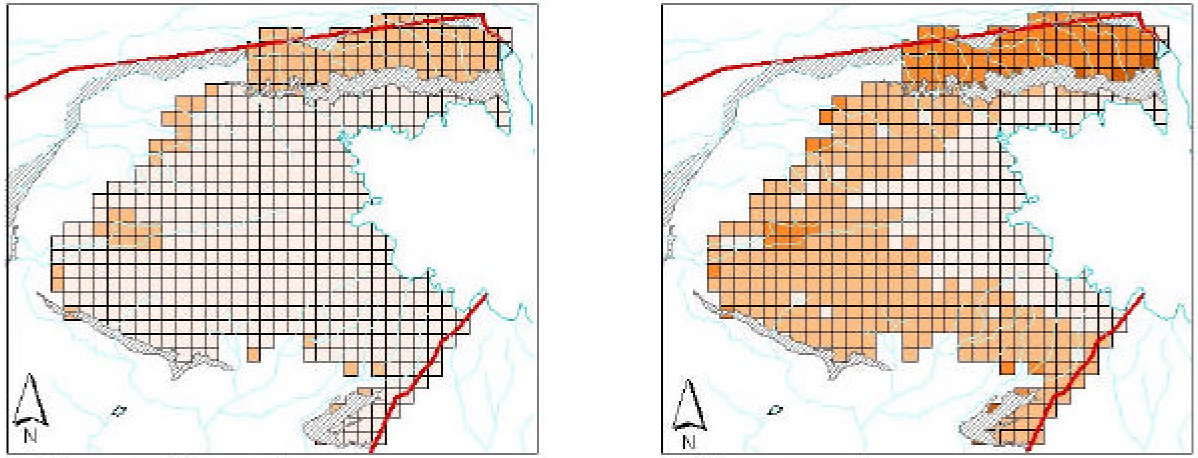
Table 6-6: Livestock in Vestur-Eyjafjallahreppur in 1709 (Magnússon and Vídalín 1913-1990)

Livestock type	Number in 1709
Dairy cattle	429
Non-dairy cattle	164
Calves	30
Ewes	1,829
Yearling ewes	410
Yearling wethers	315
Other wethers and rams	666
Lambs	682
Horses	545
Foals	39



A. Baseline scenario

B. Cold scenario



C. Extreme cold scenario

D. Warm scenario

Figure 6-13: Rangeland July utilisable biomass under different scenarios (grazing with 1709 livestock numbers)

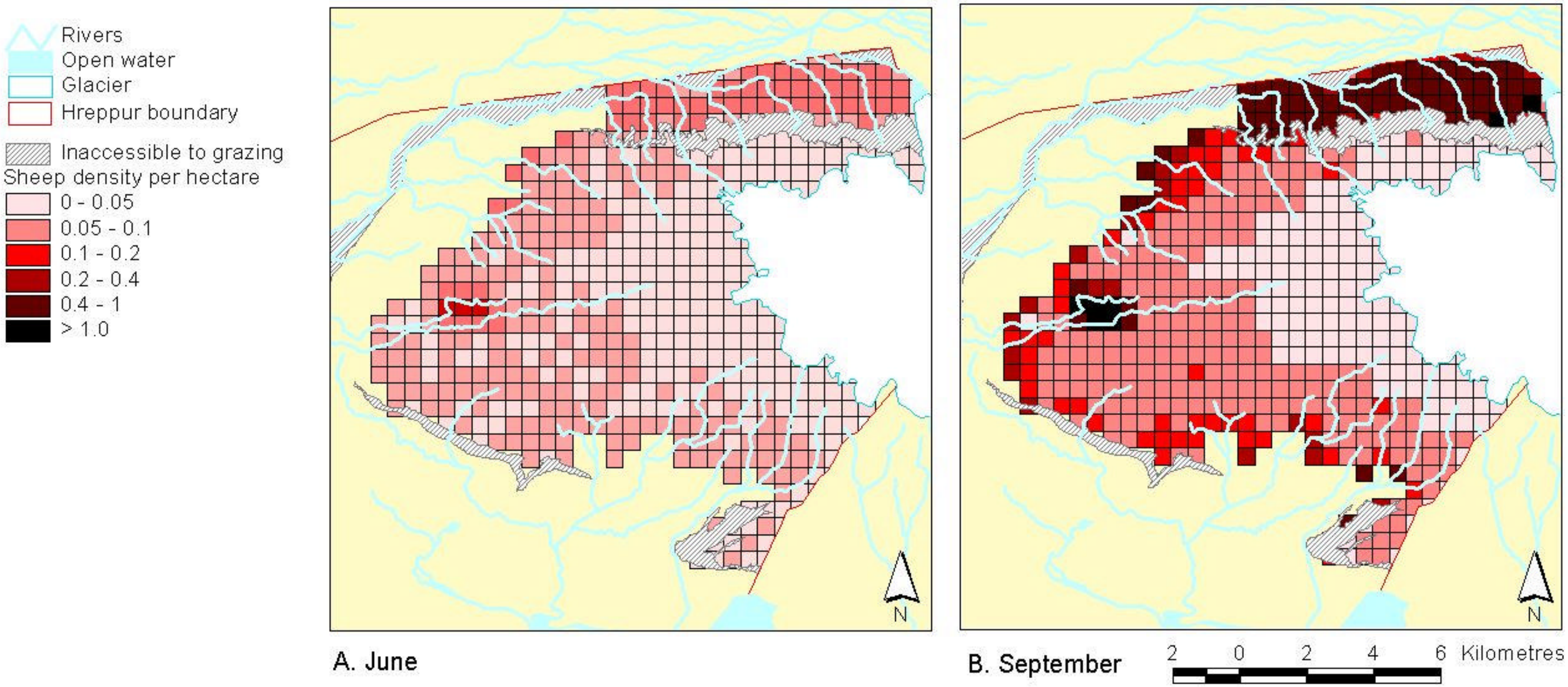
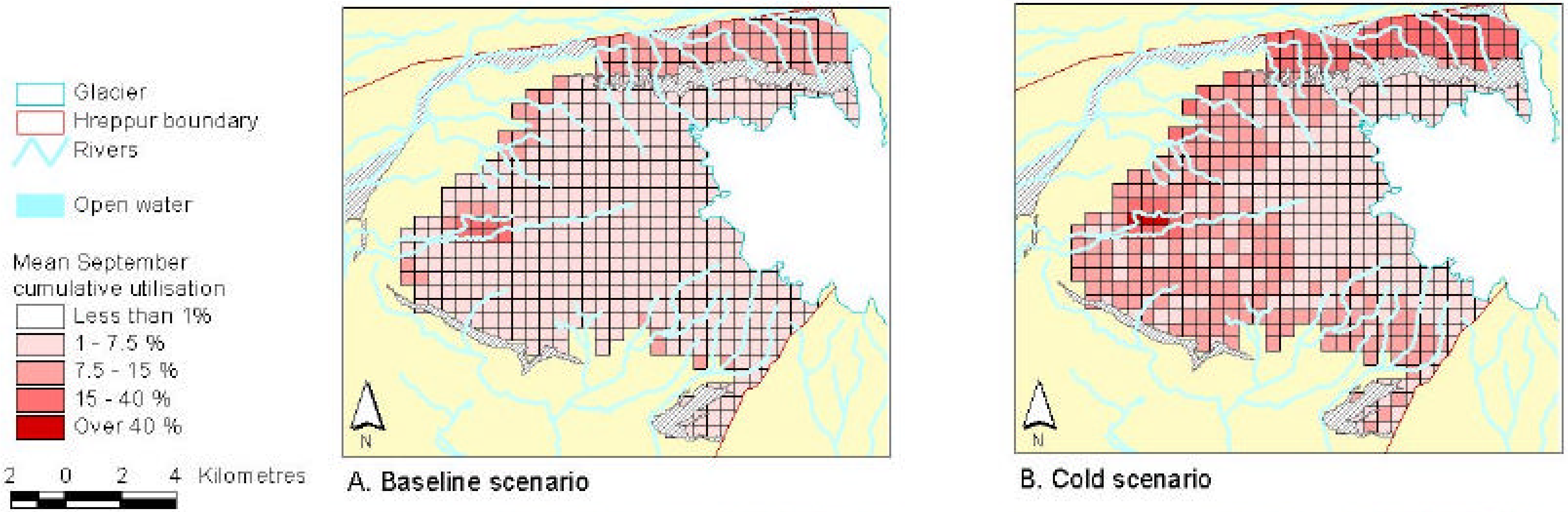
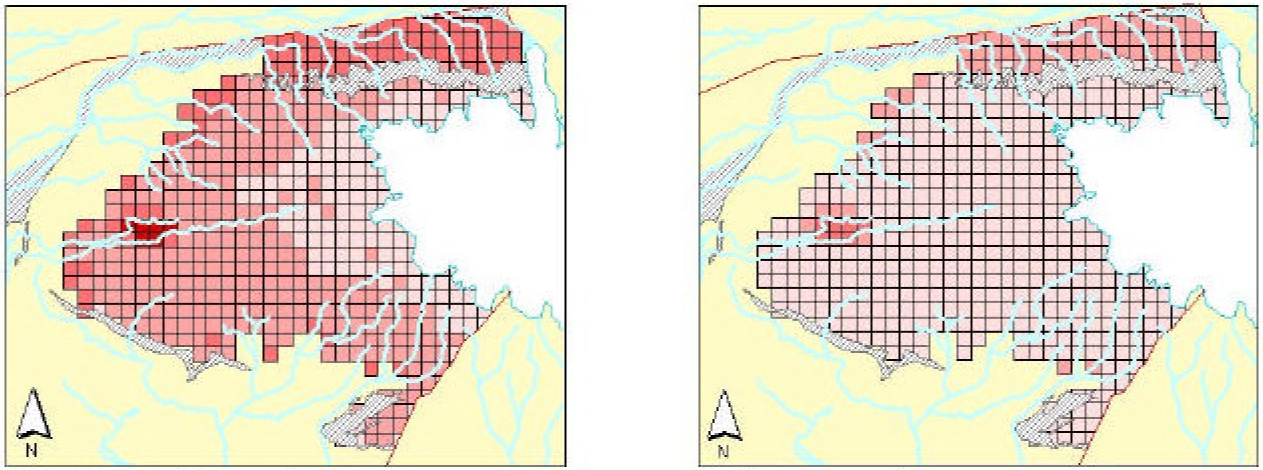


Figure 6-14: Livestock distribution on the rangeland in June and September (Baseline scenario, using 1709 livestock numbers)



A. Baseline scenario

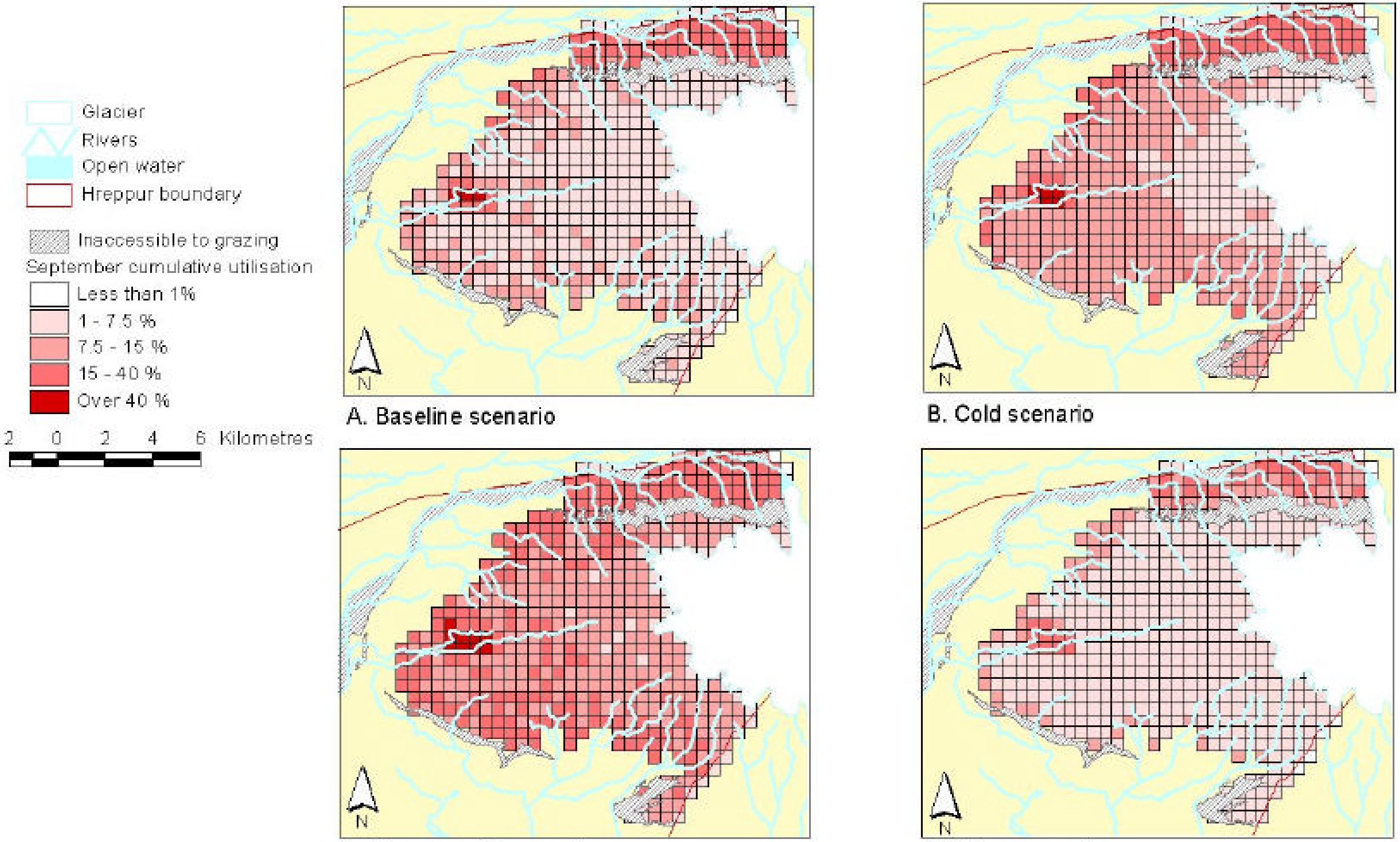
B. Cold scenario



C. Extreme cold scenario

D. Warm scenario

Figure 6-15: Rangeland September cumulative utilisation under different climate scenarios, using 1709 livestock numbers



A. Baseline scenario

B. Cold scenario

C. Extreme cold scenario

D. Warm scenario

Figure 6-16: Upland September cumulative utilisation under different climate scenarios, using adjusted livestock numbers

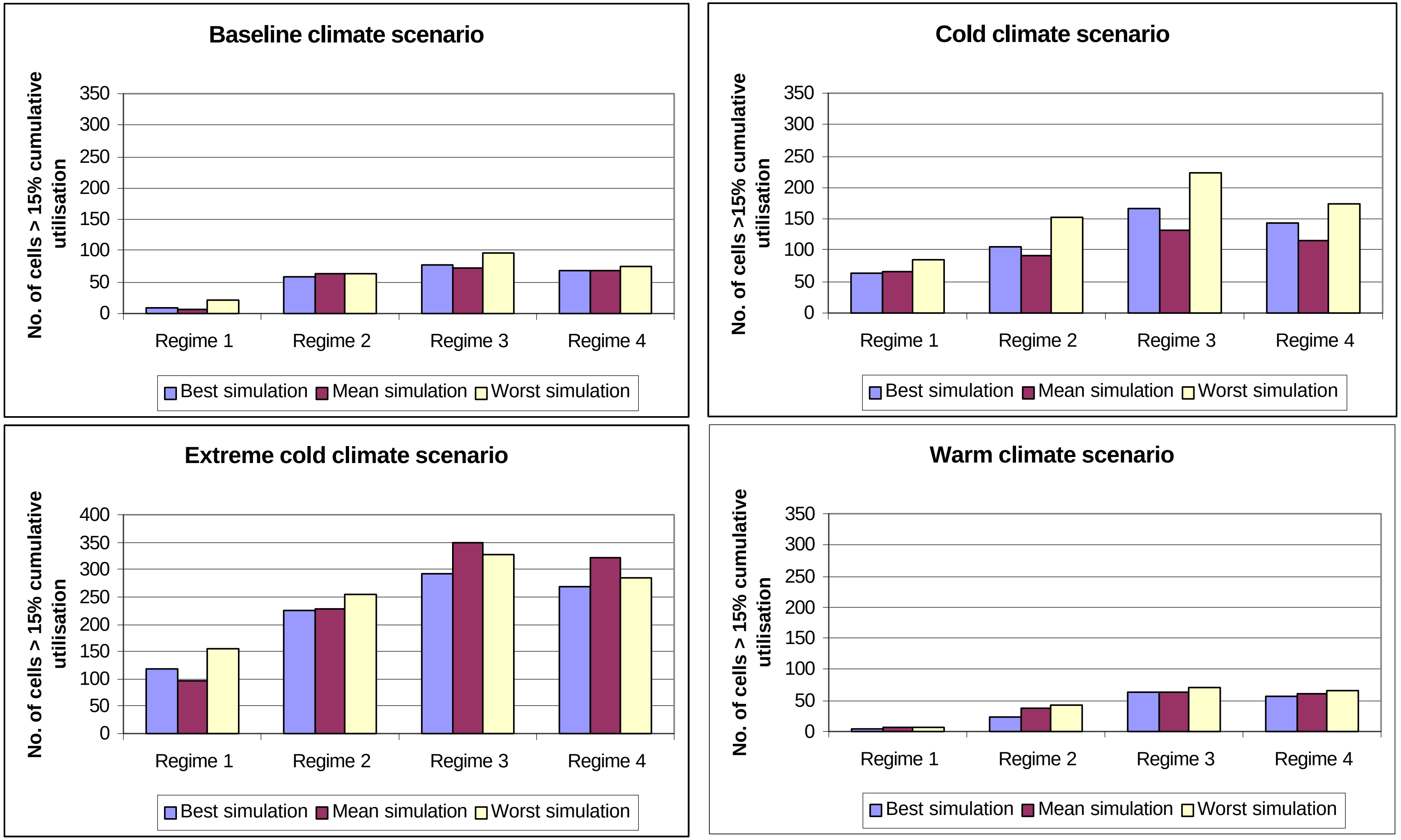


Figure 6-17: Impact of 4 grazing regimes upon the upland area that is vulnerable to over-grazing. (Regime 1: reported livestock, grazing June-September; Regime 2: Adjusted lamb numbers, June-September; Regime 3: Adjusted lamb numbers, May-September; Regime 4: Adjusted lamb numbers, June-October.)

Figures 6-18 and 6-19 show the cumulative utilisation across the outfield in September and April. As the lowland vegetation communities are mainly bog- or grassland-based, they should not suffer the effects of over-grazing below a cumulative utilisation rate of 40%. However, if cumulative utilisation is regularly above levels of 15% then vegetation composition change might occur over long periods. Figure 6-18 shows that under all the modelled climate scenarios the outfield area was capable of supporting the reported livestock in the summer without over-grazing. However, up to 139 cells (19% of the area) were being utilised at rates above 15% in the extreme cold climate scenario, which might lead to grazing damage of shrubs within those cells. Much greater impacts after winter grazing are evident in Figure 6-19. The area of bog west of the Markarfljót is overgrazed under the three coolest scenarios. The lowest levels of cumulative utilisation are evident under the warm scenario, but even then an average of 229 cells (31%) have been grazed beyond the 15% threshold. The level of cumulative utilisation increases under the cooler climatic scenarios: there is an average of 315 cells (43%) above 15% under the baseline scenario; 367 cells (50%) under the cold scenario; and 475 cells (64%) under the extreme cold scenario. A considerable area of land has been grazed beyond the 40% threshold under the extreme cold scenario: 267 cells, or 36% of the outfield area. This indicates the considerable damage to the outfield area that was possible during an extremely cold year if livestock numbers were not adjusted.

6.3.7 Lowland case study area

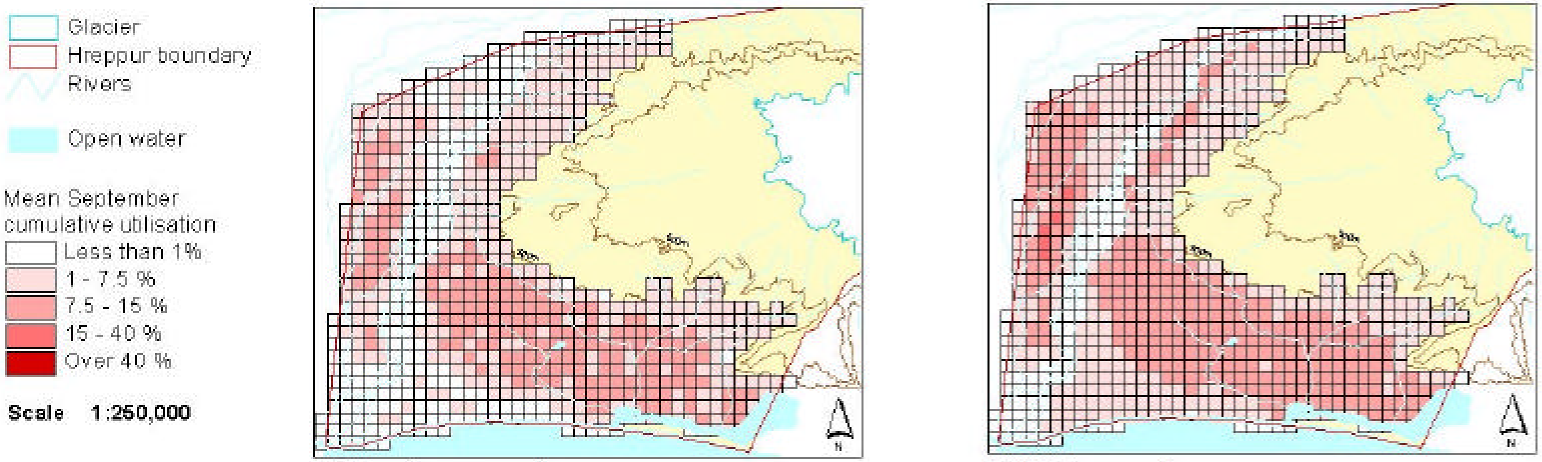
A small area in the northern part of the hreppur was chosen for studying management of the outfield in closer detail. The selected area consists of four farms: Eyvindarholt, Syðstamörk, Miðmörk, and Stóramörk, which are mentioned in both the 1703 and 1709 surveys. They have a well-defined outfield, bounded by rivers to the north and east, and a highland spur to the south. The area is covered by 82 Búmodel cells (1474 ha of grazeable land), and the vegetation is dominated by grassy heathland. The livestock recorded on the farms in 1703 and 1709 are shown in Table 6-7. In the six years between the two surveys, three of the farms (Syðstamörk, Miðmörk, and Stóramörk) changed tenants, and two (Syðstamörk and Stóramörk) were split between two tenants, both with their own livestock. This may account for the increases in sheep and horse numbers between the two surveys, particularly at Stóramörk (see Figure 6-12).

Table 6-7: Recorded livestock numbers in the lowland case study area

Livestock type	June 1703 count	December 1709 count
Dairy cattle	38	35
Non-dairy cattle	28	27
Ewes	156	412
Yearling sheep	76	134
Wethers and rams	39	146
Horses	47	71

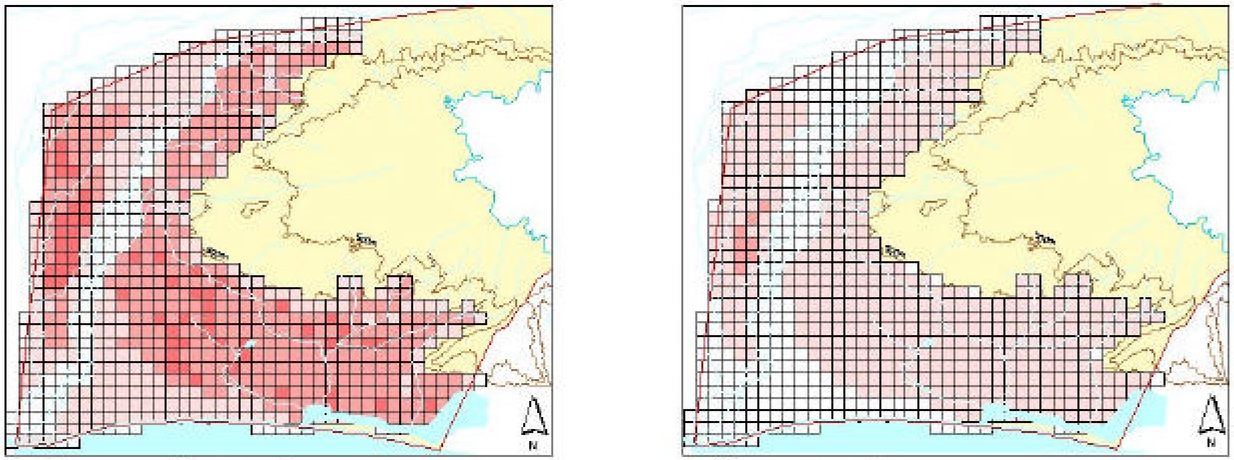
An initial set of simulations was undertaken for both 1703 and 1709 using the reported livestock numbers. The ewes and cattle were assumed to remain on the outfield in summer, with all other livestock going to the communal rangeland. All livestock except the cattle grazed the outfield in winter. As the 1709 census was taken in December and lambs are not mentioned, it is assumed that the recorded yearling ewes and wethers are this year’s lambs that have been retained into the winter. Assuming a lambing percentage of 70%, 412 ewes would produce 288 lambs, so that an estimated 46% of the current year’s lambs are retained after slaughter.

In both years, the outfield was capable of supporting the livestock through the summer without becoming vulnerable to grazing damage (given that the area was predominantly grassland). Nevertheless, grazing pressure was too high under the cooler scenarios as some cells had already been grazed beyond the 15% threshold by the end of September.



A. Baseline scenario

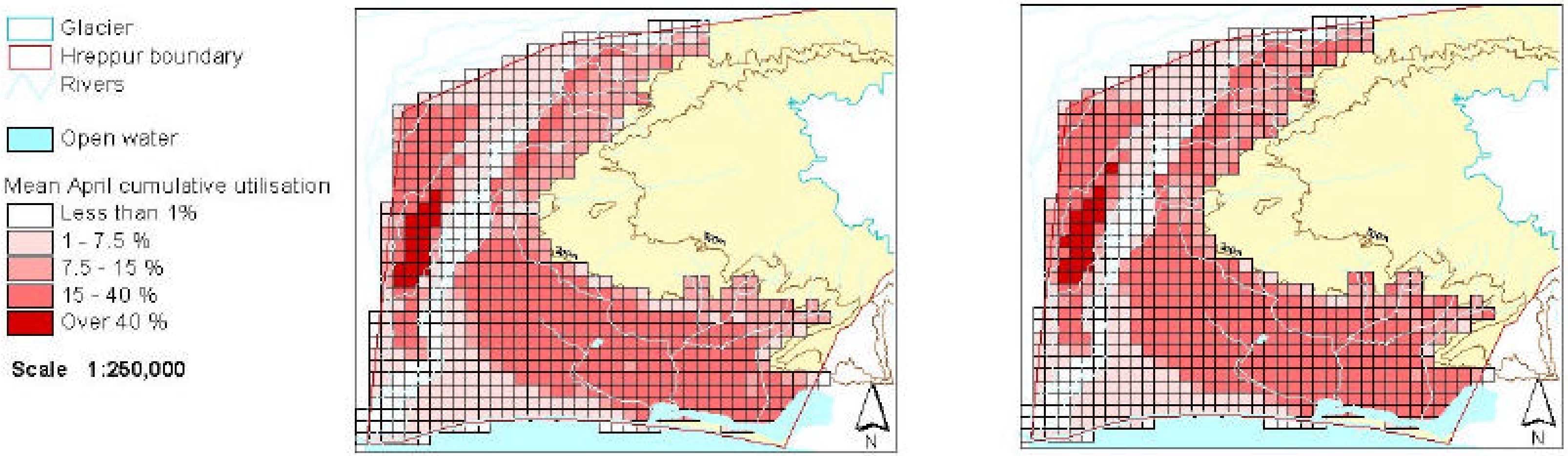
B. Cold scenario



C. Extreme cold scenario

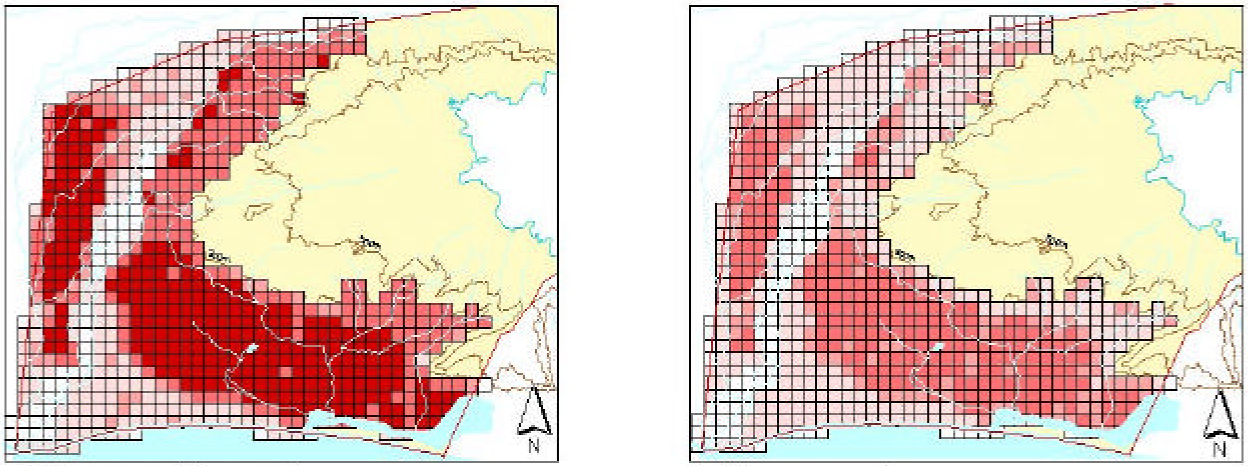
D. Warm scenario

Figure 6-18: Outfield cumulative utilisation in September under different climate scenarios



A. Baseline scenario

B. Cold scenario



C. Extreme cold scenario

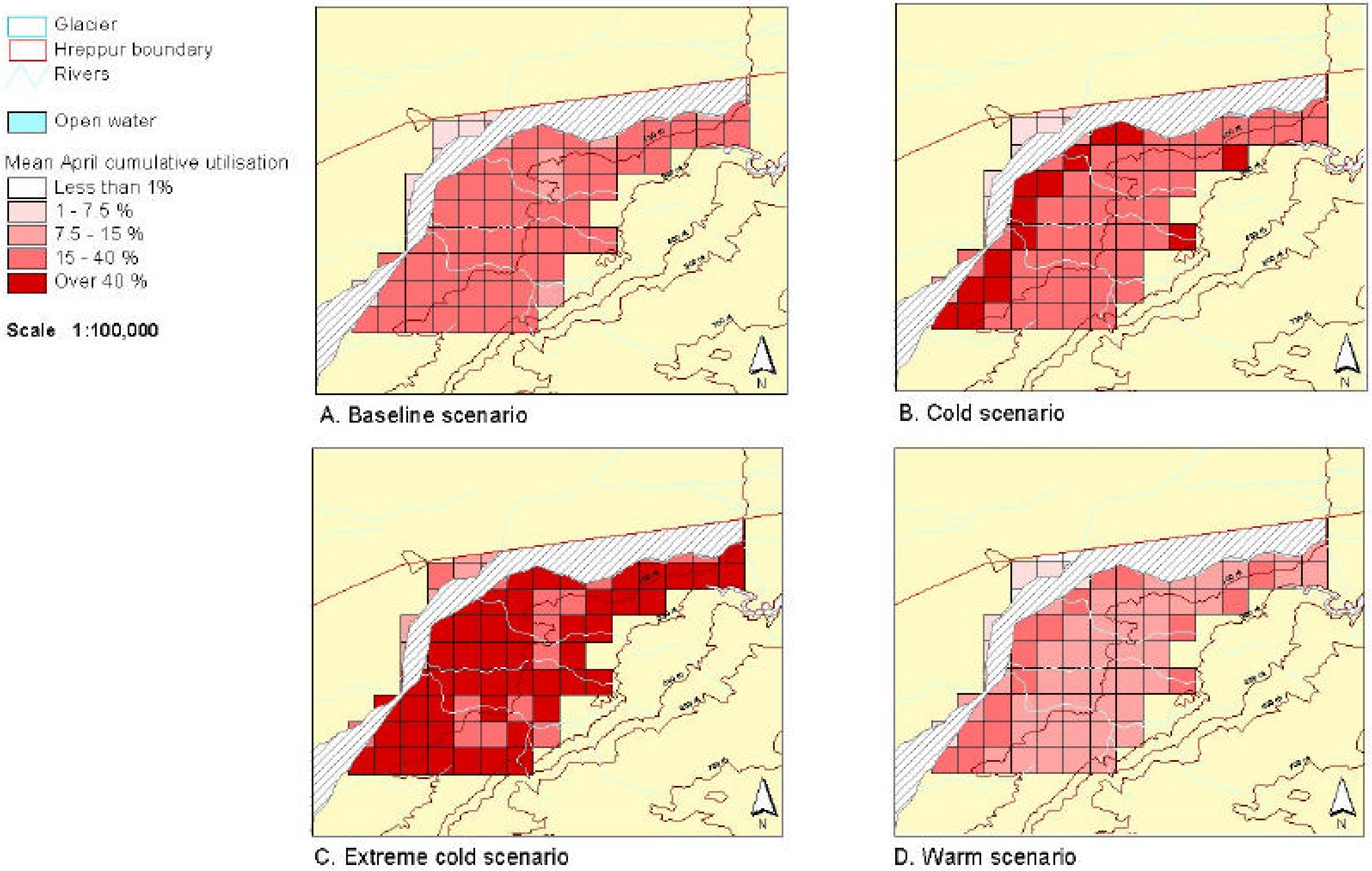
D. Warm scenario

Figure 6-19: Outfield cumulative utilisation in April under different climate scenarios

The impact of additional livestock on the outfield was evident by April in both years (Figure 6-20 and Figure 6-21). The outfield was heavily grazed in all but the warmest scenario: large areas were grazed beyond the 40% threshold in the cold and extreme cold climate scenario in 1703, and also in the baseline scenario in 1709. So heavy was the modelled grazing pressure in 1709, that the model simulation runs actually failed in the cold scenario (in March) and extreme cold scenario (in February), indicating that all available biomass had been removed.

Implementing different management strategies reduces this risk of over grazing considerably in all but the extreme cold scenario. Reducing yearling and lamb numbers to 40% at the autumn slaughter and feeding the non-dairy cattle hay over the winter both reduced utilisation rates by a significant amount (Figure 6-22), although there were still some simulation failures in the extreme cold scenario. Preventing the horses from grazing the outfield in winter had a greater impact, and there were no simulation failures in the extreme cold scenario with this management regime.

The impact of snow cover was not investigated for two reasons: the area most affected would be the upland rangeland, which is assumed to be ungrazed in winter; and the hreppur experiences one of the mildest climates in Iceland so that prolonged snow cover in the lowland is rare. With regard to hay production, it appears that the hay yields recorded in Jarðabók would have been capable of supporting the dairy cattle through the winter, but fodder for the other livestock would have had to be taken from the wet meadow in the outfield. It is known that the farmers in the south of Iceland relied heavily on grazing to see their livestock through the winter, which seems to have been possible in all but the very coldest years.



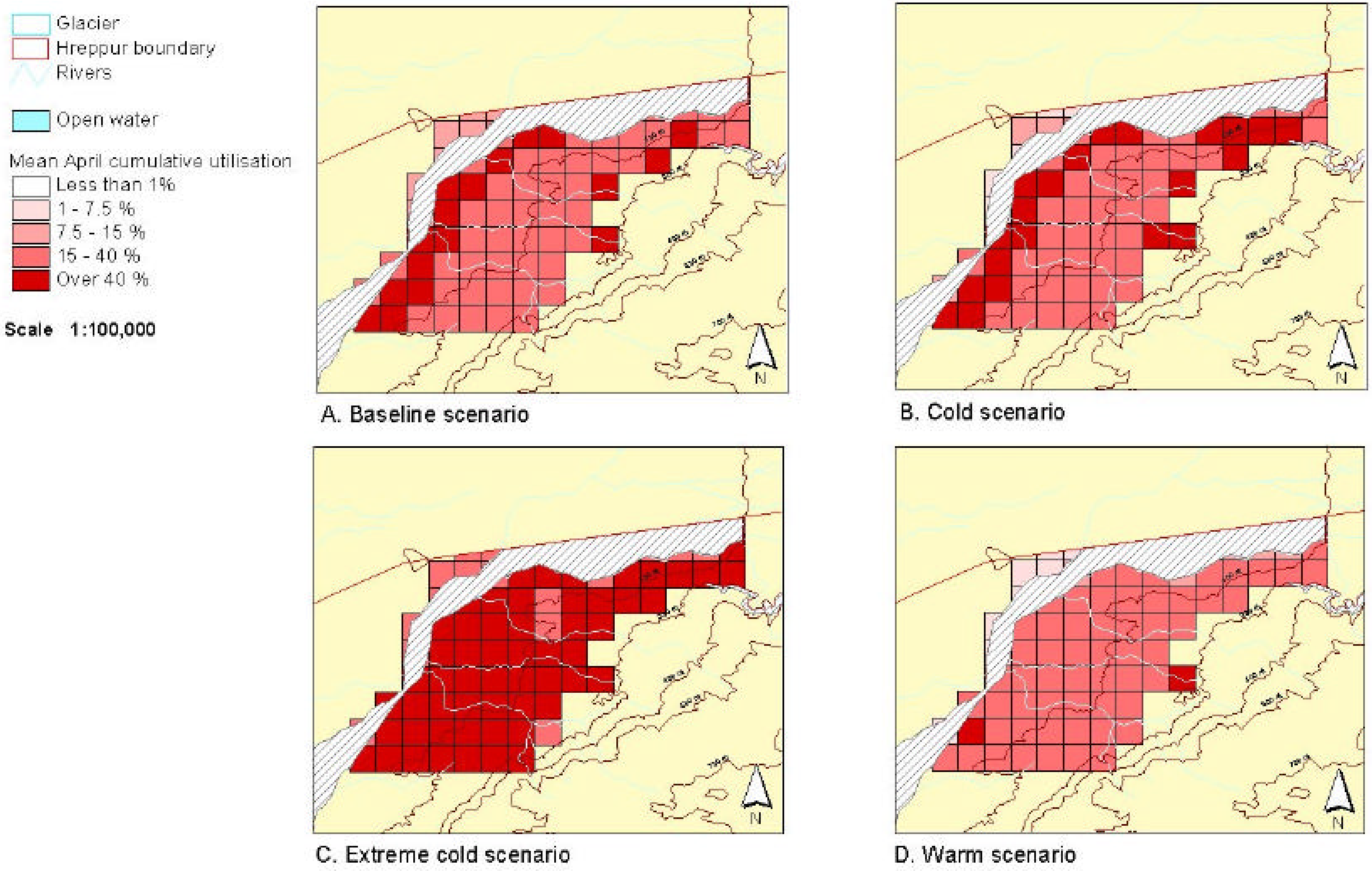
A. Baseline scenario

B. Cold scenario

C. Extreme cold scenario

D. Warm scenario

Figure 6-20: Mean April cumulative utilisation in 1703, with no deliberate management



A. Baseline scenario

B. Cold scenario

C. Extreme cold scenario

D. Warm scenario

Figure 6-21: Mean April cumulative utilisation in 1709, with no deliberate management

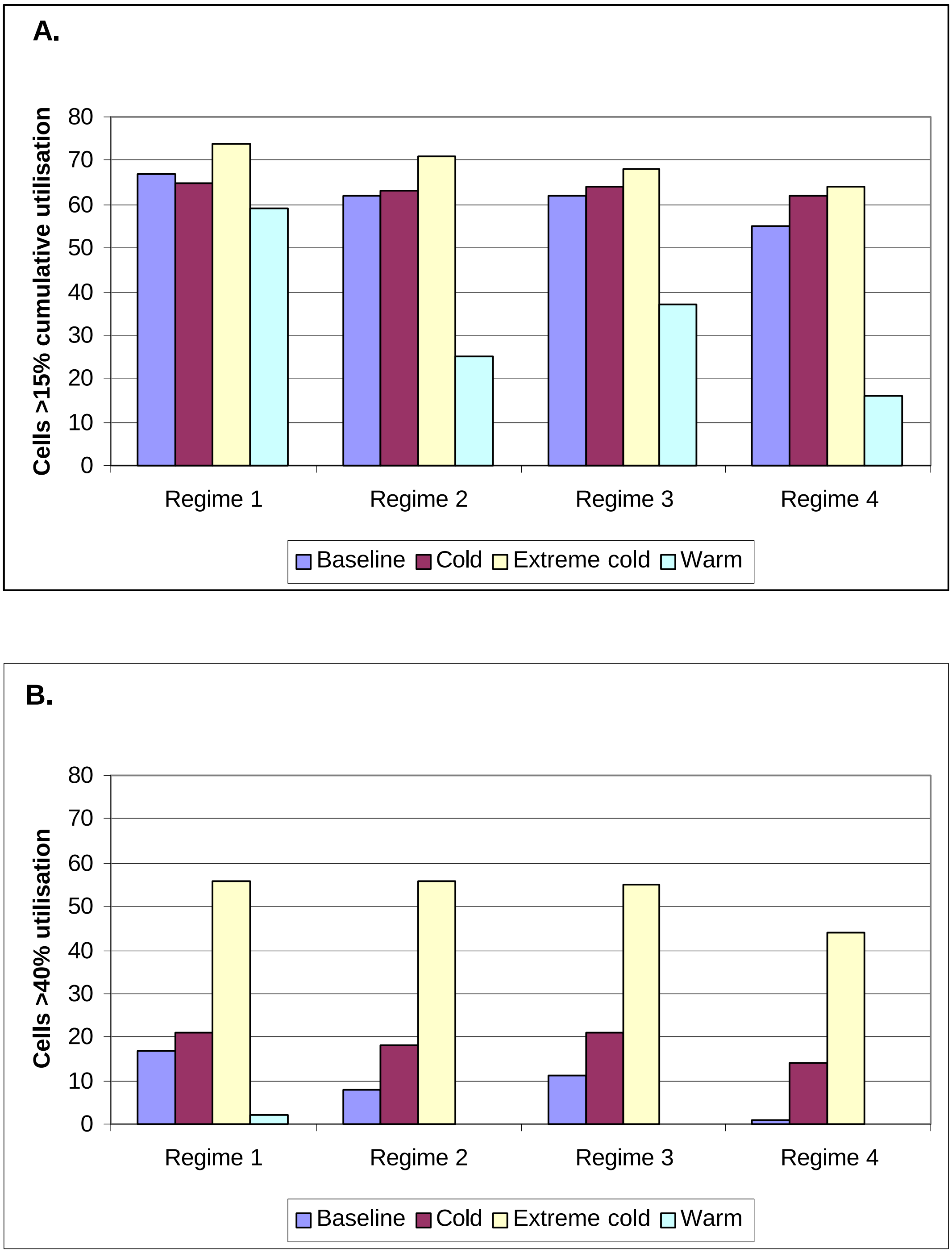


Figure 6-22: The impact of different management regimes upon the number of cells exceeding the cumulative utilisation thresholds (A) 15%, and (B) 40%.

(Grazing regimes in winter: 1) all livestock grazing the outfield apart from cattle; 2. Yearlings and lambs reduced to 40%; 3. Yearlings and lambs reduced and all cattle fed indoors; 4. Yearlings and lambs reduced, cattle fed indoors, horses fed elsewhere.)

6.3.8 Summary of modelling results for Vestur-Eyjafjallahreppur

The potential for grazing in Vestur-Eyjafjallahreppur has been investigated using Búmodel and a reconstructed vegetation cover for 1709. It appears that the estate could support its livestock throughout the year but without careful management the risk of land degradation due to over-grazing was high. It appears that the farmers relied heavily upon fodder harvested from the outfield and upon winter grazing to see their livestock through the winter. The whole hreppur grazing system appears to be operating near its maximum carrying capacity, although there are indications that some farms are operating more sustainably than others. A succession of cold years might well have resulted in serious land degradation in both the lowlands and the uplands.

Chapter 7: Discussion and Conclusions

7.1 Statement of research outcomes

The aim of the research was to define the relationship between patterns of vegetation degradation and seasonal resource use by domestic livestock in Iceland prior to the introduction of modern farming techniques. To achieve this aim, a spatially explicit mathematical simulation model, Búmodel, was created. Búmodel was developed using ecological principles, and was parameterised and validated with data from contemporary Icelandic agricultural research. Model outputs were generated for a single year on a monthly basis, and could be displayed in map form through loose coupling with GIS. The capability of Búmodel as a tool for investigating human-environmental interactions in Iceland was demonstrated by its application, where the management practices of two areas of Iceland were compared during a single time period. These case studies were used to test two hypotheses (discussed below), that had been established from a review of degradation issues in Iceland at the start of the research project.

7.2 Critique of Búmodel

The critique of the model will discuss each of the model components in turn, before a more general discussion of the model structure and its validity. Suggestions are made for possible improvements to the model, but it is recommended that these are only implemented if they will improve model performance.

7.2.1 The vegetation classification

Spatial vegetation cover in Búmodel was divided into eight communities, based upon published Icelandic vegetation classifications and fieldwork by the author. These communities were hayfield, grassy heath, dwarf shrub heath, moss heath, bog/mire vegetation, riverine vegetation, birch woodland and sparsely vegetated land. The communities are intended to primarily reflect differences in grazing potential, based upon the relative palatability of the different plant components (grasses, sedges and rushes, woody species, dicot herbs, mosses and lichens, and ferns and horsetails) within each community. Ecological differences based upon species composition are of less importance in the model.

For Búmodel to be applicable throughout Iceland, and throughout Icelandic history, these Búmodel communities must be representative of the full suite of vegetation communities throughout Iceland, and representative through time. Freshwater vegetation has been omitted from the classification: it may be occasionally grazed but is unlikely to make a major contribution to livestock diet (there is no mention of livestock grazing freshwater vegetation in the Icelandic grazing literature). The Búmodel communities are intended to be representative of vegetation cover at a landscape scale, so some distinct vegetation types that are at a scale of less than 10m have been omitted from the classification (for example snow-bed communities). Some of these localised communities can contain highly palatable species and so may attract higher levels of grazing. However, the variability in plant type composition that is embedded within the Búmodel classification and 25-ha cell structure means that the model can represent such localised variability at the landscape scale, if not at the level of individual cells. Vegetation communities that are unreachable by livestock, such as cliff vegetation, have also been omitted from the classification, as they have zero grazing potential if they are not accessible to grazing.

The applicability of the Búmodel vegetation communities in the past has already been discussed in section 2.4. The classification is applicable during the greater part of the pre-modern period, as the chief ecological disruptions of an anthropogenic origin took place in the two centuries immediately post-Settlement, and thereafter semi-natural vegetation communities can be considered to be similar to those in the modern period. The main gaps in the Búmodel vegetation communities appear at either end of the historic period. In the twentieth century deliberate cultivation became much more widespread, particularly of the lowland grasslands, bogs and hay meadows, which changed the botanical composition, yield and relative palatability of these communities. These differences are readily measurable, and one or more new vegetation communities could be included in the Búmodel classification if the model was to be applied in this time period. Reconstructing the vegetation cover in the very early historic period (9th-12th century AD) using the Búmodel communities is more problematic. There are no longer any areas of vegetation in Iceland that can be said to have been truly free of any anthropogenic impact over the past 1100 years, and so could be representative of the vegetation cover at the time of Settlement. Palynological research indicates a much more extensive cover of woodland at that time, and higher levels of biomass production in the absence of grazing (which is matched by circumstantial evidence from sites that have been ungrazed in the modern period). The Búmodel classification could be adapted to take account of these differences but a large number of assumptions about the structure and composition of the vegetation would be necessary.

There is potential for greater refinement of the Búmodel vegetation classification, although this is dependent upon the availability of research not only on community composition and palatability, but also on the seasonal variation in utilisable biomass. In particular, the research literature suggests a possible split between sloping and level bogs or fens in the bog/mire community. Birch woodland could be differentiated by the composition of its understorey, i.e. whether grasses, dwarf shrubs, or a mixture of both dominate the understorey. At present these potential differences (both in utilisable biomass and palatability) are represented by the large range of possible values in plant type composition. Fieldwork also indicated that the degree of openness in the woodland might affect biomass production in the understorey (possibly caused by the length of time that the woodland has been protected from grazing). There is also potential for the inclusion of a sedge/rush heath community in the classification, although in terms of biomass production and palatability such a category is similar to poor grassy heath. These potential refinements should only be undertaken if they are going to provide better explanations of grazing patterns rather than a more detailed map of the vegetation ecology.

7.2.2 The land use zones and livestock distribution

At present there are three land use zones in Búmodel: tún or hayfield, outfield and rangeland. No grazing is permitted on the hayfield area at any time of year in the present model. However, it is possible that the hayfield may have been grazed during the winter months and this could be incorporated into the model. The inclusion of other management options, such as the use of summer sheilings and shepherding, would also require adaptation of the land use categories. Sheilings were located in the private outfield area rather than the common rangeland and were used during the summer months. Livestock (milking ewes and dairy cows) were kept close to the shieling so that they could be milked regularly. A new land use category, the shieling area, could be defined to allow this concentration of grazing within a restricted area of the outfield during the summer but allowing livestock to freely roam the combined outfield and shieling area during the rest of the year. The issue of modelling shepherding is more difficult, as there is little published information on Icelandic shepherding practice – as most farmers seem to have left livestock to roam freely on the rangeland during the summer. In the Faroe Islands, which also have a history of Norse settlement and agriculture, shepherds moved the sheep herds between different elevations in order to make the best use of young vegetation growth: this may provide an analogy for Icelandic shepherding practices.

The distribution of the livestock within the land use zones could be improved. At present, animals are distributed between the cells of the zone according to the quantity and palatability of the utilisable biomass in each cell. Some form of cell weighting could also be applied to take account of other factors that might influence livestock distribution, such as exposure, cell accessibility, distance from water (thought to be negligible in the Icelandic situation), and the distance from the outfield area or from the dispersion point at the start of the grazing period (for the rangeland zone). (Grágás records livestock being driven to the middle of the afréttur before they were released.) The distribution of livestock on a monthly basis rules out the application of distribution functions based on time periods of a single day, such as random-walk modelling (Turner *et al.* 1994).

7.2.3 The climate scenarios

The four climate scenarios are based on the mean monthly temperature averages of 10 or 30 years. Although they are good representations of the range of annual and seasonal mean values, they do not capture possible variations within each season. For example, in the warm scenario both summer and winter are assumed to be relatively warm compared with the baseline seasonal temperature. Although it would be possible to construct scenarios that captured intra-annual variation, for example by combining a cool summer with a relatively warm winter, related information on the impact of such variation on utilisable biomass production is also required. At present the climatic scenarios have been constructed from only two observational records, one near the south coast (Sámsstaðir) and the other in a central northern area (Reykjahlíð). A more general approach might be to divide the country into zones with similar temperature regimes, and then to reconstruct climate scenarios for each of these zones. Utilisable biomass curves could be developed for each possible scenario: the main difference would be in the length of the growing season, as fieldwork suggested that peak season biomass was actually very similar between vegetation communities in the north and the south. An advantage of the zonal approach would be the ability to include oceanicity and moisture stress as influences on biomass production in certain zones.

7.2.4 The livestock parameters: types and maintenance requirements

Livestock other than sheep need to be explicitly included in Búmodel. Cattle and horses are an important part of the Icelandic agricultural system and at present are only represented as additional numbers of sheep in the model. In the past they were also managed separately from sheep: cattle were kept in the outfield area throughout the year, dairy cattle were over-wintered in byres, and horses might be sent to distant pastures during the winter (as happened in Mývatn hreppur). The impact of these different management strategies could be investigated if dairy cattle, non-dairy cattle and horses could be distributed between the land use zones on a monthly basis in the same way as the sheep cohorts.

The maintenance requirements of cattle and horses are not modelled within Búmodel but this would become necessary if they were to be included in the model. Cattle and horses are much larger animals than sheep and take longer to reach maturity. This might require a greater number of cohorts to be modelled in order to represent fully these livestock, their management and their fodder requirements. Cattle numbers could be assigned to a minimum of five classes: mature dairy cattle, immature dairy cattle, mature non-dairy cattle, immature non-dairy cattle, and calves. Horses could be categorised into mares, stallions/geldings, immature horses and foals. The farm census records in Jarðabók distinguish between livestock of different ages but this level of detail is unnecessary given the scale of the model. The main obstacle to the inclusion of cattle and horses in Búmodel is the paucity of information on their maintenance requirements and grazing habits in comparison to that available for sheep. The use of European breeds as analogies for the Icelandic ones is also difficult. The Icelandic livestock breeds have developed in isolation over a thousand years, and tend to be smaller and hardier than their European equivalents, making comparisons awkward.

Goats and pigs were kept on Icelandic farms in the pre-modern period, although never in such numbers as sheep, cattle or horses. Little is known about their management, and the Icelandic pig breed seems to have disappeared by the 16th century. Pigs are difficult to represent in a grazing model, because they do not graze but root, on which there is very little published information (much of the agricultural literature on pigs is concerned with intensive farming methods). It could be assumed that goats were managed in a similar way to sheep and had similar dietary preferences, but grazing regulations from medieval northern England indicate that goats had a far greater detrimental impact upon trees and shrubs through their habit of browsing and ring-barking (Winchester 2000). The explicit inclusion of pigs and goats into Búmodel would require an expansion in the definition of utilisable biomass to include below-ground biomass and woody material so that the feeding strategies and impact of these animals could be correctly modelled.

Búmodel uses maintenance requirements based on livestock bodyweight to predict vegetation offtake. These requirements represent the minimum level of offtake, as no account is taken of the additional fodder required for weight gain, except in the case of lambs. Although sheep may lose up to 40% of their bodyweight in late winter, no consideration is given to fluctuations in bodyweight at other times of year, which may result in changes in grazing pressure. Fluctuations in bodyweight in the region of 1-2 kg will make little difference to overall offtake. Also in need of further consideration are the fodder requirements of pregnant ewes, which can increase by up to 75% in the final stages of pregnancy, although ewe weight loss in late winter may balance this additional requirement to an extent. The additional feed requirements of lactating ewes have been taken into account in the model.

In the present version of the model the lambing date is fixed on 1st May, whereas a mid-May date may be more representative of Icelandic circumstances. As the model runs on a monthly basis, this should not make a significant difference to the output results. Livestock mortality is not considered (apart from the deliberate slaughter of lambs and wethers in the autumn), although it could be inferred from the failure of a grazing simulation. If the model were to run for a longer period than a single year, then livestock mortality would have to be incorporated into the model. This would also require the model to move livestock between cohort classes, so that this year’s lambs became next year’s yearling sheep, for example.

7.2.5 Vegetation palatability and plant preferences

This sub-model is fairly robust although finer scale discrimination between vegetation communities would be possible if plant palatability could be differentiated between early and late summer, as well as between summer and winter. This would take account of the changes in digestibility of plants as they mature over the growing season. Grazing pressure may modify this change, as there are differences in the palatability of ungrazed plant material and regrowth, particularly for grasses, as regrowth remains highly digestible because the normal process of declining digestibility with maturation has been interrupted.

At present Búmodel assumes constant plant composition within a vegetation community throughout the year. This approach does not consider how the decomposition of annual species (grasses, herbs) may affect the relative proportions of plant types in the community, although winter changes in plant palatability represent some of this shift in composition. Improvements to this aspect of the model would require a greater degree of ecological input.

7.2.6 Utilisable biomass

The utilisable biomass (UB) values used in Búmodel are based on curves of mean monthly UB in the absence of adequate data on production and senescence for each vegetation community. Light grazing has been assumed in the construction of these curves, as there was a greater amount of information available for grazed vegetation communities than for ungrazed. In any case it would be difficult to obtain ungrazed examples of some Búmodel vegetation communities: for example Icelandic grassy heath has been largely created by livestock grazing, and in most cases would undergo vegetation succession if grazing was removed.

The annual UB curves are based on the best available information, but nevertheless it was necessary to estimate the shape and magnitude of the curves in winter, especially for some of the less studied vegetation communities, such as bog/mire and birch woodland. Consultation with Icelandic vegetation experts suggested that these estimates were acceptable and that the stochastic element of UB calculation in the model encompasses the range of possible values.

7.2.7 Incorporating the long-term impacts of climate and grazing

The most obvious development of Búmodel would be to model the long-term impacts of climate and grazing management upon the vegetation cover. This would require the model to run for time periods longer than a single year. The long-term impacts of both climate and grazing can alter the spatial and altitudinal distribution of vegetation communities and the productivity of these communities.

The effects of both grazing and climate occur along a continuum of impacts. Relatively short-term impacts might include the rollover of biomass into the following year as a result of an extended growing season or light grazing in the previous year, which would only affect UB in spring and early summer. On a longer term, a year of overgrazing or a very short and cool growing season (such as occurred in Iceland in 1979) might depress biomass production for several years. On a time-scale of a decade or more, continuous overgrazing or a shift to cooler climatic conditions might result in permanent changes in botanical composition and the initiation and maintenance of erosion. (Changes of a similar magnitude would also occur if grazing was removed or the climate switched towards warmer conditions). Such changes are not necessarily gradual, in fact it is highly likely that shifts in vegetation composition or in the amount of bare ground or erosion occur at thresholds, where grazing pressure exceeds a certain level or has operated for a certain length of time. The timing of the threshold breach is likely to be linked to localised factors and would therefore be hard to predict with a general model.

Expert ecological knowledge would be required to develop Búmodel so that it could model vegetation response to management and climate over long periods of time. It would be necessary to look at the impact of grazing on individual vegetation communities, which might well vary according to the type of livestock doing the grazing. One possibility would be to examine the utilisation of individual plant types within each community, and use rule-based modelling to construct possible trajectories of vegetation change. For example, if the grass component in grassy heath is consistently utilised at levels greater than 40% for a period of five years then a percentage of the grasses in the vegetation community are replaced by less palatable sedges.

There is also the question of how management inputs should be dealt with if the model is simulating long time periods. It would be unrealistic to keep management inputs (livestock numbers, distribution, hay production) constant over the model period, but changing inputs from year to year would also increase running times and the complexity of the model. The model user must be wary of drawing conclusions about the landscape response to management solely from the grazing model, as over long time scales other factors such as volcanic eruptions (which are infrequent but can have catastrophic effects) and social change (for example in land tenure) may assume greater importance.

To summarise, the main obstacle to developing Búmodel for time scales longer than one year is the availability of suitable data. This data is required for formulating relationships of long-term vegetation response to management and climate, for calibrating model parameters, and for validation, so that the model is credible and produces reliable results for scientific hypothesis testing. The best approach might be to run the model over medium time-scales, for example 20 years, in order to examine likely trajectories of change, and how changes in management or climate might affect these trajectories.

7.2.8 Grazing offtake and winter feeding strategies

At present, Búmodel uses a single threshold for each vegetation community to calculate feedback effects of grazing upon utilisable biomass production. These thresholds are based upon the cumulative utilisation, which may not represent the full impact of grazing in the winter and spring months. At these times of year it may be more appropriate to use the monthly utilisation, but there is no information on what the threshold level might be for the initiation of negative feedbacks.

Alternative winter foddering strategies could also be explored, for example the utilisation of seaweed and shrubby fodder. This would require information on the digestibility and dry matter content of these fodders, in order to calculate the quantities necessary to fulfil livestock maintenance requirements. It should also be possible to incorporate supplementary feeding of winter grazing livestock into the model.

7.2.9 Summary of model critique

The objective of Búmodel is to examine spatial and temporal patterns of vegetation utilisation by grazing livestock. These patterns can indicate which areas may be vulnerable to vegetation and soil degradation, and the relative contributions of management and climate to these patterns of utilisation can be discerned. The model achieves its objective by predicting the vegetation biomass production and offtake by livestock. These parameters are predicted at the landscape scale: factors which may influence local concentrations of livestock have not been considered. These factors, for example the location of shelter, streams and tracks, are associated with increased risks of trampling but also increased fertilisation. Búmodel is not a deterministic predictive model; instead it calculates the range of possible outcomes from a single set of inputs, to take account of the inherent variability of natural systems. Búmodel is intended as a simulation of the Icelandic grazing system rather than an ecological model, although every effort has been made to include the appropriate ecological relationships. Despite some simplifications of the ecological relationships in the model, it should be remembered that:

> ‘although it may seem paradoxical, in general, it is not true that good predictions can only be obtained from a model that is mechanistically correct.’ (Rykiel 1996: 234).

Búmodel is intended to be applicable for the whole of Iceland, as it has been constructed using data that had been collected from around the country. Although the modelling focus was upon the two study areas, Eyjafjallahreppur and Mývatn hreppur, the model correctly predicted utilisable biomass and offtake for a site, Auðkúluheiði, outwith the study areas. It is recommended that further validation is undertaken if the model is to be applied to areas where the climatic conditions are likely to be significantly different from the rest of mainland Iceland, for example the Westmann Islands, or the extreme north-west peninsula.

The scope of Búmodel could be extended in a number of ways, which have been discussed in sections 7.2.1 to 7.2.8. The biggest obstacle to the further development of the model is the availability of scientific data that can be used to parameterise and calibrate the model and independent data sets against which the model can be validated.

7.3 Discussion of the hypotheses

The hypotheses were designed as tests of Búmodel's applicability to questions concerning historic grazing patterns. By using two contrasting study areas and a tightly bounded period in the early eighteenth century it is possible to look at changes in farm management and their possible impacts at a fine level of spatial resolution. By using a modelling approach multiple ideas can be tested and the range of possible responses to changes in management and climate can be thoroughly investigated.

Two historical documentary sources have been used to obtain livestock and management inputs for the two study areas, Vestur-Eyjafjallahreppur and Hofstaðir in Mývatn hreppur. These sources are the 1703 church livestock register (Vésteinsson, *pers. comm.*) and the 1706-1714 national farm census, Jarðabók (Magnússon and Vídalín 1913-1990), which is published in Icelandic (the translation of the Hofstaðir entry was done by Ragnar Edvardsson, and the Vestur-Eyjafjallahreppur entries were translated by the author). Historical documentary evidence must be analysed carefully, in order to avoid errors of misinterpretation. The two livestock surveys have been cross-checked against each other: it was thought that farmers might have under-reported livestock in Jarðabók (due to fears of increased taxation), but in general herds either remained at similar levels or increased in size between 1703 and 1709/1712. Individual livestock cohorts and survey dates are reported in both surveys, which aids interpretation. Jarðabók livestock numbers have been crosschecked against other translations (Amorosi *pers. comm.*, Vésteinsson *pers. comm.*).

7.3.1 Hypothesis one

The first hypothesis was that natural biomass production during the pre-modern period was sufficient to support the numbers of livestock indicated by historical data. This hypothesis has been tested using Búmodel to investigate patterns of vegetation biomass utilisation under four different climate scenarios defined from long meteorological observation records. The four scenarios (baseline, cold, extreme cold, and warm) span the range of temperature regimes found in Iceland over the past 150 years, and are assumed to be representative of the climatic range throughout the historical period in Iceland.

On the Hofstaðir estate there was sufficient vegetation to support the reported livestock numbers throughout the year, although it is probable that the farmers made use of the communal rangeland south of the lake during the summer months. Even if the winter grazing area was reduced by snow and ice cover in winter there was sufficient biomass available for the livestock. In Vestur-Eyjafjallahreppur there was also sufficient vegetation biomass to support reported livestock numbers if both the outfield and the communal rangeland were used.

However, even though the pastures in both study areas *could* support livestock under all climate scenarios, it seems that significant grazing damage was likely to occur without careful livestock management, particularly under the cooler climate scenarios. The pastures used for winter grazing were more vulnerable than those that were grazed only during the summer. On average the growing season in Iceland lasts for five months (May to September) in the lowlands, during which time sufficient utilisable biomass must be produced to sustain grazing for the remaining seven months of the year. Grazing has a greater impact in winter because no new production is being added to the pool of available biomass. The average palatability of the vegetation is also reduced so livestock have to consume more in order to fulfil their dietary requirements (these requirements increase in winter due to the harsher grazing conditions). The pastures in the southern study area seem to have been more vulnerable to over-grazing than those in the northern area: as values of annual cumulative utilisation and winter monthly utilisation were higher, and a greater proportion of the area was grazed beyond the feedback thresholds of 15% and 40%.

7.3.2 Hypothesis two

The second hypothesis was that alternative land management strategies could have maintained livestock numbers and vegetation cover, whilst avoiding extensive erosion and land degradation. The strategies that were used in Iceland can be derived from the historical literature and include reducing the numbers of livestock in winter, grazing horses on communal winter pastures, supplementary feeding of livestock with fodder from the tún or from the outfield, shepherding and shieling activity. Reducing livestock numbers in the autumn ensured that there were sufficient grazing and fodder stocks for the remaining animals. They were then likely to survive winter in better condition: in the case of pregnant ewes, this would result in a higher spring birth and lamb survival rates, so that overall herd size was maintained. Grazing horses in communal winter pastures reduced grazing pressure on individual farm outfields. It is also unlikely that many horses were required during the winter months because of the difficulty of travel as a result of snow cover, stormy weather and high river levels. Livestock might be fed fodder from the tún or the outfield in addition to winter grazing. Hay harvesting was labour intensive and the hreppur system of mutual support seems to have been a disincentive to farmers stockpiling hay for cold winters. Fodder from the outfield would also have been of poorer quality than that from the tún, so livestock would have needed to consume more in order to meet their maintenance requirements. It is also likely that outfield fodder was more difficult to dry and store properly. Shepherding and shieling activity might mitigate overgrazing by distributing livestock more evenly in the landscape, but their impact has not been investigated in this project.

In testing this hypothesis, the differences between the two study areas became obvious. The Jarðabók record for Hofstaðir gives a general impression of a farm that was not experiencing difficulties in supporting its livestock and inhabitants, whereas the records from Vestur-Eyjafjallahreppur paint a much more gloomy picture, with mention of destroyed pastures and farm abandonment. These differences are reflected in the cumulative and monthly utilisation modelling results, as farming at Hofstaðir seems to be much more sustainable than farming in the southern hreppur. This may be related to the relative condition of the two areas in the early eighteenth century: Simpson *et al.* (in press) demonstrate by sedimentary analysis that the landscape on the Hofstaðir estate was more stable during this period, with lower levels of inferred erosion than the regional average, whereas Vestur-Eyjfjallahreppur was already significantly degraded, and the inferred erosion rates increased during the 18th and 19th centuries (Dugmore and Erskine 1994).

At Hofstaðir the cumulative utilisation of biomass is generally below threshold levels. In fact, the numbers of livestock grazing the estate during the summer could have been increased by 25% without increasing the risk of grazing damage. Nevertheless, without proper management it was possible that grazing damage to dwarf shrubs might have occurred during cold winters, particularly if snow cover persisted for long periods of time, thus increasing grazing pressure on snow-free areas. Even under these conditions the risk of overgrazing seems to be relatively small as average monthly utilisation figures in late winter and early spring are low (<5%). Grazing damage could have been avoided entirely in the colder winters if the numbers of lambs and wethers were reduced by 30-50% and/or the remaining animals were given supplementary fodder. This fodder could have been harvested from the wet meadow on the banks of the Laxá close to the farmstead: approximately 2.7 ha would have had to be harvested in order to feed the entire sheep flock for a single month. Given that these strategies were feasible, the second hypothesis holds true for the Hofstaðir estate.

In Vestur-Eyjafjallahreppur, the rangeland communal pastures, which consist mostly of dwarf shrub heath and sparsely vegetated land, are at risk of overgrazing under the cold and extreme cold scenarios, and there is a risk of damage on the bog area on the rangeland under the two warmer scenarios. The lambs, yearlings and wethers grazed the rangeland for four months in the summer, from June to September. The best way of avoiding grazing damage on the upland area would be to reduce absolute numbers of livestock, reduce the grazing period or to utilise other areas for summer grazing. Overgrazing could have been reduced in the warmer scenarios by shepherding, as the distribution of livestock is very patchy, with high concentrations on a few areas. Shortening the grazing season on the rangeland or reducing the numbers of livestock that grazed there would have placed additional grazing pressure on the lowland outfield pastures. The Þórsmörk region east of Eyjafjallahreppur may have provided some additional grazing land, as there were no permanent farms there in the early eighteenth century. Any livestock left to graze this area would probably have required shepherding, as Þórsmörk is wooded and very hilly, and livestock could easily have been lost. It is also hard to access, being fourteen kilometres from the nearest farm (Stóramörk), with several glacial rivers to cross.

The outfield of Vestur-Eyjafjallahreppur was capable of supporting recorded livestock numbers in the summer, but there was a high risk of overgrazing in the winter. If the entire hreppur flock was grazed on the outfield in winter without supplementary feeding under the extreme cold climate scenario, then over a third of the outfield was utilised to levels above the 40% threshold, indicating extensive grazing damage. There was sufficient tún hay to feed all of the dairy cattle on the hreppur, but it would have been necessary to harvest fodder for non-dairy cattle and other livestock from the wet meadow in the outfield. In order to feed the numbers of reported sheep and non-dairy cattle on the hreppur for a single month, 121 ha of the outfield would have needed to be harvested for hay. If the horses on the hreppur were also fed then an additional 111 ha would have needed to be harvested.

A case study area consisting of four farms in the north of the hreppur was used to investigate the impact of alternative management strategies upon grazing patterns. (Modelling of the entire hreppur area was not undertaken because the simulation runs were extremely time-consuming.) The case study area had a high risk of winter grazing damage when there was minimal management. However, reducing lamb and yearling numbers in autumn and hay feeding of non-dairy cattle over winter lessened this risk (particularly above the critical 40% threshold) under the baseline and warm scenarios. Removing the horses from the outfield in winter (as happened in the Mývatn study area) had the greatest impact, but even then a large number of cells were at risk of overgrazing (above 40%) under the extreme cold scenario.

It seems that the second hypothesis cannot be proved for the southern study area unless winter pastures outwith the hreppur are being utilised or there is a high level of supplementary winter-feeding (which the historical evidence would indicate is not the case). The pastures of Vestur-Eyjafjallahreppur were already in poor condition by the early 1700s, so further degradation could only be avoided by a substantial reduction of livestock numbers or a substantial increase in supplementary winter feeding. This conclusion is based upon the historical information and a vegetation reconstruction that assumes a large percentage of bare ground in both the lowland and upland areas. It is also possible that the years prior to the Jarðabók survey had been particularly advantageous for grazing in this region, and therefore the hreppur pastures could support a higher number of livestock than would be the case in colder years.

7.3.3 The social aspects of land degradation

The issues raised by the model application to the two study areas suggest that there is potential for collaboration with historians and archaeologists to investigate the social and political aspects of land degradation in Iceland. The use of the historical livestock surveys in conjunction with the environmental model would allow the investigation of different farm optimisation strategies – were farmers trying to optimise livestock numbers or cash income (through the production of butter and homespun cloth), or were they trying to minimise labour inputs and land degradation? It would also be possible to examine the margins for error in farm survival and long-term sustainability by investigating the balance between livestock numbers and additional sources of subsistence such as fishing and bird or egg collecting.

In Vestur-Eyjajfallhreppur a large number of the farms appear to have changed tenants between 1703 and 1709 (16 out of the 26 recorded in both surveys). This applied to both large and small farms, and there was no discernible relationship between herd size and changing tenants, as some farms increased their herds between 1703 and 1709, and others reduced them. Large farms tended to be owned by institutions (the Church or the Crown) or by members of the social hierarchy (priests or sheriffs). These larger farms also tended to be more capable of producing hay to feed both their dairy cattle and additional livestock over the winter, but some smaller farms also had hay surpluses. The provision of labour for mowing was one of the tenant obligations frequently mentioned in the Jarðabók record for the hreppur, along with the requirement to lend horses to the landowner. These obligations might place an additional burden upon small tenant farms that were already suffering from environmental stress. The cattle rental value (leigukúgildi) and the land rental value appear to have been proportional to each other, so there is no indication that smaller farms were adversely burdened in comparison to larger ones.

It is difficult to draw out any distinctive social aspects to the situation at Hofstaðir without comparison with other farms in Mývatn hreppur. The farm appears to have been well managed, and there are indications that the estate was in good condition compared to the hreppur as a whole (Simpson *et al.*, in press). It might even have been possible for the estate to take in extra animals from other farms during the summer months without damage to its grazing area.

7.4 Contribution to wider disciplinary fields

7.4.1 Contribution to human and landscape ecology

Búmodel enables ecologists, archaeologists and historians to investigate the flexibility in the Icelandic agricultural system given the limitations of climate and vegetation cover. It provides an environmental science-based counterpoint to the work by Daniel Vasey in Iceland on human buffering mechanisms (Vasey 1996). The model enables the testing of ideas of historical contingency – were the historical outcomes that are visible in the landscape and in the archaeological record (such as farm abandonment, vegetation change and soil erosion) inevitable given the environmental and social constraints in the past, or were they avoidable? Such constraints seem to be visible in the contrasts between Hofstaðir and Vestur-Eyjafjallahreppur, where the initial condition of the landscape was an important regulator of livestock numbers and the potential for further degradation. Búmodel also enables the investigation of 'what-if' scenarios, so the changes necessary to avoid degradation can be explored.

The development of Búmodel has produced a methodology and model framework that could be applied to other extensive livestock-based agricultural systems, both in other North Atlantic islands such as the Faroes and Greenland, and elsewhere in mainland Europe. This methodology provides a way of synthesising the available information for a landscape, both from historical and archaeological sources (farm location, livestock numbers and management practices) and from environmental sources (palynology, soil sediment analysis and climate history). This holistic approach, which combines both spatial and temporal perspectives, gives a broader view of human and environmental interactions in the past and their impact upon the landscape.

7.4.2 Contribution to agriculture

Búmodel combines current agricultural knowledge into a spatially based stochastic simulation model, something that was not previously available for the Icelandic ecosystem. Although Búmodel has been constructed for use in a pre-modern context, it would be relatively simple to adapt it for modern circumstances. It would be necessary to modify the livestock inputs of the model to take account of higher lambing percentages and growth rates, and to adapt the lowland vegetation types to take account of changes in fertilisation, drainage and reseeding.

The model provides a way of exploring the impacts of management decisions in both the present and the past. In particular it could be used for establishing suitable stocking rates on rangeland, as fixed carrying capacities are of limited use when vegetation distribution is spatially heterogeneous, variable throughout the year, and highly responsive to climatic variability. Búmodel could be used to anticipate which areas of vegetation would be most vulnerable to overgrazing, and the vegetation response to management measures such as enclosure. It could also be used to develop management plans for dealing with scenarios such as extremely cold weather conditions or loss of pasture.

Finally, the construction of the model has brought to light certain areas where the currently available research is either inadequate or absent. In particular, more research is needed on the relationship between precipitation and vegetation growth, particularly as it is likely that the North Atlantic region will become wetter and stormier according to current models of climate change. Another area in need of further research is the feed unit value of different vegetation types and its seasonal variability.

7.5 Conclusions

This research into farm management and vegetation degradation in pre-modern Iceland has resulted in the development of a new tool, Búmodel, for the investigation of human and environmental interactions in a livestock-based agricultural setting. The model has been constructed using Icelandic historical and agricultural information. It has been validated for use in the Icelandic context through consultation with Icelandic experts and through a validation exercise on an independent contemporary grazing experiment in the central northern region of Iceland. The application of the model to questions of livestock and vegetation management in the past has been demonstrated by its application to two contrasting study areas in the south and north of Iceland.

Chapter 8: Reference List

Aðalsteinsson, S., 1990. Importance of sheep in early Icelandic agriculture. *Acta Archaeologica*, **61**, p. 285-291.

Amorosi, T., 1992. Climate impact and human response in northeast Iceland: archaeological investigations at Svalbarð, 1986-1988. In: Morris, C.D. and Rackham, D.J. (eds.) *Norse and later settlement and subsistence in the north Atlantic*. University of Glasgow: Department of Archaeology, p. 103-138.

Amorosi, T., Buckland, P.C., Dugmore, A.J., Ingimundarson, J.H. and McGovern, T.H., 1997. Raiding the landscape: human impact in the Scandinavian north Atlantic. *Human Ecology*, **25**(3), p. 491-518.

Amorosi, T., Buckland, P.C., Edwards, K.J., Mainland, I., McGovern, T.H., Sadler, J.P. and Skidmore, P., 1998. They did not live by grass alone: the politics and palaeoecology of animal fodder in the North Atlantic region. *Environmental Archaeology,* **1**, p. 41-54.

Archer, S. and Arnalds, A., 1982. Spring grazing on Icelandic rangelands: a review of factors to consider. *Íslenzkar Landbúnaðarrannsóknir* **14**(1-2), p. 55-68.

Archer, S. and Tiezen, L.L., 1980. Growth and physiological responses of tundra plants to defoliation. *Arctic and Alpine Research,* **12**(4), p. 531-552.

Archibold, O. W., 1994. *Ecology of world vegetation*. London: Chapman and Hall.

Armstrong, H.M., Gordon, I.J., Grant, S.A., Hutchings N.J., Milne, J.A. and Sibbald, A.R., 1997a. A model of the grazing of hill vegetation by sheep in the UK I: the prediction of vegetation biomass. *Journal of Applied Ecology,* **34**, p. 166-185.

Armstrong, H.M., Gordon, I.J., Hutchings, N.J., Illius, A.W., Milne, J.A., and Sibbald, A.R., 1997b. A model of the grazing of hill vegetation by sheep in the UK II: The prediction of offtake by sheep. *Journal of Applied Ecology,* **34**, p. 186-207.

Arnalds, Ó., 1984. Eolian nature and erosion of some Icelandic soils. *Íslenzkar Landbúnaðarrannsóknir*, **16**(1-2), p. 21-35.

Arnalds, Ó., 1990. Characterization and erosion of Andisols in Iceland. Ph.D. thesis. Texas A&M University.

Arnalds, Ó., Aradóttir, A.L. and Thorsteinsson, I., 1987. The nature and restoration of denuded areas in Iceland. *Arctic and Alpine Research*, **19**(4), p. 518-525.

Arnalds, Ó., Þorainsdóttir, E.Þ., Metusalemsson, S., Jonsson, A., Gretarsson,E. and Arnason, A., 2001. *Soil erosion in Iceland*. Reykjavík: Soil Conservation Service, Agricultural Research Institute, Iceland.

Arnold, G. W. and Dudzinski, M.L., 1978. *The ethology of free-ranging domestic animals*. Oxford: Elsevier.

Ball, A. J., Thompson, J.M., Alston, C.L., Blakely, A.R. and Hinch, G.N., 1998. Changes in maintenance requirements of mature sheep fed at different levels of feed intake at maintenance, during weight loss and realimentation. *Livestock Production Science*, **53**, p. 191-204.

Barker, J.C. and Walls, F. W., 2002. *Livestock manure production rates and nutrient content*. URL: http://ipmwww.ncsu.edu/agchem/chptr10/1011.pdf [4th March 2002].

Barlow, L. K., Sadler, J.P., Ogilvie, A.E.J., Buckland, P.C., Amorosi, T., Ingimundarson, J.H., Skidmore, P., Dugmore, A.J. and McGovern, T.H., 1997. Interdisciplinary investigations of the end of the Norse Western Settlement in Greenland. *The Holocene*, **7**(4), p. 489-499.

Bart, J., 1995. Acceptance criteria for using individual-based models to make management decisions. *Ecological Applications*, **5**(2), p. 411-420.

Bergþórsson, P., 1969. An estimate of drift ice and temperature in Iceland in 1000 years. *Jökull*, **19**, p. 94-101.

Bergþórsson, P., 1985. Sensitivity of Icelandic agriculture to climatic variations. *Climatic Change*, **7**, p. 111-127.

Bergþórsson, P., Björnsson, H., Dýrmundsson, Ó., Gudmundsson, B., Helgadóttir, Á. and Jónmundsson, J.V., 1987. The effect of climatic variations on agriculture in Iceland. In: Parry, M.L., Carter, T.R. and Konijn, N.T. (eds.) *The impact of* *climatic variations on agriculture. Volume 1: Assessment in Cool Temperate and Cold Regions*. Dordrecht: IIASA and UNEP, p. 387-444.

Biot, Y., 1993. How long can high stocking densities be sustained? In: Behnke, R.H., Scoones, I. and Kerven, C. (eds.) *Range ecology at disequilibrium: New models of natural variability and pastoral adaption in African savannas*. London: Overseas Development Institute, p. 153-172.

Bjarnarson, A. H., 1978. Erosion, tree growth and land regeneration in Iceland. In: Holdgate, M.W. and Woodman, M.J. (eds.) *The breakdown and restoration of ecosystems*. London: Plenum Press, p. 241-248.

Björnsson, H. and Helgadóttir, Á., 1988. The effect of temperature variation on grass yield, and the implication for dairy farming. In: Parry, M.L., Carter, T.R. and Konijn, N.T. (eds.) *The impact of climatic variations on agriculture. Volume 1: Assessment in Cool Temperate and Cold Regions*. Dordrecht: IIASA and UNEP, p. 445-74.

Blaikie, P. and Brookfield, H., 1987. *Land degradation and society*. London: Methuen.

Borchgrevink, A-B. Ø., 1977. The *Seter* areas of rural Norway. A traditional multi-purpose resource. *Northern Studies,* **9**, p. 3-24.

Brady, N.C. and Weil, R.R., 1999. *The nature and properties of soils*. New Jersey: Prentice Hall, 12th edition.

Briggs, D.J. and Courtney, F.M., 1985. *Agriculture and environment. The physical geography of temperate agricultural systems.* London: Longman.

Broad, H. J. and Hough, M.N., 1993. The growing and grazing season in the United Kingdom. *Grass and Forage Science,* **48**, p. 26-37.

Buckland, P. and Dugmore, A.J., 1991. 'If this is a refugium, why are my feet so bloody cold?'. The origins of the Icelandic biota in the light of recent research. In: Maizels, J.K. and Caseldine, C. (eds.) *Environmental change in Iceland: past and present*. Dordrecht: Kluwer, p.107-126.

Buckland, P.C., Dugmore, A.J., Perry, D.W., Savory, D. and Sveinbjarnardóttir, G.,

1991. Holt in Eyjafjallasveit, Iceland: A paleoecological study of the impact of Landnám. *Acta Archaeologica*, **61**, p. 252-270.

Butlin, R. A. and Roberts, N. (eds.), 1995. *Ecological relations in historical times. Human impact and adaptation.* Oxford: Blackwell.

Byock, J., 1993. *Medieval Iceland. Society, saga and power*. Middlesex: Hisarlik Press.

Byock, J., 2001. *Viking age Iceland*. London: Penguin.

Crawley, M., 1997. Plant-herbivore dynamics. In: Crawley, M. (ed.) *Plant ecology.* Oxford: Blackwell Science, 2nd edition, p. 401-474.

Crumley, C.L., 1994. Historical Ecology: a multidimensional ecological orientation. In: Crumley, C.L. (ed.) *Historical ecology: cultural knowledge and changing landscapes.* Santa Fe, New Mexico: School of American Research Press, p. 1-13.

Dansgaard, W., Johnsen, S.J., Reeh, N., Gundestrup, N., Clausen, H.B. and Hammer, C.U., 1975. Climatic changes, norsemen and modern man. *Nature,* **255**, p. 24-28.

Davidson, D. A. and Simpson, I.A., 1999. The time dimension in landscape ecology: cultural soils and spatial pattern in early landscapes. In: Wiens, J.A. and Ross, M.R. (eds.) *Issues in landscape ecology: proceedings of the International Association for Landscape Ecology Fifth World Congress*. Colorado, USA: International Association for Landscape Ecology, p. 55-58.

Deaton, M.L. and Winebrake, J.J., 2000. *Dynamic modeling of environmental systems*. New York: Springer-Verlag.

Defense Mapping Agency/Icelandic Geodetic Survey, 1990. *Eyjafjallajökull*, sheet 1812 III, 1:50,000. C761 series.

Dennis, A., Foote, P. and Perkins, R., (editors and translators), 2000. *Laws of early Iceland: Grágás*. Winnipeg: University of Manitoba Press.

Dugmore, A.J., 1989. Tephrochronological studies of Holocene glacier fluctuations in south Iceland. In: Oerlemans, J. (ed.) *Glacier fluctuations and climate change*. Dordrecht: Kluwer Academic Publishers, p.37-55.

Dugmore, A.J. and Buckland, P.C., 1991. Tephrochronology and late Holocene soil erosion in southern Iceland. In: Maizels, J.K. and Caseldine, C. (eds.) *Environmental change in Iceland: past and present.* London: Kluwer Academic Publishers, p.147-159.

Dugmore, A.J. and Erskine, C.C., 1994. Local and regional patterns of soil erosion in southern Iceland. In: Stötter, J. and Wilhelm, F. (eds.) *Environmental Change in Iceland.* Munich: Münchener Geographische Abhandlungen, p. 63-78.

Dugmore, A.J., Newton, A.J., Larsen, G. and Cook, G.T., 2000. Tephrochronology, environmental change and the Norse settlement of Iceland. *Environmental Archaeology*, **5**, p. 21-34.

Dugmore, A.J. and Simpson, I.A., (in press). 1,200 years of Icelandic landscape change reconstructed using tephrochronology. *Earth Surface Processes and Landforms*.

Dýrmundsson, Ó. and Jónmundsson, J.V., 1987. The effects on the carrying capacity of rangeland pastures. In: Parry, M.L., Carter, T.R. and Konijn, N.T. (eds.) *The impact of climatic variations on agriculture. Volume 1: Assessment in Cool Temperate and Cold Regions*. Dordrecht: IIASA and UNEP, p. 475-88.

Eggertsson, T., 1992. Analyzing institutional successes and failures: a millennium of common mountain pastures in Iceland. *International Review of Law and Economics*, **12**, p. 423-437.

Eggertsson, T., 1996. No experiments, monumental disasters: Why it took a thousand years to develop a specialized fishing industry in Iceland. *Journal of Economic Behaviour and Organisation*, **30**, p. 1-23.

Eggertsson, T., 1998. Sources of risk, institutions for survival, and a game against nature in premodern Iceland. *Explorations in Economic History*, **35**, p. 1-30.

Einarsson, E.H., Larsen, G. and Þorarinsson, S., 1980. The Sólheimar tephra layer and the Katla eruption of ~1357. *Acta Naturalia Islandica,* **28**, p. 1-24.

Einarsson, M.A., 1976. *The climate of Iceland*. Reykjavík: Idunn.

Einarsson, M.A., 1979. Climatic conditions of the Lake Mývatn area. *Oikos*, **32**(1-2), p. 29-37.

Einarsson, T., 1963. Pollen-analytical studies on the vegetation and climate history of Iceland in Late and Post-glacial times. In: Löve, A. and Löve, D. (eds.) *North Atlantic biota and their history.* Oxford: Pergamon Press, p.355-365.

Evans, R., 1998. The erosional impacts of grazing animals. *Progress in Physical Geography,* **22**(2), p. 251-268.

Eysteinsson, Þ., and Blöndal, S., 2000. The forests of Iceland at the time of Settlement: their utilisation and eventual fate. In prep.

Fedra, K., 1993. GIS and environmental modelling. In: Goodchild, M.F., Parks, B.O. and Steyaert, L.T. (eds.) *Environmental modelling with GIS.* Oxford: Oxford University Press.

Fernandez-Gimenez, M. E. and Allen-Diaz, B., 1999. Testing a non-equilibrium model of rangeland vegetation dynamics in Mongolia. *Journal of Applied Ecology,* **36**, p. 871-885.

Forbes, B. C. and Jeffries, R.L., 1999. Revegetation of disturbed arctic sites: constraints and applications. *Biological Conservation,* **88**, p. 15-24.

Forman, R.T.T. and Godron, M., 1986. *Landscape ecology*. New York: John Wiley & Sons.

Foy, J. K., Teague, W.K. and Hanson, J.D., 1999. Evaluation of the upgraded SPUR model (SPUR 2.4). *Ecological Modelling,* **118**(2-3), p. 149-165.

Fredskild, B., 1992. Erosion and vegetational changes in southern Greenland caused by agriculture. *Geografisk Tidsskrift,* **92**, p. 14-21.

Friðriksson, A. and Vésteinsson, O. (eds.), 1998. *Hofstaðir 1998. Interim report*. Reykjavík: Fornleifastofnun Íslands. Report FS062-91016.

Fridriksson, S., 1975. *Surtsey. Evolution of life on a volcanic island.* London:

butterworths.

Friðriksson, S., 1972. Grass and grass utilization in Iceland. *Ecology,* **53**(5), p. 785-796.

Friðriksson, S., 1978. The degradation of Icelandic ecosystems. In: Holdgate, M.W. and Woodman, M.J. (eds.) *The breakdown and restoration of ecosystems.* London: Plenum Press, p.145-154.

Friðriksson, S. and Sigurðsson, F.H., 1983. The effect of air temperature on grass growth. *Íslenzkar Landbúnaðarrannsóknir,* **15**(1-2), p. 41-54.

Gerrard, J.M., 1991. An assessment of some of the factors involved in recent landscape change in Iceland. In: Maizels, J.K. and Caseldine, C. (eds.) *Environmental change in Iceland:past and present.* London: Kluwer Academic Publishers, p.237-253.

Gísladóttir, G., 1998. *Environmental characterisation and change in south-west Iceland*. Ph.D. thesis. Stockholm University.

Grant, S. A., Torvell, L., Smith, H.K., Suckling, D.E., Forbes, T.D.A. and Hodgson, J., 1987. Comparative studies of diet selection by sheep and cattle: blanket bog and heather moor. *Journal of Ecology,* **75**, p. 947-960.

Grant, S.A., Lamb, W.I.C., Kerr, C.D. and Bolton, G.R., 1976. The utilization of blanket bog vegetation by grazing sheep. *Journal of Applied Ecology,* **13**, p. 857-869.

Grönvold, K., Óskarsson, N., Johnsen, S.J., Clausen, H.B., Hammar, C.U., Bond, G. and Bard, E., 1995. Ash layers from Iceland in the Greenland GRIP ice core correlated with oceanic and land sediments. *Earth and Planetary Science Letters,* **135**, p. 149-155.

Grove, J., 1988. *The little ice age*. London: Methuen.

Guðbergsson, G., 1975. Myndun móajarðvegs í Skagafirði (Soil formation in Skagafjörður, northern Iceland). *Íslenzkar Landbúnaðarrannsóknir,* **7**(1-2), p. 20-45.

Guðbergsson, G., 1996. The influence of human habitation on soil and vegetation in three counties in North Iceland. *Búvísindi*, **10**, p. 31-89.

Guðbergsson, G.M., 1980. Vegetation mapping in Iceland. *Íslenzkar Landbúnaðarrannsóknir*, **12**(2), p. 59-83.

Gudmundsson, B., 1987. Implications for agricultural policy. In: Parry, M.L., Carter, T.R. and Konijn, N.T. (eds.) *The impact of climatic variations on agriculture. Volume 1: Assessment in Cool Temperate and Cold Regions*. Dordrecht: IIASA and UNEP, p. 489-501.

Guðmundsson, B., 1974. Spring temperature and growth conditions with particular reference to grassland. *Íslenzkar Landbúnaðarrannsóknir*, **6**(1-2), p. 23-36.

Guðmundsson, G., 1996. Gathering and processing of lyme-grass (*Elymus arenarius*) in Iceland: an ethnohistorical account. *Vegetation History and Archaeobotany*, **5**, p. 13-23.

Gudmundsson, H. J., 1997. A review of the Holocene environmental history of Iceland. *Quaternary Science Reviews*, **16**, p. 81-92.

Guðmundsson, Ó., 1991. Evaluation of feed energy in relation to grazing livestock. *Norwegian Journal of Agricultural Sciences*, **Supplement 5**, p. 17-35.

Halfidason, H., Larsen, G. and Ólafsson, G., 1992. The recent sedimentation history of Thingvallavatn, Iceland. *Oikos*, **64**(1-2), p. 80-95.

Hallsdóttir, M., 1987. *Pollen analytical studies of human influence on vegetation in relation to the Landnám tephra layer in southwestern Iceland*. Ph.D. thesis. Lund University.

Hallson, S. V., 1964. The use of seaweeds in Iceland. *Comptes Rendues du 4 congres international des sigues marines*. New York: Pergamon, p. 398-405.

Haraldsson, H., 1981. The Markarfljót sandur area, south Iceland. *Striae*, **15**, p. 1-58.

Hardin, G., 1968. The tragedy of the commons. *Science*, **162**, p. 1243-1248.

Hastrup, K., 1990. *Nature and policy in Iceland 1400-1800: an anthropological* *analysis of history and mentality*. Oxford: Clarendon Press.

Hill Farming Research Organisation, 1979. *Science and hill farming*. Edinburgh: Hill Farming Research Organisation.

Icelandic Meteorological Office, 2001. *Research and processing: Icelandic climate data*. URL: http://www.vedur.is/english/index_eng.html [24th January 2002].

Ilahaine, H., 1999. The Berber agdal institution: indigenous range management in the Atlas mountains. *Ethnology*, **38**(1), p. 21-45.

Jacobsen, N. K., 1987. Studies on soils and potential for soil erosion in the sheep farming area of south Greenland. *Arctic and Alpine Research*, **19**(4), p. 498-507.

Jennings, A. E., Hagen, S., Harðardóttir, J., Stein, R., Ogilvie, A.E.J. and Jónsdóttir, I., 2001. Oceanographic change and terrestrial human impacts in a post A.D. 1400 sediment record from the southwest Iceland shelf. *Climatic Change*, **48**, p. 83-100.

Jennings, A. E. and Weiner, N.J., 1996. Environmental change in eastern Greenland during the last 1300 years: evidence from foraminifera and lithofacies in Nansen Fjord, 68 °N. *The Holocene*, **6**, p. 179-191.

Jónasson, H., 1972. Flóra Mývatnssveitar. *Acta Botanica Islandica*, **1**, p. 32-42.

Jónasson, P. M., 1979. The Lake Mývatn ecosystem, Iceland. *Oikos*, **32**(1-2), p. 289-305.

Jónsdóttir, S. 1994. *Foraging activity and sheep performance and its relevance for range management in northern Iceland*. Masters thesis, University College of North Wales.

Jónsson, G., 1993. Institutional change in Icelandic agriculture, 1780-1940. *Scandinavian Economic History Review*, **41**(2), p.101-28.

Jørgensen, S.E., 1991. Environmental management modelling. In: Hansen, P.E. and Jørgensen, S.E. (eds.) *Introduction to environmental management.* Amsterdam: Elsevier, p.377-395.

Keller, C., 1990. Vikings in the west Atlantic: a model of Norse Greenlandic medieval society. *Acta Archaeologica*, **61**, p. 126-141.

Kent, M. and Coker, P., 1992. *Vegetation description and analysis: a practical approach.* Chichester: John Wiley.

Kirch, P. V. and Hunt , T.L. (eds.), 1996. *Historical ecology in the Pacific islands: prehistoric environmental and landscape change*. New Haven, CT: Yale University Press.

Körner, C., 1999. *Alpine plant life: functional plant ecology of high mountain ecosystems*. Berlin: Springer.

Kristinsson, H., 1995. Post-settlement history of Icelandic forests. *Búvísindi,* **9**, p. 31-35.

Kristinsson, H., 1998. *A guide to the flowering plants and ferns of Iceland*. Reykjavík: Mál og menning, 2nd edition.

Lamb, H. H., 1995. *Climate, history and the modern world*. London: Routledge, 2nd edition.

Larsen, G., 1981. Tephrochronology by microprobe glass analysis. In: Self, S. and Sparks, R.S.J. (eds.) *Tephra studies.* Dordrecht: Reidel, p. 95-102.

Larsen, G., 1982. Tephrochronology of Jökuldalur and the surrounding area. In: Þórarinsdóttir, H., Óskarsson, Ó.H. and Steinþórsson, S. (eds.) *Eldur er i norðri.* Reykjavík: Sögufelag, p. 51-66.

Larsen, G., 1984. Recent volcanic history of the Veiðivötn fissure swarm in southern Iceland - an approach to volcanic risk assessment. *Journal of Volcanology and Geothermal Research,* **22**, p. 56-68.

Larsen, G., 1996. Gjóskutimatal og gjóskulög fra tíma norræns landnáms á Íslandi. In: Grímsdóttir, G. Á. (ed.) *Um Landnám á Íslandi, Ráðstefnurit V*. Reykjavík: Societas Scientarum Islandica, p. 81-106.

Lárusson, B., 1967. *The old Icelandic land registers*. Lund, Sweden: Lund University.

Laws, J. A. and Newton, J.E., 1987. The effect of stocking rate and grazing manangement of sheep during winter on liveweight performance and herbage production. *Research and Development in Agriculture,* **4**(3), p.141-46.

Löve, Á. and Löve, D. (eds.), 1963. *North Atlantic biota and their history*. Oxford: Pergamon Press.

Lucas, G. (ed.), 1999. *Hofstaðir 1999. Interim report.* Reykjavík: Fornleifastofnun Íslands. Report FS102-91017.

Mackintosh, A. N., Dugmore, A.J. and Hubbard, A.L., 2002. Holocene climatic changes in Iceland: evidence from modelling glacier length fluctuations at Sólheimajökull. *Quaternary International,* **91**, p. 39-52.

Macniven, A., 2002. Where are Eyjafjallasveit's earliest settlement sites? A review of the documentary evidence. *Northern Studies*, in press.

Maeda, T., H. Takenaka, H. and Warkentin, B.P., 1977. Physical properties of allophane soils. *Advances in Agronomy,* **29**, p. 229-264.

Magnússon, Á. and Vídalín, P., 1913-1990. *Jarðabók. Vol. 1-13*. Copenhagen: Hið Íslenzka Fræðafélag.

Magnússon, B., Elmarsdóttir, Á. and Barkarson, B., 1998. *Hrossahagar: Horse ranges in Iceland*. URL: http://www.rala.is/umhvd/hhagar [23rd January 2002].

Magnússon, Borgþór, Elmarsdóttir, Á., Barkarson, B. and Maronsson, B., 1999. Langtímamælingar og eftirlit í hrossahögum (History and control of horse grazing). URL: http://www.rala.is/radunautafundir [23rd January 2002].

Magnússon, B. and Magnússon, S.H., 1992. *Vegetation and plant preferences of sheep in a grazing trial on an alpine heathland range in northern Iceland*, RALA report 159. Agricultural Research Institute, Reykjavík, Iceland.

Magnússon, S.H., and Magnússon, B., 1990. Studies in the grazing of a drained lowland fen in Iceland. II. Plant preferences of horses during summer. *Búvísindi,* **4,** p.109-124.

McGovern, T.H., 1995. *Manual of FARMPACT 5.0: an economic simulation for Norse Greenland*. New York: NABO Software Product.

McGovern, T.H, Bigelow, G.F., Amorosi, T. and Russell, D., 1988. Northern islands, human error, and environmental degradation: a view of social and ecological change in the medieval north Atlantic. *Human Ecology*, **16**(3), p. 225-269.

Miller, W.I., 1990. *Bloodtaking and peacemaking. Feud, law, and society in Saga Iceland*. Chicago and London: The University of Chicago Press.

Milton, A. and Stegun, I.A., 1970. *Handbook of mathematical functions with formulas, graphs and mathematical tables*. Washington (DC): US Dept. of Commerce, National Bureau of Standards.

Moore, P. D. and Chapman, S.B., 1986. *Methods in plant ecology*. Oxford: Blackwell.

Morgan, R., 1985. Soil degradation and erosion as a result of agricultural practice. In: Richards, K.S., Arnett, R.R. and Ellis, S. (eds.) *Geomorphology and Soils.* London: Allen & Unwin, 1st edition, p.379-395.

Netting, R., 1996. What Alpine peasants have in common: observations on communal tenure in a Swiss village. In: Bates, D.G. and Lees, S.H. (eds.). *Case studies in human ecology.* New York: Plenum Press, p.219-231.

Ogilvie, A. E. J., 1984. The impact of climate on grass growth and hay yield in Iceland: A.D. 1601 to 1780. In: Mörner, N.A. and Karlén, W. (eds.). *Climatic changes on a yearly to millennial basis: geological, historical, and instrumental records*. Dordrecht: D. Reidel, p 343-352.

Ogilvie, A. E. J., Barlow, L.K. and Jennings, A.E., 2000. North Atlantic climate *c*. AD 1000: millennial reflections on the Viking discoveries of Iceland, Greenland and North America. *Weather*, **55**, p. 34-45.

Ogilvie, A.E.J., 1984. The past climate and sea-ice record from Iceland, part 1: data to AD 1780. *Climatic Change,* **6**, p.131-152.

Ogilvie, A.E.J., 1986. The climate of Iceland, 1701-1784. *Jökull,* **36**, p. 57-73.

Ogilvie, A.E.J., 1990. Climatic changes in Iceland A.D. c. 865 to 1598. *Acta Archaeologica,* **61**, p. 233-251.

Ogilvie, A.E.J., 1992. Documentary evidence for changes in the climate of Iceland, A.D. 1500 to 1800. In: Bradley, R.S. and Jones, P.D. (eds.) *Climate since A.D. 1500.* London: Routledge, p.92-117.

Ólafsdóttir, R. and Guðmundsson, H.J., 2002. Holocene land degradation and climatic change in northeastern Iceland. *The Holocene,* **12**(2), p. 159-167.

Ólafsdóttir, R., Schlyter, P. and Haraldsson, H., 2001. Simulating Icelandic vegetation cover during the Holocene: implications for long-term land degradation. *Geografiska Annaler Series A: Physical Geography,* **83A**(4), p. 203-215.

Ólafsson, G., 1973. The plant preference of grazing sheep in Iceland. *Íslenzkar Landbúnaðarrannsóknir,* **5**(1-2), p. 3-63.

Ólafsson, G., 1980. The nutritive value of range plants . *Íslenzkar Landbúnaðarrannsóknir,* **12**(2), p. 127-134.

Ólafsson, J., 1979. Physical characteristics of Lake Mývatn and River Laxá. *Oikos,* **32**(1-2), p. 38-66.

Ostrom, E., 1990. *Governing the commons. The evolution of institutions for collective action.* Cambridge: Cambridge University Press.

Påhlsson, I., 1981. A pollen analytical study on a peat deposit at Lágafell, southern Iceland. *Striae,* **15**, p. 60-64.

Parfitt, R. L. and Clayden, B., 1991. Andisols - the development of a new order in Soil Taxonomy. *Geoderma,* **49**, p.181-198.

Pickup, G., 1994. Modelling patterns of defoliation by grazing animals in rangelands. *Journal of Applied Ecology,* **31**, p. 231-246.

Prock, S. and Körner, C., 1996. A cross-continental comparison of phenology, leaf dynamics and dry matter allocation in arctic and temperate zone herbaceous plants from contrasting altitudes. *Ecological Bulletins,* **45**, p. 93-103.

RALA, 1978a. *Utilisation and conservation of grasslands. Progress report 1976*. Reykjavík: Agricultural Research Institute, Iceland. RALA Report no. 29.

RALA, 1978b. *Utilisation and conservation of grasslands. Progress report 1977*. Reykjavík: Agricultural Research Institute, Iceland. RALA Report no. 38

RALA, 1979. *Utilisation and conservation of grasslands. Progress report 1978*. Reykjavík: Agricultural Research Institute, Iceland. RALA Report no. 50.

RALA, 1980. *Utilisation and conservation of grasslands. Progress report 1979*. Reykjavík: Agricultural Research Institute, Iceland. RALA report no. 63

RALA, 1981. *Utilisation and conservation of grasslands. Progress report 1980*. Reykjavík: Agricultural Research Institute, Iceland. RALA report no. 79.

RALA, 2001. *Soil Map of Iceland*, *1:500,000*. Reykjavík, Iceland: RALA.

RALA/Icelandic Survey Department, 1982a. *Vegetation map of Iceland*, Sheet 285, 1:40,000. Reykjavík: RALA.

RALA, 1982b. *Vegetation map of Iceland*, Sheet 305, 1:40,000. Reykjavík: RALA.

Rieley, J. and Page, S., 1990. *Ecology of plant communities. A phytosociological account of the British vegetation.* Harlow, Essex: Longman Scientific & Technical.

Rook, A. J., 2000. Principles of foraging and grazing behaviour. In: Hopkins, A. (ed.), *Grass. Its production and utilization*. Oxford: Blackwell, 3rd edition, p. 229-246

Rundgren, M. and Ingólfsson, Ó., 1999. Plant survival in Iceland during periods of glaciation. *Journal of Biogeography*, **26**(2), p. 387-396.

Runolfsson, S., 1978. Soil conservation in Iceland. In: Holdgate, M.W. and Woodman, M.J. (eds.), *The breakdown and restoration of ecosystems*. New York: Plenum Press, p. 231-238.

Rykiel, E.J., 1996. Testing ecological models: the meaning of validation. *Ecological Modelling*, **90**, p. 229-244.

Sadler, J.P. and Dugmore, A.J., 1995. Habitat distribution of terrestrial Coleoptra in Iceland as indicated by numerical analysis. *Journal of Biogeography,* **22**, p. 141-148.

Sadler, J.P. and Skidmore, P., 1995. Introductions, extinctions or continuity? Faunal change in the North Atlantic islands. In: Butlin, R.A. and Roberts, N. (eds.), *Ecological relations in historical times. Human impact and adaptation.* Oxford: Blackwell, p. 206-225.

Sheets, P.D. and Grayson, D.K. (eds.) 1979. *Volcanic activity and human ecology*. London: Academic Press.

Sigurdsson, A., 1980. *Icelandic-English dictionary*. Reykjavík: Prentsmidjan Leiftur, 3rd edition.

Simmons, I. G., 1996. *Changing the face of the earth. Culture, environment, history*. Oxford: Blackwell, 2nd edition.

Simpson, I.A., Guðmundsson, G., Thomson, A.M. and Cluett, J. (in press). Assessing the role of winter grazing in historic land degradation, Mývatnssveit, north-east Iceland. *Geoarchaeology*.

Simpson, I.A., Adderley, W.P., Guðmundsson, G., Hallsdóttir, M., Sigurgeirsson, M.A. and Snæsdóttir, M., 2002. Soil limitations to agrarian land production in premodern Iceland. *Human Ecology,* **30**(4), p. 423-443.

Simpson, I.A., Dugmore, A.J., Thomson, A. and Vésteinsson, Ó., 2001. Crossing the thresholds: human ecology and historical patterns of landscape degradation. *Catena,* **42**, p. 175-192.

Smith, K.P., 1995. Landnám: the settlement of Iceland in archaeological and historical perspective. *World Archaeology,* **26**, p. 319-347.

Soil Survey Staff, 1998. *Soil Taxonomy: a basic system of soil classification for making and interpreting soil surveys*. Washington, D.C.: USDA Natural Resources Conservation Service, 2nd edition.

Steindórsson, S., 1962. *On the age and immigration of the Icelandic flora*. Reykjavík:

Prentsmiðjan Leiftur.

Steindórsson, S., 1980. Vegetation classification in Iceland. *Íslenzkar Landbúnaðarrannsóknir*, **12**(2), p. 11-52.

Stocking, M.A. and Murnaghan, N., 2001. *Handbook for the field assessment of land degradation*. London: Earthscan.

Stötter, J., Wastl, M., Caseldine, C. and Häberle. T., 1999. Holocene palaeoclimatic reconstruction in northern Iceland: approaches and results. *Quaternary Science Reviews*, **18**, p. 457-474.

Sveinbjarnardóttir, G., 1990. Sheilings in Iceland: an archaeological and historical survey. *Acta Archaeologica*, **61**, p. 73-93.

Sveinbjarnardóttir, G., 1992. *Farm abandonment in medieval and post-medieval Iceland*. Oxford: Oxbow Monograph 17.

Thomson, A.M. 1997. *Human environmental interactions: modelling the Icelandic landscape in the past*. M.Sc. thesis. University of Edinburgh.

Þorarinsson, S., 1944. Tefrokronoliska studier på Island. *Geografiska Annaler,* **26**, p. 1-217.

Þorarinsson, S., 1961a. Uppblástur á Íslandi í ljósi öskulagarannsókna (Wind erosion in Iceland. A tephrochronological study). *Ársrit Skógræktarfélags Íslands [Icelandic Forestry Society Yearbook],* **1960-1961**, p. 17-54.

Þorarinsson, S., 1961b. Population changes in Iceland. *The Geographical Review,* **51**(4), p. 519-533.

Þorarinsson, S., 1967. The eruption of Hekla in historical times. In: Þorarinsson, S. (ed.) *The eruption of Hekla 1947-1948.* Reykjavík: Societas Scientiarum Islandica, p. 1-170.

Þorarinsson, S., 1975. Katla og annáll Kötlugosa. *Árbók Ferðafélags Íslands,* **1975**, p.125-149.

Þorarinsson, S., 1979a. Tephrochronology and its application in Iceland. *Jökull,* **29**, p.

33-36.

Þorarinsson, S., 1979b. The postglacial history of the Mývatn area. *Oikos* **32**(1-2), p.17-28.

Þorarinsson, S., 1979c. On the damage caused by volcanic eruptions with special reference to tephra and gases. In: Sheets, P.D. and Grayson, D.K. (eds.) *Volcanic activity and human ecology*. London: Academic Press, p. 125-160.

Thorhallsdóttir, A.G., 1997. Dynamics in plant selection of grazing animals and its influence on sward development. Paper presented at *NABO meeting*, Reykjavík, August 1997.

Thórhallsdóttir, A.G. and Thorsteinsson, I., 1993. Behaviour and plant selection. *Búvísindi,* **7**, p. 59-77.

Thorsteinsson, I., 1978. *Vegetation and land use*. Reykjavík: Lesarkir Landverndar.

Thorsteinsson, I., Ólafsson, G. and Van Dyne, G.M., 1971. Range resources of Iceland. *Journal of Range Management*, **24**(2), p. 86-93.

Thorsteinsson, I., 1964. Studies on the plant preferences of sheep. *Freyr*, **11**, p.194-201.

Thorsteinsson, I., 1980a. Environmental data, botanical composition and production of plant communities and the plant preference of sheep. *Íslenzkar Landbúnaðarrannsóknir,* **12**(2), p. 85-99.

Thorsteinsson, I., 1980b. Grazing intensity - proper use of rangelands. *Íslenzkar Landbúnaðarrannsóknir,* **12**(2), p.113-122.

Thorsteinsson, I., 1980c. The grazing value of plant communities. *Íslenzkar Landbúnaðarrannsóknir,* **12**(2), p. 123-125.

Thorsteinsson, I., 1986. The effect of grazing on stability and development of northern rangelands: a case study of Iceland. In: Guðmundsson, Ó. (ed.) *Grazing research at northern latitudes*. New York: Plenum Press, p. 37-43.

Thorsteinsson, I. and Arnalds, Ó., 1992. The vegetation and soils of the Thingvallavatn area. *Oikos,* **64**(1-2), p.105-116.

Thorsteinsson, I. and Ólafsson, G., 1967. Plant preference of sheep in open rangeland and reforested area. *Ársrit Skógræktarfélags Íslands,* **1967**, p. 6-14.

Þorvaldsson, G., 1996. The effects of weather on onset of spring growth in grass fields and pastures in Iceland. *Búvísindi,* **10**, p.165-176.

Thorvaldsson, G. and Björnsson, H., 1990. The effects of weather on growth, crude protein and digestibility of some grass species in Iceland. *Búvísindi,* **4**, p.19-36.

Turner, M.J., Wu, Y., Wallace, L.L., Ronme, W.H. and Brenkert, A., 1994. Simulating winter interactions among ungulates, vegetation, and fire in Northern Yellowstone Park. *Ecological Applications,* **4**(3), p. 472-496.

Vasey, D., 1996. Population regulation, ecology, and political economy in medieval Iceland. *American Ethnologist,* **23**(2), p. 366-392.

Vésteinsson, O. (ed.) 1996. *Fornleifaskráning í Skútustaðahreppi I.* Reykjavík: Fornleifastofnun Íslands. Report FS022-96011.

Vésteinsson, O., McGovern, T.H. and Keller, C., 2002. Enduring impacts: social and environmental aspects of Viking Age settlement in Iceland and Greenland. *Archaeologia Islandica,* **2**, p. 98-136.

Vésteinsson, O., 1998. Patterns of settlement in Iceland: a study in prehistory. *Saga-Book,* **28**, p. 1-29.

Webb, R., 1972. Vegetation cover on Icelandic thúfur. *Acta Botanica Islandica,* **1**, p. 51-60.

Webber, P.J., 1974. Tundra primary productivity. In: Ives, J.D. and Barry, R.G. (eds.) *Arctic and alpine environments.* London: Methuen.

Weber, G.E, Jeltsch, F., Van Rooyen, N. and Milton, S.J., 1998. Simulated long-term vegetation response to grazing heterogeneity in semi-arid rangelands. *Journal of Applied Ecology,* **35**, p. 687-699.

West, J.F., 1972. *Faroe: the emergence of a nation*. London: C. Hurst & Co.

Winchester, A.J.L., 2000. *The harvest of the hills: rural life in northern England and* *the Scottish Borders, 1400-1700.* Edinburgh: Edinburgh University Press.

World Reference Base, 1998. *World Reference Base for soil resources*. Rome: FAO-ISSS-ISRIC.

Zutter, C.M. 1992. Icelandic plant and land-use patterns: Archaeobotanical analysis of the Svalbarð midden (6706 - 60), Northeastern Iceland. In: Morris, C.D. and Rackham, D.J. (eds.) *Norse and later settlement and subsistence in the north Atlantic.* University of Glasgow: Department of Archaeology, p. 139-148.

Appendix A: Búmodel Visual Basic code

A.1 BigModule macro

```
Option Explicit
'BigModule is the universal module, from which all other modules are called.
'It reads in all the input data and assigns this data to global variables

Public Limits As Worksheet, PasInputs As Worksheet, PasResults As Worksheet
Public LiveInputs As Worksheet, OffResults As Worksheet, HerbInputs As Worksheet
Public HerbResults As Worksheet, OutResults As Worksheet
Dim count As Integer, CellId As Integer, Row As Integer, Col As Integer
Public CellArray() As Variant
Public HerbArray() As Currency, SenRate(11, 7) As Currency
Public Location As Integer
Public NumCells As Integer
Public CellIdArray() As Variant, UpCellId() As Variant, OutCellId() As Variant
Public CellType() As Variant, UpCellArray() As Variant, OutCellArray() As Variant
Dim j As Integer, k As Integer, x As Integer, y As Integer, z As Integer, a As Integer, b As Integer, c As Integer
Dim LT As String
Public UpNum As Integer, OutNum As Integer
Public EweNum As Integer, LambNum As Integer, YoungNum As Integer, RamNum As Integer, WinterYoungNum As Integer
Public RetainLambs As Currency, EweWt As Currency, LambWt(1) As Currency, YoungWt As Currency, RamWt As Currency
Public WinLoss As Currency, ClimateScen As Variant, Fertiliser As Currency
Public HayFeedUnits As Currency, HayStore As Currency, HayReserves() As Currency
Public runcount As Integer, RunNum As Integer, FailCount(11) As Integer, OrderRes As String
Public CellHerbage() As Currency
Public CellSheep() As Currency
Public CellKgOff() As Currency, CellUtil() As Currency, CumUtil() As Currency
```

```
Sub Auto_Open()
    InitialiseIt    'runs the initialisation procedure
End Sub
```

```
Sub InitialiseIt() 'initialises values in the input form
'runs automatically when the spreadsheet Búmodel is opened in Excel
```

```
    Application.ScreenUpdating = False
    Worksheets("Livestock Inputs").Activate
    Range("B2") = "0"       'ewe numbers
    Range("B3") = "0"       'lamb numbers
    Range("B4") = "0"       'young sheep numbers
    Range("B5") = "0"       'ram numbers
    '
    Range("B11") = "45.00"  'ewe weight
    Range("B12") = "57.50"  'young sheep weight
    Range("B13") = "65.00"  'ram weight
    '
    Range("B8") = "= B4"    'number of immature sheep retained over the winter
    Range("B9") = "= B3"    'number of lambs retained over the winter
    Range("B14") = "0"         '% of body weight lost over winter
    Range("B17") = "Baseline"          'climate scenario
    '
    Range("B30") = "0"  'feed units consumed in previous winter- used to calculate fertiliser
    Range("B35") = "0"         ' hay stored from previous winter
End Sub
```

```
Sub BigModule()
InputData
'reads data from the input worksheets PastureInputs and LivestockInputs
x = 0
RunNum = 1
For x = 1 To runcount
    'loops for each simulation run
    PlantTypes.PlantTypes
    'calls the plant composition and palatability sub-model
    SheepFeed.SheepFeed
    'calls the maintenance requirements sub-model
    HayCalcs.HayModel
    'calls the hay yield sub-model
    SheepDistribution.Distribution
    'calls the biomass production-offtake feedback sub-model
    OffResults.Activate
    RunNum = RunNum + 1
    'next simulation
Next x
If runcount > 1 Then
```

```
    StatResults.Results
    'calls the descriptive statistics sub-model
End If
End Sub
```

```
Sub InputData()
    Application.ScreenUpdating = False
    'set codes for worksheets
    Set Limits = Worksheets("Limits")
    Set PasInputs = Worksheets("Pasture Inputs")
    Set PasResults = Worksheets("Pasture Results")
    Set LiveInputs = Worksheets("Livestock Inputs")
    Set OffResults = Worksheets("Offtake Results")
    Set HerbInputs = Worksheets("Herbage Inputs")
    Set HerbResults = Worksheets("Herbage Results")
    Set OutResults = Worksheets("Statistical Results")
    '
    PasInputs.Activate
    'calculates the number of cells in the model
    CellId = ActiveSheet.Cells(2, 1)
    count = 1
    Do While CellId > 0
        'loops until there are no more cell-ids to read
        count = count + 1
        CellId = ActiveSheet.Cells(count, 1)
    Loop
    NumCells = count - 2
    '
    'puts the cell-ids into a separate array
    ReDim CellIdArray(NumCells - 1)
    Range("A2").Select
    For Row = 0 To (NumCells - 1)
        CellIdArray(Row) = Selection.Offset(Row, 0)
    Next Row
    'counts how many cells are in each landuse type
    LT = ActiveSheet.Cells(2, 11)
    count = 2
    x = 0
    y = 0
    z = 0
```

```
Do
    'loops until there are no cells remaining
    If LT = "U" Then x = x + 1
    If LT = "O" Then y = y + 1
    count = count + 1
    LT = ActiveSheet.Cells(count, 11)
Loop Until LT = ""
UpNum = x
'number of rangeland cells
OutNum = y
'number of outfield cells
ReDim CellArray(NumCells - 1, 11)
‘
'copies all the cell contents into the array
Range("A1").Select
For Row = 0 To (NumCells - 1)
    For Col = 0 To 11
        CellArray(Row, Col) = Selection.Offset(Row + 1, Col)
    Next Col
Next Row
'
'copies cell contents into separate arrays, according to their landuse type
'creates dynamic arrays that contain the cell ids of the cells in each landuse type
If UpNum > 0 Then
    ReDim UpCellId(UpNum - 1)
    ReDim UpCellArray(UpNum - 1, 11)
End If
If OutNum > 0 Then
    ReDim OutCellId(OutNum - 1)
    ReDim OutCellArray(OutNum - 1, 11)
End If
a = 0
b = 0
c = 0
For j = 0 To (NumCells - 1)
    If CellArray(j, 10) = "U" Then
        UpCellId(a) = CellArray(j, 0)
        For k = 0 To 11
            UpCellArray(a, k) = CellArray(j, k)
        Next k
```

```
      a = a + 1
    ElseIf CellArray(j, 10) = "O" Then
      OutCellId(b) = CellArray(j, 0)
      For k = 0 To 11
        OutCellArray(b, k) = CellArray(j, k)
      Next k
      b = b + 1
    End If
Next j
'
Worksheets("Livestock Inputs").Activate
'initialise livestock number variables
EweNum = 0
LambNum = 0
YoungNum = 0
RamNum = 0
WinterYoungNum = 0
'
'read in livestock numbers from worksheet LivestockInputs
EweNum = ActiveSheet.Range("B2")    'number of ewes
LambNum = ActiveSheet.Range("B3")   'number of lambs
YoungNum = ActiveSheet.Range("B4")  'number of yearlings
RamNum = ActiveSheet.Range("B5")    'number of rams/wethers
'
WinterYoungNum = ActiveSheet.Range("B8")    'number of yearlings retained in winter
RetainLambs = ActiveSheet.Range("B9")       'number of lambs retained in winter
'
EweWt = ActiveSheet.Range("B11")                'average weight of ewes
LambWt(1) = 0.0783 * EweWt                   'lamb birth rate calculated from average ewe
        weight
YoungWt = ActiveSheet.Range("B12")              'average yearling weight
RamWt = ActiveSheet.Range("B13")                'average ram/wether weight
WinLoss = 1 - (ActiveSheet.Range("B14") / 100)  '% weight lost in winter
'
ClimateScen = ActiveSheet.Range("B17")   'climate scenario (baseline, cold, extreme
        cold, warm)
runcount = ActiveSheet.Range("B26")     'number of simulation runs
OrderRes = ActiveSheet.Range("B27")   'ordering of results - by cell-id or land-use type
Fertiliser = ActiveSheet.Range("B33")      'fertiliser application on hayfield
HayFeedUnits = ActiveSheet.Range("B31")     'kg of hay per feed unit
```

```
HayStore = ActiveSheet.Range("B35")         'amount of hay stored from previous year
'
HerbInputs.Activate
ReDim HerbArray(NumCells - 1, 7, 11)
If ClimateScen = "Baseline" Then
   Range("C2").Select
ElseIf ClimateScen = "Extreme Cold" Then
   Range("C11").Select
ElseIf ClimateScen = "Warm" Then
   Range("C20").Select
Else: Range("C29").Select
End If
'
'fills in utilisable biomass array from worksheet
For Row = 1 To 7
   For Col = 0 To 11
      For x = 0 To NumCells - 1
         HerbArray(x, Row, Col) = Selection.Offset(Row, Col)
      Next x
   Next Col
Next Row
'
'read in the values for the senesence/litterfall rate
'used for calculating the natural rate of biomass decline in winter
HerbInputs.Activate
If ClimateScen = "Baseline" Then
   Range("B40").Select
ElseIf ClimateScen = "Extreme Cold" Then
   Range("B49").Select
ElseIf ClimateScen = "Warm" Then
   Range("B58").Select
Else: Range("B67").Select
End If
'
For Row = 1 To 7
   For Col = 0 To 6
      SenRate(Col + 5, Row) = Selection.Offset(Row, Col)
   Next Col
Next Row
'
```

```
    'defining the output arrays
    ReDim CellHerbage(NumCells - 1, 11, runcount)
    ReDim CellSheep(NumCells - 1, 11, runcount)
    ReDim CellKgOff(NumCells - 1, 11, runcount)
    ReDim CumUtil(NumCells - 1, 11, runcount)
    ReDim CellUtil(NumCells - 1, 11, runcount)
    ReDim HayReserves(runcount)
    For k = 0 To 11
        'initialise failure counts
        FailCount(k) = 0
        HayFailCount(k) = 0
    Next k
    '
    'assign location for calculating hay yields
    If LiveInputs.Range("B16") = "South" Then
        Location = 1
    ElseIf LiveInputs.Range("B16") = "North" Then
        Location = 2
    End If
End Sub
```

A.2 Plant types macro

```
Option Explicit
'This program calculates the proportions of different plant types within each model cell.
‘ This is based on the area of different vegetation classes within each cell. A palatability
‘ score is then calculated, which represents the relative attractiveness of each cell, based
‘ on the relative palatability of the plant types that the cell contains.

Dim CellId As Integer
Dim HayArea As Currency, GrassArea As Currency, ShrubArea As Currency
Dim MossArea As Currency, BogArea As Currency, HalfbogArea As Currency
Dim BirchArea As Currency, SparseArea As Currency
Dim count As Integer
Dim GrassAndForbs As Currency, GrassType As Currency, SedgeType As Currency
Dim WoodyType As Currency, ForbType As Currency, MossType As Currency
Dim FernType As Currency, BareType As Currency
Dim xGrass As Currency, xSedge As Currency, xWoody As Currency, xForb As Currency
Dim xMoss As Currency, xFern As Currency, xBare As Currency
Public CellVegScore() As Currency, WinterVegScore() As Currency, CellVegArea() As Currency
```

```
Dim PalatabilityScore As Currency
Public SumPArray() As Currency, WinPArray() As Currency
Dim remainder As Currency, xx As Single, xx2 As Single
Dim Limits As Worksheet, Inputs As Worksheet, Results As Worksheet
Dim adjGrass As Currency, adjSedge As Currency, adjWoody As Currency, adjForb As
        Currency
Dim adjMoss As Currency, adjFern As Currency, adjBare As Currency
Dim check As Currency, inittotalcover As Currency, initremcover As Currency
Dim Row As Integer, Col As Integer
```

```
Sub PlantTypes()
  Application.ScreenUpdating = False
  PasInputs.Activate
  Set Limits = Worksheets("Limits")
  Set PasInputs = Worksheets("Pasture Inputs")
  Set PasResults = Worksheets("Pasture Results")
  'define the dynamic arrays based upon the number of cells
  ReDim CellVegScore(NumCells - 1, 7)
  ReDim WinterVegScore(NumCells - 1, 7)
  ReDim CellVegArea(NumCells - 1)
  ReDim SumPArray(NumCells - 1)
  ReDim WinPArray(NumCells - 1)
  '
  count = 0
  Do While count < NumCells
    'calculate the area of each vegetation community in each cell
    HayArea = CellArray(count, 1) / 10000        'hayfield
    GrassArea = CellArray(count, 2) / 10000      'grassy heath
    ShrubArea = CellArray(count, 3) / 10000      'dwarf shrub heath
    MossArea = CellArray(count, 4) / 10000       'moss heath
    BogArea = CellArray(count, 5) / 10000        'bog/mire
    HalfbogArea = CellArray(count, 6) / 10000    'riverine vegetation
    BirchArea = CellArray(count, 7) / 10000      'birch woodland
    SparseArea = CellArray(count, 8) / 10000     'sparsely vegetated land
    'the CellVegArea does not include areas of hay meadow, which are assumed to be
    'protected from grazing, and does not include the areas that are inaccessible to
    'grazing (areas of openwater, or that are too steep)
    CellVegArea(count) = GrassArea + ShrubArea + MossArea + BogArea +
       HalfbogArea + BirchArea + SparseArea
```

```
'initialise plant type variables
GrassAndForbs = 0   'grass and herbs
GrassType = 0       'grass
SedgeType = 0       'sedges and rushes
WoodyType = 0       'woody species
ForbType = 0        'dicot herbs
MossType = 0        'mosses and lichens
FernType = 0        'ferns and horsetails
BareType = 0        'bare ground
xGrass = 0
xSedge = 0
xWoody = 0
xForb = 0
xMoss = 0
xFern = 0
xBare = 0
'
adjGrass = 0
adjSedge = 0
adjWoody = 0
adjForb = 0
adjMoss = 0
adjFern = 0
adjBare = 0

CellVegScore(count, 0) = 0      'initialise summer palatability score
WinterVegScore(count, 0) = 0    'initialise winter palatability score
'
'grassy heath vegetation community
If GrassArea > 0 Then
   remainder = 0
   'grasses and herbs make up 50-80% of the total vegetation cover
   GrassAndForbs = (xx * (0.8 - 0.5) + 0.5)
   'from plant type range limits defined in the Búmodel vegetation community
    classification
   GrassType = (Limits.Cells(15, 3) - Limits.Cells(15, 2)) * Rnd + Limits.Cells(15, 2)
   '
   'random factor to allow for variation in botanical composition
   Randomize
   xx = 1 - Rnd
```

```
'calculate cover of dominant plant types
If GrassType < 0.5 Then
   ForbType = GrassAndForbs - GrassType
Else: ForbType = (Limits.Cells(18, 3) - Limits.Cells(18, 2)) * Rnd + Limits.Cells(18,
 2)
End If
'calculate cover of secondary plant types
SedgeType = (Limits.Cells(16, 3) - Limits.Cells(16, 2)) * Rnd + Limits.Cells(16, 2)
WoodyType = (Limits.Cells(17, 3) - Limits.Cells(17, 2)) * Rnd + Limits.Cells(17, 2)
MossType = (Limits.Cells(19, 3) - Limits.Cells(19, 2)) * Rnd + Limits.Cells(19, 2)
FernType = (Limits.Cells(20, 3) - Limits.Cells(20, 2)) * Rnd + Limits.Cells(20, 2)
BareType = (Limits.Cells(21, 3) - Limits.Cells(21, 2)) * Rnd + Limits.Cells(21, 2)
'
initremcover = SedgeType + WoodyType + MossType + FernType + BareType
remainder = 1 - GrassType - ForbType
remainder = remainder - initremcover
'adjust cover of secondary plant types
adjSedge = (SedgeType / initremcover) * remainder
SedgeType = SedgeType + adjSedge
adjWoody = (WoodyType / initremcover) * remainder
WoodyType = WoodyType + adjWoody
adjMoss = (MossType / initremcover) * remainder
MossType = MossType + adjMoss
adjFern = (FernType / initremcover) * remainder
FernType = FernType + adjFern
adjBare = (BareType / initremcover) * remainder
BareType = BareType + adjBare
'
'check sum of covers = 1
check = (GrassType + SedgeType + WoodyType + ForbType + MossType +
 FernType + BareType)
If Abs(1 - check) > 0.001 Then
 Results.Cells(16, 1) = "Error in check"
End If
'
xGrass = xGrass + (GrassArea * GrassType)
xSedge = xSedge + (GrassArea * SedgeType)
xWoody = xWoody + (GrassArea * WoodyType)
xForb = xForb + (GrassArea * ForbType)
xMoss = xMoss + (GrassArea * MossType)
```

```
    xFern = xFern + (GrassArea * FernType)
    xBare = xBare + (GrassArea * BareType)
    'calculate summer palatability score
    CellVegScore(count, 1) = (GrassArea * GrassType * 15) + (GrassArea *
     SedgeType * 10) + (GrassArea * WoodyType * 10) + (GrassArea * ForbType *
     10) + (GrassArea * MossType * 0) + (GrassArea * FernType * 10)
    'calculate winter palatbility score
    WinterVegScore(count, 1) = (GrassArea * GrassType * 5) + (GrassArea *
     SedgeType * 5) + (GrassArea * WoodyType * 10) + (GrassArea * ForbType * 0) +
     (GrassArea * MossType * 0) + (GrassArea * FernType * 5)
Else: CellVegScore(count, 1) = 0
    WinterVegScore(count, 1) = 0
End If

'for dwarf shrub heath vegetation community
If ShrubArea > 0 Then
    remainder = 0
    'woody species are the dominant vegetation cover
    Randomize
    xx = Rnd
    'calculate cover of dominant plant types
    'calculate cover of woody species
    WoodyType = (xx * (Limits.Cells(27, 3) - Limits.Cells(27, 2))) + Limits.Cells(27, 2)
    remainder = 1 - WoodyType
    'calculate moss cover
    If Limits.Cells(29, 3) > WoodyType Then
        MossType = (WoodyType - Limits.Cells(29, 2)) * Rnd + Limits.Cells(29, 2)
    Else: MossType = (Limits.Cells(29, 3) - Limits.Cells(29, 2)) * Rnd +
     Limits.Cells(29, 2)
    End If
    'calculate cover of secondary plant types
    GrassType = (Limits.Cells(25, 3) - Limits.Cells(25, 2)) * Rnd + Limits.Cells(25, 2)
    SedgeType = (Limits.Cells(26, 3) - Limits.Cells(26, 2)) * Rnd + Limits.Cells(26, 2)
    ForbType = (Limits.Cells(28, 3) - Limits.Cells(28, 2)) * Rnd + Limits.Cells(28, 2)
    FernType = (Limits.Cells(30, 3) - Limits.Cells(30, 2)) * Rnd + Limits.Cells(30, 2)
    BareType = (Limits.Cells(31, 3) - Limits.Cells(31, 2)) * Rnd + Limits.Cells(31, 2)
    '
    initremcover = GrassType + SedgeType + ForbType + FernType + MossType +
     BareType
    remainder = remainder - initremcover
```

```
    'adjust cover of secondary plant types
    adjGrass = (GrassType / initremcover) * remainder
    GrassType = GrassType + adjGrass
    adjSedge = (SedgeType / initremcover) * remainder
    SedgeType = SedgeType + adjSedge
    adjForb = (ForbType / initremcover) * remainder
    ForbType = ForbType + adjForb
    adjMoss = (MossType / initremcover) * remainder
    MossType = MossType + adjMoss
    adjFern = (FernType / initremcover) * remainder
    FernType = FernType + adjFern
    adjBare = (BareType / initremcover) * remainder
    BareType = BareType + adjBare
    'check sum of covers = 1
    check = (GrassType + SedgeType + WoodyType + ForbType + MossType +
     FernType + BareType)
    If Abs(1 - check) > 0.001 Then
     Results.Cells(16, 1) = "Error in check"
    End If
    xGrass = xGrass + (ShrubArea * GrassType)
    xSedge = xSedge + (ShrubArea * SedgeType)
    xWoody = xWoody + (ShrubArea * WoodyType)
    xForb = xForb + (ShrubArea * ForbType)
    xMoss = xMoss + (ShrubArea * MossType)
    xFern = xFern + (ShrubArea * FernType)
    xBare = xBare + (ShrubArea * BareType)
    'calculate summer palatability score
    CellVegScore(count, 2) = (ShrubArea * GrassType * 15) + (ShrubArea *
     SedgeType * 5) + (ShrubArea * WoodyType * 5) + (ShrubArea * ForbType * 10) +
     (ShrubArea * MossType * 0) + (ShrubArea * FernType * 10)
    'calculate winter palatability score
    WinterVegScore(count, 2) = (ShrubArea * GrassType * 5) + (ShrubArea *
     SedgeType * 5) + (ShrubArea * WoodyType * 10) + (ShrubArea * ForbType * 0) +
     (ShrubArea * MossType * 0) + (ShrubArea * FernType * 5)
Else: CellVegScore(count, 2) = 0
    WinterVegScore(count, 2) = 0
End If

'moss/lichen heath vegetation community
If MossArea > 0 Then
```

```
remainder = 0
Randomize
'mosses and lichens make up more than 50% of the total vegetation cover
'calculate cover of dominant plant types
MossType = (xx * (Limits.Cells(39, 3) - Limits.Cells(39, 2))) + Limits.Cells(39, 2)
remainder = 1# - MossType
'calculate cover of secondary plant types
GrassType = (Limits.Cells(35, 3) - Limits.Cells(35, 2)) * Rnd + Limits.Cells(35, 2)
SedgeType = (Limits.Cells(36, 3) - Limits.Cells(36, 2)) * Rnd + Limits.Cells(36, 2)
WoodyType = (Limits.Cells(37, 3) - Limits.Cells(37, 2)) * Rnd + Limits.Cells(37, 2)
ForbType = (Limits.Cells(38, 3) - Limits.Cells(38, 2)) * Rnd + Limits.Cells(38, 2)
FernType = (Limits.Cells(40, 3) - Limits.Cells(40, 2)) * Rnd + Limits.Cells(40, 2)
BareType = (Limits.Cells(41, 3) - Limits.Cells(41, 2)) * Rnd + Limits.Cells(41, 2)
'
initremcover = GrassType + SedgeType + ForbType + FernType + WoodyType +
 BareType
remainder = remainder - initremcover
'adjust cover of seconday plant types
adjGrass = (GrassType / initremcover) * remainder
GrassType = GrassType + adjGrass
adjSedge = (SedgeType / initremcover) * remainder
SedgeType = SedgeType + adjSedge
adjForb = (ForbType / initremcover) * remainder
ForbType = ForbType + adjForb
adjWoody = (WoodyType / initremcover) * remainder
WoodyType = WoodyType + adjWoody
adjFern = (FernType / initremcover) * remainder
FernType = FernType + adjFern
adjBare = (BareType / initremcover) * remainder
BareType = BareType + adjBare
'check sum of covers = 1
check = (GrassType + SedgeType + WoodyType + ForbType + MossType +
 FernType + BareType)
If Abs(1 - check) > 0.001 Then
 Results.Cells(16, 1) = "Error in check"
End If
'
xGrass = xGrass + (MossArea * GrassType)
xSedge = xSedge + (MossArea * SedgeType)
xWoody = xWoody + (MossArea * WoodyType)
```

```
    xForb = xForb + (MossArea * ForbType)
    xMoss = xMoss + (MossArea * MossType)
    xFern = xFern + (MossArea * FernType)
    xBare = xBare + (MossArea * BareType)
    'calculate summer palatability score
    CellVegScore(count, 3) = (MossArea * GrassType * 15) + (MossArea *
     SedgeType * 10) + (MossArea * WoodyType * 5) + (MossArea * ForbType * 10) +
     (MossArea * MossType * 0) + (MossArea * FernType * 10)
    'calculate winter palatability score
    WinterVegScore(count, 3) = (MossArea * GrassType * 5) + (MossArea *
     SedgeType * 5) + (MossArea * WoodyType * 5) + (MossArea * ForbType * 5) +
     (MossArea * MossType * 0) + (MossArea * FernType * 5)
Else: CellVegScore(count, 3) = 0
    WinterVegScore(count, 3) = 0
End If

'bog/mire vegetation community
If BogArea > 0 Then
    remainder = 0
    'Sedges and rushes are the dominant plant types
    'calculate cover of dominant plant types
    Randomize
    SedgeType = (Rnd * (Limits.Cells(46, 3) - Limits.Cells(46, 2))) + Limits.Cells(46, 2)
    remainder = 1# - SedgeType
    'calculate cover of secondary plant types
    GrassType = (Limits.Cells(45, 3) - Limits.Cells(45, 2)) * Rnd + Limits.Cells(45, 2)
    MossType = (Limits.Cells(49, 3) - Limits.Cells(49, 2)) * Rnd + Limits.Cells(49, 2)
    WoodyType = (Limits.Cells(47, 3) - Limits.Cells(47, 2)) * Rnd + Limits.Cells(47, 2)
    ForbType = (Limits.Cells(48, 3) - Limits.Cells(48, 2)) * Rnd + Limits.Cells(48, 2)
    FernType = (Limits.Cells(50, 3) - Limits.Cells(50, 2)) * Rnd + Limits.Cells(50, 2)
    BareType = (Limits.Cells(51, 3) - Limits.Cells(51, 2)) * Rnd + Limits.Cells(51, 2)
    '
    initremcover = GrassType + MossType + ForbType + FernType + WoodyType +
     BareType
    remainder = remainder - initremcover
    'adjust cover of secondary plant types
    adjGrass = (GrassType / initremcover) * remainder
    GrassType = GrassType + adjGrass
    adjMoss = (MossType / initremcover) * remainder
    MossType = MossType + adjMoss
```

```
   adjForb = (ForbType / initremcover) * remainder
   ForbType = ForbType + adjForb
   adjWoody = (WoodyType / initremcover) * remainder
   WoodyType = WoodyType + adjWoody
   adjFern = (FernType / initremcover) * remainder
   FernType = FernType + adjFern
   adjBare = (BareType / initremcover) * remainder
   BareType = BareType + adjBare
   'check sum of covers = 1
   check = (GrassType + SedgeType + WoodyType + ForbType + MossType +
    FernType + BareType)
   If Abs(1 - check) > 0.001 Then
    Results.Cells(16, 1) = "Error in check"
   End If
   '
   xGrass = xGrass + (BogArea * GrassType)
   xSedge = xSedge + (BogArea * SedgeType)
   xWoody = xWoody + (BogArea * WoodyType)
   xForb = xForb + (BogArea * ForbType)
   xMoss = xMoss + (BogArea * MossType)
   xFern = xFern + (BogArea * FernType)
   xBare = xBare + (BogArea * BareType)
   'calculate summer palatability score
   CellVegScore(count, 4) = (BogArea * GrassType * 15) + (BogArea * SedgeType *
    10) + (BogArea * WoodyType * 5) + (BogArea * ForbType * 10) + (BogArea *
    MossType * 0) + (BogArea * FernType * 10)
   'calculate winter palatability score
   WinterVegScore(count, 4) = (BogArea * GrassType * 5) + (BogArea * SedgeType
    * 5) + (BogArea * WoodyType * 5) + (BogArea * ForbType * 0) + (BogArea *
    MossType * 0) + (BogArea * FernType * 5)
Else: CellVegScore(count, 4) = 0
   WinterVegScore(count, 4) = 0
End If

'riverine vegetation community
If HalfbogArea > 0 Then
   remainder = 0
   Randomize
   'herbs are dominant plant type
   ForbType = (Rnd * (Limits.Cells(58, 3) - Limits.Cells(58, 2))) + Limits.Cells(58, 2)
```

```
remainder = 1 - ForbType
'calculate cover of secondary plant types
GrassType = (Limits.Cells(55, 3) - Limits.Cells(55, 2)) * Rnd + Limits.Cells(55, 2)
MossType = (Limits.Cells(59, 3) - Limits.Cells(59, 2)) * Rnd + Limits.Cells(59, 2)
WoodyType = (Limits.Cells(57, 3) - Limits.Cells(57, 2)) * Rnd + Limits.Cells(57, 2)
SedgeType = (Limits.Cells(56, 3) - Limits.Cells(56, 2)) * Rnd + Limits.Cells(56, 2)
FernType = (Limits.Cells(60, 3) - Limits.Cells(60, 2)) * Rnd + Limits.Cells(60, 2)
BareType = (Limits.Cells(61, 3) - Limits.Cells(61, 2)) * Rnd + Limits.Cells(61, 2)
'
initremcover = GrassType + MossType + SedgeType + FernType + WoodyType +
 BareType
remainder = remainder - initremcover
'adjust cover of secondary plant types
adjGrass = (GrassType / initremcover) * remainder
GrassType = GrassType + adjGrass
adjMoss = (MossType / initremcover) * remainder
MossType = MossType + adjMoss
adjSedge = (SedgeType / initremcover) * remainder
SedgeType = SedgeType + adjSedge
adjWoody = (WoodyType / initremcover) * remainder
WoodyType = WoodyType + adjWoody
adjFern = (FernType / initremcover) * remainder
FernType = FernType + adjFern
adjBare = (BareType / initremcover) * remainder
BareType = BareType + adjBare
'check sum of covers = 1
check = (GrassType + SedgeType + WoodyType + ForbType + MossType +
 FernType + BareType)
If Abs(1 - check) > 0.001 Then
 Results.Cells(16, 1) = "Error in check"
End If
xGrass = xGrass + (HalfbogArea * GrassType)
xSedge = xSedge + (HalfbogArea * SedgeType)
xWoody = xWoody + (HalfbogArea * WoodyType)
xForb = xForb + (HalfbogArea * ForbType)
xMoss = xMoss + (HalfbogArea * MossType)
xFern = xFern + (HalfbogArea * FernType)
xBare = xBare + (HalfbogArea * BareType)
'calculate summer palatability score
```

```
    CellVegScore(count, 5) = (HalfbogArea * GrassType * 15) + (HalfbogArea *
     SedgeType * 10) + (HalfbogArea * WoodyType * 10) + (HalfbogArea * ForbType *
     15) + (HalfbogArea * MossType * 0) + (HalfbogArea * FernType * 10)
    'calculate winter palatability score
    WinterVegScore(count, 5) = (HalfbogArea * GrassType * 5) + (HalfbogArea *
     SedgeType * 5) + (HalfbogArea * WoodyType * 5) + (HalfbogArea * ForbType * 5)
     + (HalfbogArea * MossType * 0) + (HalfbogArea * FernType * 5)
Else: CellVegScore(count, 5) = 0
    WinterVegScore(count, 5) = 0
End If

'birch woodland vegetation community
If BirchArea > 0 Then
    remainder = 1
    Randomize
    'no one plant type is dominant
    GrassType = (Limits.Cells(65, 3) - Limits.Cells(65, 2)) * Rnd + Limits.Cells(65, 2)
    SedgeType = (Limits.Cells(66, 3) - Limits.Cells(66, 2)) * Rnd + Limits.Cells(66, 2)
    WoodyType = (Limits.Cells(67, 3) - Limits.Cells(67, 2)) * Rnd + Limits.Cells(67, 2)
    ForbType = (Limits.Cells(68, 3) - Limits.Cells(68, 2)) * Rnd + Limits.Cells(68, 2)
    MossType = (Limits.Cells(69, 3) - Limits.Cells(69, 2)) * Rnd + Limits.Cells(69, 2)
    FernType = (Limits.Cells(70, 3) - Limits.Cells(70, 2)) * Rnd + Limits.Cells(70, 2)
    BareType = (Limits.Cells(71, 3) - Limits.Cells(71, 2)) * Rnd + Limits.Cells(71, 2)
    '
    initremcover = GrassType + SedgeType + ForbType + FernType + WoodyType +
     MossType + BareType
    remainder = remainder - initremcover
    'adjust cover of plant types
    adjGrass = (GrassType / initremcover) * remainder
    GrassType = GrassType + adjGrass
    adjSedge = (SedgeType / initremcover) * remainder
    SedgeType = SedgeType + adjSedge
    adjForb = (ForbType / initremcover) * remainder
    ForbType = ForbType + adjForb
    adjWoody = (WoodyType / initremcover) * remainder
    WoodyType = WoodyType + adjWoody
    adjFern = (FernType / initremcover) * remainder
    FernType = FernType + adjFern
    adjMoss = (MossType / initremcover) * remainder
    MossType = MossType + adjMoss
```

```
    adjBare = (BareType / initremcover) * remainder
    BareType = BareType + adjBare
    'check sum of covers = 1
    check = (GrassType + SedgeType + WoodyType + ForbType + MossType +
     FernType + BareType)
    If Abs(1 - check) > 0.001 Then
     Results.Cells(16, 1) = "Error in check"
    End If
    '
    xGrass = xGrass + (BirchArea * GrassType)
    xSedge = xSedge + (BirchArea * SedgeType)
    xWoody = xWoody + (BirchArea * WoodyType)
    xForb = xForb + (BirchArea * ForbType)
    xMoss = xMoss + (BirchArea * MossType)
    xFern = xFern + (BirchArea * FernType)
    xBare = xBare + (BirchArea * BareType)
    'calculate summer palatability score
    CellVegScore(count, 6) = (BirchArea * GrassType * 15) + (BirchArea * SedgeType
     * 10) + (BirchArea * WoodyType * 10) + (BirchArea * ForbType * 15) + (BirchArea
     * MossType * 0) + (BirchArea * FernType * 10)
    'calculate winter palatability score
    WinterVegScore(count, 6) = (BirchArea * GrassType * 5) + (BirchArea *
     SedgeType * 5) + (BirchArea * WoodyType * 10) + (BirchArea * ForbType * 0) +
     (BirchArea * MossType * 0) + (BirchArea * FernType * 5)
Else: CellVegScore(count, 6) = 0
    WinterVegScore(count, 6) = 0
End If

'sparsely vegetated land vegetation community
If SparseArea > 0 Then
    remainder = 1#
    Randomize
    'bare ground is dominant cover type
    BareType = (Rnd * (Limits.Cells(81, 3) - Limits.Cells(81, 2))) + Limits.Cells(81, 2)
    remainder = remainder - BareType
    'calculate secondary plant types
    GrassType = (Limits.Cells(75, 3) - Limits.Cells(75, 2)) * Rnd + Limits.Cells(75, 2)
    SedgeType = (Limits.Cells(76, 3) - Limits.Cells(76, 2)) * Rnd + Limits.Cells(76, 2)
    WoodyType = (Limits.Cells(77, 3) - Limits.Cells(77, 2)) * Rnd + Limits.Cells(77, 2)
    ForbType = (Limits.Cells(78, 3) - Limits.Cells(78, 2)) * Rnd + Limits.Cells(78, 2)
```

```
MossType = (Limits.Cells(79, 3) - Limits.Cells(79, 2)) * Rnd + Limits.Cells(79, 2)
FernType = (Limits.Cells(80, 3) - Limits.Cells(80, 2)) * Rnd + Limits.Cells(80, 2)
'
initremcover = GrassType + SedgeType + ForbType + FernType + WoodyType +
 MossType
remainder = remainder - initremcover
'adjust cover of secondary plant types
adjGrass = (GrassType / initremcover) * remainder
GrassType = GrassType + adjGrass
adjSedge = (SedgeType / initremcover) * remainder
SedgeType = SedgeType + adjSedge
adjForb = (ForbType / initremcover) * remainder
ForbType = ForbType + adjForb
adjWoody = (WoodyType / initremcover) * remainder
WoodyType = WoodyType + adjWoody
adjFern = (FernType / initremcover) * remainder
FernType = FernType + adjFern
adjMoss = (MossType / initremcover) * remainder
MossType = MossType + adjMoss
'check sum of covers = 1
check = (GrassType + SedgeType + WoodyType + ForbType + MossType +
 FernType + BareType)
If Abs(1 - check) > 0.001 Then
 Results.Cells(16, 1) = "Error in check"
End If
'
xGrass = xGrass + (SparseArea * GrassType)
xSedge = xSedge + (SparseArea * SedgeType)
xWoody = xWoody + (SparseArea * WoodyType)
xForb = xForb + (SparseArea * ForbType)
xMoss = xMoss + (SparseArea * MossType)
xFern = xFern + (SparseArea * FernType)
xBare = xBare + (SparseArea * BareType)
'calculate summer palatability score
CellVegScore(count, 7) = (SparseArea * GrassType * 15) + (SparseArea *
 SedgeType * 5) + (SparseArea * WoodyType * 5) + (SparseArea * ForbType * 10)
 + (SparseArea * MossType * 0) + (SparseArea * FernType * 10)
'calculate winter palatability score
```

```
    WinterVegScore(count, 7) = (SparseArea * GrassType * 5) + (SparseArea *
     SedgeType * 5) + (SparseArea * WoodyType * 5) + (SparseArea * ForbType * 5)
     + (SparseArea * MossType * 0) + (SparseArea * FernType * 5)
Else: CellVegScore(count, 7) = 0
    WinterVegScore(count, 7) = 0
End If

'write botanical composition values to worksheet
PasResults.Activate
Cells(1, 2) = RunNum
Cells(count + 4, 1) = CellIdArray(count)
Cells(count + 4, 2) = xGrass
Cells(count + 4, 3) = xSedge
Cells(count + 4, 4) = xWoody
Cells(count + 4, 5) = xForb
Cells(count + 4, 6) = xMoss
Cells(count + 4, 7) = xFern
Cells(count + 4, 8) = xBare
'calculate average summer palatability of the cell
If CellVegArea(count) > 0 Then
   Cells(count + 4, 9) = (CellVegScore(count, 0) + CellVegScore(count, 1) +
     CellVegScore(count, 2) + CellVegScore(count, 3) + CellVegScore(count, 4) +
     CellVegScore(count, 5) + CellVegScore(count, 6) + CellVegScore(count, 7)) /
     CellVegArea(count)
   SumPArray(count) = (CellVegScore(count, 0) + CellVegScore(count, 1) +
     CellVegScore(count, 2) + CellVegScore(count, 3) + CellVegScore(count, 4) +
     CellVegScore(count, 5) + CellVegScore(count, 6) + CellVegScore(count, 7))
  'calculate average winter palatability for the cell
   Cells(count + 4, 10) = (WinterVegScore(count, 0) + WinterVegScore(count, 1) +
     WinterVegScore(count, 2) + WinterVegScore(count, 3) + WinterVegScore(count,
     4) + WinterVegScore(count, 5) + WinterVegScore(count, 6) +
     WinterVegScore(count, 7)) / CellVegArea(count)
   WinPArray(count) = (WinterVegScore(count, 0) + WinterVegScore(count, 1) +
     WinterVegScore(count, 2) + WinterVegScore(count, 3) + WinterVegScore(count,
     4) + WinterVegScore(count, 5) + WinterVegScore(count, 6) +
     WinterVegScore(count, 7))
Else
    Cells(count + 4, 9) = 0
    SumPArray(count) = 0
    Cells(count + 4, 10) = 0
```

```
      WinPArray(count) = 0
    End If
    count = count + 1
    Range("A4").Select
    SheepDistribution.ColourCoding (9)  'colour code the output worksheet according to
      cell land-use type
    PasInputs.Activate
  Loop
End Sub
```

A.3 Sheep feed macro

```
Option Explicit
'This program calculates the individual feed requirements of the sheep flock over the
‘ course of twelve months, taking account of the different feed requirements of ewes,
‘ lambs, yearling sheep and rams/wethers. The equations used to calculate feed
‘requirements have been taken from the work of Breirem (1975), in Ólafsson (1980), and
‘ are based on the live weights of sheep. These feed requirements are adjusted to take
‘ account of the additional requirements of sheep grazing outside, rather than indoors
‘(Olafur Gudmundsson 1991)on different types of pasture and in different weather
‘conditions.
‘
Public WinterLambNum As Integer
'variables containing the feed requirements for livestock according to land type and month
Dim EweReq(2, 11) As Currency, LambReq(2, 11) As Currency, YoungReq(2, 11) As
      Currency, RamReq(2, 11) As Currency
'variables defining the upper and lower limits of daily feed requirements
Dim EweUp1 As Currency, EweLow1 As Currency, LambUp1 As Currency, LambLow1
      As Currency
Dim YoungUp1 As Currency, YoungLow1 As Currency, RamUp1 As Currency, RamLow1
      As Currency
'variables for winter feed requirements, assuming adjusted bodyweight
Dim WEweUp1 As Currency, WEweLow1 As Currency, WYoungUp1 As Currency,
      WYoungLow1 As Currency
Dim WRamUp1 As Currency, WRamLow1 As Currency
'counter variables
Dim days As Integer, v As Integer, n As Integer, x As Integer, j As Integer, k As Integer
Dim month As Integer, daycount As Integer, i As Integer, temp As Integer
Dim LambWtGain As Currency      'the amount of weight a lamb gains in a month
Dim LambsPerEwe As Currency     'number of lambs per ewe
```

```
'array containing the feed units required for each kg of weight gain, varying over time
Dim GainReq(11, 1)
Dim MilkReq As Currency            'the extra feed units required for a milking ewe
Dim xx As Single                   'random number generator variable
Dim XtraFeed(3, 11) As Currency     'factor of increase for livestock kept outside
'arrays containing number of each livestock cohort in each land use type in each month
Public UpNums(3, 11) As Integer, OutNums(3, 11) As Integer, BarnNums(3, 11) As
        Integer
'arrays containing total feed requirement of each cohort in each month
Public EweYear(2, 11) As Currency, LambYear(2, 11) As Currency, YoungYear(2, 11) As
        Currency, RamYear(2, 11) As Currency
```

```
Sub SheepFeed()
  Application.ScreenUpdating = False
  Worksheets("Livestock Inputs").Activate
  WinterLambNum = 0
  'assign feed/growth for lambs values to array from Limits sheet
  Worksheets("Limits").Activate
  For v = 1 To 12
    ActiveSheet.Cells((v + 2), 5).Select
    GainReq(v - 1, 0) = ActiveCell.Value
    ActiveSheet.Cells((v + 2), 6).Select
    GainReq(v - 1, 1) = ActiveCell.Value
  Next v

'calculate the upper and lower feed requirement limits based on average weight
  EweUp1 = (0.0084 * EweWt) + 0.1737
  EweLow1 = (0.0071 * EweWt) + 0.1383
  YoungUp1 = (0.0084 * YoungWt) + 0.1737
  YoungLow1 = (0.0084 * YoungWt) + 0.1383
  RamUp1 = (0.0084 * RamWt) + 0.1737
  RamLow1 = (0.0071 * RamWt) + 0.1383
'if % of bodyweight lost in winter >0 then adjust winter maintenance requirements based
        on new weights
  If WinLoss > 0 Then
    WEweUp1 = (0.0084 * EweWt * WinLoss) + 0.1737
    WEweLow1 = (0.0071 * EweWt * WinLoss) + 0.1383
    WYoungUp1 = (0.0084 * YoungWt * WinLoss) + 0.1737
    WYoungLow1 = (0.0084 * YoungWt * WinLoss) + 0.1383
    WRamUp1 = (0.0084 * RamWt * WinLoss) + 0.1737
```

```
   WRamLow1 = (0.0071 * RamWt * WinLoss) + 0.1383
Else
'else winter requirements = summer requirements
   WEweUp1 = EweUp1
   WEweLow1 = EweLow1
   WYoungUp1 = YoungUp1
   WYoungLow1 = YoungLow1
   WRamUp1 = RamUp1
   WRamLow1 = RamLow1
End If

FeedArray                    'calls the FeedArray procedure
days = 0                    ' initialise counter variables
daycount = 0
month = 0
v = 1
Randomize       'a random factor represents the variation in feed requirements
xx = Rnd

For month = 0 To 11
   'Loop which calculates individual and total feed requirements for each month in turn
   'May = 0, June = 1, July = 2, August = 3, September = 4, October = 5,
   'November = 6, December = 7, January = 8, February = 9, March = 10 and April = 11
   If month = 1 Or 4 Or 6 Or 11 Then   'adjusts days and daycount variables to take
      days = 30                           ' account of months of different length
   ElseIf month = 9 Then
      days = 28
   Else:   days = 31
   End If
   daycount = daycount + days
   '
   'lamb weights are  calculated from an adjusted equation from (Armstrong et al. 1997)
   If month = 0 Then LambWt(1) = 0.0783 * EweWt
   LambWt(0) = ((0.00312 * daycount) + 0.0783) * EweWt
   LambWtGain = LambWt(0) - LambWt(1)
   'lamb weights increase over time so the upper and lower limits of their feed
   ‘ requirements need to be increased accordingly on a monthly basis
   'Weight is estimated mid-month in the equation below
   LambUp1 = (0.0084 * ((LambWtGain / 2) + LambWt(1))) + 0.1737
   LambLow1 = (0.0071 * ((LambWtGain / 2) + LambWt(1))) + 0.1383
```

```
  '
For k = 0 To 2      'k = landuse type, 0 = rangeland, 1 = outfield, 2 = byre
  If month = 0 Then
    'May: lambs still feeding from ewes
    EweReq(k, month) = ReqCalc(EweUp1, EweLow1, days) * XtraFeed(k, month)
    YoungReq(k, month) = ReqCalc(YoungUp1, YoungLow1, days) * XtraFeed(k,
     month)
    RamReq(k, month) = ReqCalc(RamUp1, RamLow1, days) * XtraFeed(k, month)
    LambReq(k, month) = (ReqCalc(LambUp1, LambLow1, days) + (GainReq(month,
     1) * LambWtGain)) * XtraFeed(k, month)
    MilkReq = LambReq(k, month) / 0.7
    If EweNum > 0 Then
      LambsPerEwe = LambNum / EweNum
      'feed requirements of ewes are increases during lactation
      EweReq(k, month) = EweReq(k, month) + (LambsPerEwe * MilkReq)
      LambReq(k, month) = 0
    End If
  ElseIf month = 1 Then
'June: lambs are weaned mid-month but ewes continue lactating
    EweReq(k, month) = ReqCalc(EweUp1, EweLow1, days) * XtraFeed(k, month)
    YoungReq(k, month) = ReqCalc(YoungUp1, YoungLow1, days) * XtraFeed(k,
     month)
    RamReq(k, month) = ReqCalc(RamUp1, RamLow1, days) * XtraFeed(k, month)
    LambReq(k, month) = (ReqCalc(LambUp1, LambLow1, days) + (GainReq(month,
     1) * LambWtGain)) * XtraFeed(k, month)
    MilkReq = (LambReq(k, month) / 0.7)
    If EweNum > 0 Then
      LambsPerEwe = LambNum / EweNum
      EweReq(k, month) = EweReq(k, month) + (LambsPerEwe * MilkReq)
      LambReq(k, month) = LambReq(k, month) / 2
    End If
  ElseIf month = 2 Or month = 3 Then    'lambs are weaned but ewes are still lactating
    EweReq(k, month) = ReqCalc(EweUp1, EweLow1, days) * XtraFeed(k, month)
    YoungReq(k, month) = ReqCalc(YoungUp1, YoungLow1, days) * XtraFeed(k,
     month)
    RamReq(k, month) = ReqCalc(RamUp1, RamLow1, days) * XtraFeed(k, month)
    LambReq(k, month) = (ReqCalc(LambUp1, LambLow1, days) + (GainReq(month,
     1) * LambWtGain)) * XtraFeed(k, month)
    MilkReq = (LambReq(k, 1) / 0.7)
    If EweNum > 0 Then
```

```
         LambsPerEwe = LambNum / EweNum
         EweReq(k, month) = EweReq(k, month) + (LambsPerEwe * MilkReq)
      End If
   ElseIf month >= 7 And month < 12 Then
   'winter months - ewes are no longer lactating
      EweReq(k, month) = ReqCalc(WEweUp1, WEweLow1, days) * XtraFeed(k,
       month)
      YoungReq(k, month) = ReqCalc(WYoungUp1, WYoungLow1, days) * XtraFeed(k,
       month)
      RamReq(k, month) = ReqCalc(WRamUp1, WRamLow1, days) * XtraFeed(k,
       month)
      LambReq(k, month) = (ReqCalc(LambUp1, LambLow1, days) + (GainReq(month,
       1) * LambWtGain)) * XtraFeed(k, month)
   Else                              'remaining summer and autumn months, ewes not lactating
      EweReq(k, month) = ReqCalc(EweUp1, EweLow1, days) * XtraFeed(k, month)
      YoungReq(k, month) = ReqCalc(YoungUp1, YoungLow1, days) * XtraFeed(k,
       month)
      RamReq(k, month) = ReqCalc(RamUp1, RamLow1, days) * XtraFeed(k, month)
      LambReq(k, month) = (ReqCalc(LambUp1, LambLow1, days) + (GainReq(month,
       1) * LambWtGain)) * XtraFeed(k, month)
   End If
   Next k
   'lamb weight is updated
   LambWt(1) = LambWt(0)
   If month = 4 Then          'month = September
      If LambNum > 0 And EweNum > 0 Then
         WinterLambNum = RetainLambs
      End If
   End If
Next month

SheepLocation                      ' calls the SheepLocation procedure
month = 0
For month = 0 To 11
   For n = 0 To 1
     'initialise variables
     EweYear(n, month) = 0
     LambYear(n, month) = 0
     YoungYear(n, month) = 0
     RamYear(n, month) = 0
```

```
    Next n
Next month
For month = 0 To 11
    'calculates the total feed requirements for each cohort in each month
    If UpNums(0, month) > 0 Then
        EweYear(0, month) = EweReq(0, month) * UpNums(0, month)
    ElseIf OutNums(0, month) > 0 Then
        EweYear(1, month) = EweReq(1, month) * OutNums(0, month)
    Else: EweYear(2, month) = EweReq(2, month) * BarnNums(0, month)
    End If
    '
    If UpNums(1, month) > 0 Then
        LambYear(0, month) = LambReq(0, month) * UpNums(1, month)
    ElseIf OutNums(1, month) > 0 Then
        LambYear(1, month) = LambReq(1, month) * OutNums(1, month)
    Else: LambYear(2, month) = LambReq(2, month) * BarnNums(1, month)
    End If
    '
    If UpNums(2, month) > 0 Then
        YoungYear(0, month) = YoungReq(0, month) * UpNums(2, month)
    ElseIf OutNums(2, month) > 0 Then
        YoungYear(1, month) = YoungReq(1, month) * OutNums(2, month)
    Else: YoungYear(2, month) = YoungReq(2, month) * BarnNums(2, month)
    End If
    '
    If UpNums(3, month) > 0 Then
        RamYear(0, month) = RamReq(0, month) * UpNums(3, month)
    ElseIf OutNums(3, month) > 0 Then
        RamYear(1, month) = RamReq(1, month) * OutNums(3, month)
    Else: RamYear(2, month) = RamReq(2, month) * BarnNums(3, month)
    End If
Next month

Worksheets("Offtake Results").Activate
'output individual monthly requirements for each cohort in each landuse type
For j = 0 To 2              'j = land use type
    For month = 0 To 11
        Cells(j + 2, month + 2) = EweReq(j, month)
        Cells(j + 5, month + 2) = LambReq(j, month)
        Cells(j + 8, month + 2) = YoungReq(j, month)
```

```
        Cells(j + 11, month + 2) = RamReq(j, month)
    Next month
  Next j
End Sub
```

```
'function to randomise feed unit requirements within range limits
Function ReqCalc(upper As Currency, lower As Currency, days As Integer) As Currency
  ReqCalc = (Rnd * (upper - lower) + lower) * days
End Function
```

```
Sub FeedArray()
'reads in the feed increases required for animals 'grazing each land type according to the
' climate scenario. The first term in the Xtrafeed array denotes the land type:
' 0=Rangeland, 1=Outfield. The second term denotes the month.
  Worksheets("Limits").Activate
  If ClimateScen = "Warm" Then
    j = 30
  ElseIf ClimateScen = "Baseline" Then
    j = 34
  ElseIf ClimateScen = "Cold" Then
    j = 38
  ElseIf ClimateScen = "Extreme Cold" Then
    j = 42
  End If
  For v = 1 To 12
    ActiveSheet.Cells(j, v + 5).Select
    XtraFeed(0, v - 1) = ActiveCell.Value
    ActiveSheet.Cells(j + 1, v + 5).Select
    XtraFeed(1, v - 1) = ActiveCell.Value
  Next v
  'if animals are kept indoors then they do not require extra feeding
  For v = 0 To 11
    XtraFeed(2, v) = 1
  Next v
End Sub
```

```
Sub SheepLocation()
  'Initialising the sheep/landuse array
  i = 0
  month = 0
```

```
    For i = 0 To 3
        For month = 0 To 11
            UpNums(i, month) = 0
            OutNums(i, month) = 0
            BarnNums(i, month) = 0
        Next month
    Next i
    'reading in the number of sheep on each landuse type in each month
    Worksheets("Livestock Inputs").Activate
    Range("B21").Select
    For i = 0 To 3
        temp = 0
        If i = 0 Then temp = EweNum
        If i = 1 Then temp = LambNum
        If i = 2 Then temp = YoungNum
        If i = 3 Then temp = RamNum
        For month = 0 To 11
            If (month > 4 And i = 1) Then temp = WinterLambNum
            If (month > 4 And i = 2) Then temp = WinterYoungNum
            Range("B21").Offset(i, month).Select
            If Selection.Value = "U" Then UpNums(i, month) = temp
            If Selection.Value = "O" Then OutNums(i, month) = temp
            If Selection.Value = "B" Then BarnNums(i, month) = temp
        Next month
    Next i
End Sub
```

A.4 HayCalcs macro

```
Option Explicit
'This module calculates the amount of hay that can be produced from the hayfield and the
' number of feed units available from this hay. It then compares the number of feed units
'required by the winter-fed livestock with the quantity available.

Dim SumTemp As Currency, WinTemp As Currency
Dim HayArea As Currency, HayYield As Currency
Public TotalHay As Currency, TotalHayFeed As Currency
Public HayFailCount(11) As Integer
Dim c As Integer, i As Integer, x As Integer, mth As String
```

```
Sub HayModel()
```

```
'initialise variables
SumTemp = 0
WinTemp = 0
HayArea = 0
HayYield = 0
TotalHay = 0
TotalHayFeed = 0
c = 0
'Assign summer and winter temperatures according to location and climatic scenario
If Location = 1 Then                    'Southern location
   If ClimateScen = "Baseline" Then
      SumTemp = 7.88
      WinTemp = 0.41
   ElseIf ClimateScen = "Extreme Cold" Then
      SumTemp = 7.34
      WinTemp = -1.06
   ElseIf ClimateScen = "Cold" Then
      SumTemp = 7.57
      WinTemp = -0.44
   ElseIf ClimateScen = "Warm" Then
      SumTemp = 9#
      WinTemp = 1.59
   End If
ElseIf Location = 2 Then                'Northern location
If ClimateScen = "Baseline" Then
      SumTemp = 7.99
      WinTemp = 0.34
   ElseIf ClimateScen = "Extreme Cold" Then
      SumTemp = 7.34
      WinTemp = -1.09
   ElseIf ClimateScen = "Cold" Then
      SumTemp = 7.54
      WinTemp = -0.5
   ElseIf ClimateScen = "Warm" Then
      SumTemp = 9.19
      WinTemp = 1.54
   End If
End If
'Calculate the area of hayfield from the Pasture Inputs sheet
For c = 0 To (OutNum - 1)
```

```
   HayArea = HayArea + (OutCellArray(c, 1) / 10000)
Next
'
HerbResults.Activate
Range("B2").Select
'If hayfield area = 0 then stored hay is the only hay available
If HayArea = 0 Then
   HayYield = 0
   TotalHay = HayStore
   If HayStore > 0 Then
      TotalHayFeed = TotalHay / HayFeedUnits
   End If
Else
'predicts the hay harvested in July from equation in Bergþórsson et al. (1987)
   HayYield = -66 + (226 * WinTemp) + (186 * SumTemp) + (25.8 * Fertiliser / HayArea)
   TotalHay = HayStore + (HayYield * HayArea)      'total hay available in kg DM
   TotalHayFeed = TotalHay / HayFeedUnits          'total feed units available from hay
End If
ActiveCell = TotalHay

'Calculate the hay consumed by byred livestock over the winter
For i = 0 To 11
   HayConsumption EweYear(2, i)
   HayConsumption LambYear(2, i)
   HayConsumption YoungYear(2, i)
   HayConsumption RamYear(2, i)
   If TotalHayFeed < 0 Then                        'Hay deficit
      If runcount = 1 Then
         HayDeficitForm
         Exit For
      Else
         HayFailSub
         Exit For
      End If
   End If
Next i
If TotalHayFeed > 0 And runcount = 1 Then          'Hay surplus
   HayExcessForm TotalHayFeed
ElseIf TotalHayFeed > 0 And runcount > 1 Then
   HayReserves(RunNum) = TotalHayFeed * HayFeedUnits
```

```
Else: HayReserves(RunNum) = 0
End If
ActiveCell.Offset(0, RunNum) = HayReserves(RunNum)
End Sub
```

```
Sub HayConsumption(SheepYear As Currency)
'calculate hay consumption by each livestock cohort
   TotalHayFeed = TotalHayFeed - SheepYear
End Sub
```

```
Sub HayDeficitForm()
   If i = 0 Then mth = "May"
   If i = 1 Then mth = "June"
   If i = 2 Then mth = "July"
   If i = 3 Then mth = "August"
   If i = 4 Then mth = "September"
   If i = 5 Then mth = "October"
   If i = 6 Then mth = "November"
   If i = 7 Then mth = "December"
   If i = 8 Then mth = "January"
   If i = 9 Then mth = "February"
   If i = 10 Then mth = "March"
   If i = 11 Then mth = "April"
   MsgBox "At current livestock levels your hay stores are exhausted by " + mth + "."
End Sub
```

```
Sub HayExcessForm(Reserves As Currency)
   Reserves = TotalHayFeed * HayFeedUnits
   MsgBox "All your livestock have survived the winter. There is " + Str(Int(Reserves)) + "
         kg of hay remaining."
End Sub
```

```
Sub HayFailSub()
'counts the number of hay simulation failures for multiple runs
   For x = i To 11
      HayFailCount(x) = HayFailCount(x) + 1
   Next x
End Sub
```

A.5 SheepDistribution macro

```
Option Explicit
'Biomass production and offtake feedback model
'
Dim TotalPalProd(11) As Currency
Dim PalProd() As Currency
Dim CellId As Integer
Dim SHhayfield As Currency, SHgrass As Currency, SHshrub As Currency
Dim SHmoss As Currency, SHbog As Currency, SHhalfbog As Currency
Dim SHbirch As Currency, SHsparse As Currency
Public TotalPal As Currency, TotalSheep As Currency
Dim numRows As Integer, numCols As Integer
Dim Row As Integer, Col As Integer
Dim x As Integer, v As Integer, a As Variant, b As Variant, c As Variant
Dim y As Integer, month As Integer, i As Integer
Dim element, xx
Dim RandomCell() As Variant, rndcell() As Variant
Dim UpPalProd(11) As Double, OutPalProd(11) As Double
Dim UpTotal(11) As Integer, OutTotal(11) As Integer
Dim endmonth As Integer
Dim num As Currency, tquant As Currency, jj As Currency, tExcount As Currency, mth As Currency
Dim TotYear As Currency, totreq As Currency

'variables for calculating offtake
Dim PeakUB() As Currency
Dim TotalPeakUB() As Currency
Dim CellComSH() As Double
Dim CellFeedUnits() As Double, TotFeedUnits(11) As Double
Dim CellFeed() As Double
Dim Cell3dfu() As Double
Dim Cell3dKg() As Double
Dim FUVal(7) As Currency, haykg As Single, grasskg As Single, dwarfkg As Single, mosskg As Single
Dim bogkg As Single, halfbogkg As Single, birchkg As Single, sparsekg As Single
Dim TotalOff As Currency
Dim AvgCellFU() As Variant, SumOfftake() As Currency, SumSheep() As Variant
Dim excess As Currency, okcells As Integer, flag As Integer, excesspercell As Currency
```

```
Sub Distribution()
```

```
    Application.ScreenUpdating = False

'Define dynamic arrays using number of cells
    ReDim PeakUB(NumCells - 1, 7)
    ReDim TotalPeakUB(NumCells - 1)
    ReDim PalProd(NumCells - 1, 11)
    ReDim CellFeedUnits(NumCells - 1, 11)
    ReDim CellFeed(11, NumCells - 1)
    ReDim Cell3dfu(NumCells - 1, 11, 7)
    ReDim Cell3dKg(NumCells - 1, 11, 7)
    ReDim CellComSH(NumCells - 1, 11, 7)
    ReDim AvgCellFU(NumCells - 1)
    ReDim SumOfftake(NumCells - 1)
    ReDim SumSheep(runcount, 11)
'calculate the total number of sheep on each landuse type in each month
    Worksheets("check window").Activate
    Range("B6").Select
    For month = 0 To 11
        UpTotal(month) = 0
        OutTotal(month) = 0
        For i = 0 To 3      'for each livestock cohort
            UpTotal(month) = UpTotal(month) + UpNums(i, month)
            OutTotal(month) = OutTotal(month) + OutNums(i, month)
        Next i
        Selection.Offset(0, month) = UpTotal(month)
        Selection.Offset(1, month) = OutTotal(month)
    Next month
    'read in the values of kg of dry matter required for one feed unit in each vegetation type
    Limits.Activate
    Range("F18").Select
    For b = 0 To 7
      FUVal(b) = Selection.Offset(b, 0)
    Next b

'initialise variables
    For i = 0 To 11
        UpPalProd(i) = 0
        OutPalProd(i) = 0
        SumSheep(RunNum, i) = 0
    Next i
```

```
    For i = 0 To NumCells - 1
        For month = 0 To 11
            CellSheep(i, month, RunNum) = 0
            CellHerbage(i, month, RunNum) = 0
            CellUtil(i, month, RunNum) = 0
            CumUtil(i, month, RunNum) = 0
        Next month
    Next i
    For i = 0 To NumCells - 1
        SumOfftake(i) = 0
    Next i

' A new random number value is used for each cell in turn
   ReDim RandomCell(NumCells - 1)
   ReDim rndcell(NumCells - 1)
   Randomize
    For x = 0 To NumCells - 1
        Do
            xx = Rnd
            rndcell(x) = xx
            RandomCell(x) = normpick(xx)    'function normpick is given below
        Loop Until RandomCell(x) >= -1 And RandomCell(x) <= 1
    Next x
    'calculate utilisable biomass at peak of growing season as a proxy for net primary
    ‘productivity for each vegetation community in turn
    For x = 0 To NumCells - 1
        If ClimateScen = "Baseline" Or ClimateScen = "Warm" Then
            i = 2          'in the baseline or warm scenario the peak is in July
        Else: i = 3        'in the cold scenarios the peak is in August
        End If
            PeakUB(x, 0) = (CellArray(x, 1) / 10000) * SHRange(RandomCell(x), HerbArray(x,
             0, i))
            PeakUB(x, 1) = (CellArray(x, 2) / 10000) * SHRange(RandomCell(x), HerbArray(x,
             1, i))
            PeakUB(x, 2) = (CellArray(x, 3) / 10000) * SHRange(RandomCell(x), HerbArray(x,
             2, i))
            PeakUB(x, 3) = (CellArray(x, 4) / 10000) * SHRange(RandomCell(x), HerbArray(x,
             3, i))
            PeakUB(x, 4) = (CellArray(x, 5) / 10000) * SHRange(RandomCell(x), HerbArray(x,
             4, i))
```

```
        PeakUB(x, 5) = (CellArray(x, 6) / 10000) * SHRange(RandomCell(x), HerbArray(x,
         5, i))
        PeakUB(x, 6) = (CellArray(x, 7) / 10000) * SHRange(RandomCell(x), HerbArray(x,
         6, i))
        PeakUB(x, 7) = (CellArray(x, 8) / 10000) * SHRange(RandomCell(x), HerbArray(x,
         7, i))
        'total peak UB in each cell
        TotalPeakUB(x) = PeakUB(x, 0) + PeakUB(x, 1) + PeakUB(x, 2) + PeakUB(x, 3) +
         PeakUB(x, 4) + PeakUB(x, 5) + PeakUB(x, 6) + PeakUB(x, 7)
 Next x
For v = 0 To 11      'for each month
    'for rangeland
    If UpNum > 0 Then
        CellCalculations v, UpCellId(), UpPalProd(v), UpTotal(v), 0
        'CellCalculations procedure listed below
        TotYear = EweYear(0, v) + LambYear(0, v) + YoungYear(0, v) + RamYear(0, v)
        'if feed units available < feed units required then set output values for remaining
        'months to 0 (or 100% for monthly utilisation)
        If TotYear > TotFeedUnits(v) Then
            For Each element In UpCellId()
            For month = v To 11
                CellHerbage(element - 1, month, RunNum) = 0
                CellKgOff(element - 1, month, RunNum) = 0
                CellUtil(element - 1, month, RunNum) = 100
                CellSheep(element - 1, month, RunNum) = 0
            Next month
            Next element
            If runcount = 1 Then
                StarvationForm "upland", TotYear
                FailureSub
                Exit For
            Else
                FailureSub
                Exit For
            End If
        End If
    End If
    'for outfield
    If OutNum > 0 Then
        CellCalculations v, OutCellId(), OutPalProd(v), OutTotal(v), 1
```

```
      TotYear = EweYear(1, v) + LambYear(1, v) + YoungYear(1, v) + RamYear(1, v)
      If TotYear >= TotFeedUnits(v) Then
        For Each element In OutCellId
        For month = v To 11
          CellHerbage(element - 1, month, RunNum) = 0
          CellKgOff(element - 1, month, RunNum) = 0
          CellUtil(element - 1, month, RunNum) = 100
          CellSheep(element - 1, month, RunNum) = 0
        Next month
        Next element
        If runcount = 1 Then
          StarvationForm "outfield", TotYear
         FailureSub
          Exit For
        Else
          FailureSub
          Exit For
        End If
        'FailureSub
      End If
    End If
  Next v

'write outputs to HerbageResults and OfftakeResults spreadsheet
  If runcount = RunNum Then       'if final run in simulation set
    HerbResults.Activate
    Cells(1, 2) = RunNum
    Range("A4").Select
    For month = 0 To 11
      For x = 0 To NumCells - 1
        Selection.Offset(x, 0) = CellIdArray(x)
        Selection.Offset(x, month + 1) = CellHerbage(x, month, RunNum)
        Selection.Offset(x, month + 13) = CellSheep(x, month, RunNum)
      Next x
    Next month
    'colour code the results so that the different landuse types can be distinguished
    ColourCoding (24)
    '
    OffResults.Activate
    Cells(15, 2) = RunNum + 1
```

```
        Range("A18").Select
        For x = 0 To (NumCells - 1)
            Selection.Offset(x, 0) = CellIdArray(x)
            For month = 0 To 11
                Selection.Offset(x, month + 1) = CellKgOff(x, month, RunNum)
                Selection.Offset(x, month + 13) = CumUtil(x, month, RunNum)
                Selection.Offset(x, month + 25) = CellUtil(x, month, RunNum)
            Next month
        Next x
        'colour coding the results so that different land use types can be distinguished
        ColourCoding (36)
    End If
End Sub
```

```
Sub CellCalculations(i As Integer, LandId As Variant, LandPalProd As Double, LandTotal
             As Integer, landcode As Integer)
'i = month, LandId = cell-id, LandPalProd = palatability score and UB, LandTotal =
'livestock numbers, landcode = land use zone for each month in turn calculate the
'standing herbage in each cell
    For Each element In LandId
        If i <= 5 Or i = 11 Then        'if month is between April and October
            'calculate monthly Ub of each vegetation community in the cell
          CellComSH(element - 1, i, 1) = (CellArray(element - 1, 2) / 10000) *
             SHRange(RandomCell(element - 1), HerbArray(element - 1, 1, i))
          CellComSH(element - 1, i, 2) = (CellArray(element - 1, 3) / 10000) *
             SHRange(RandomCell(element - 1), HerbArray(element - 1, 2, i))
          CellComSH(element - 1, i, 3) = (CellArray(element - 1, 4) / 10000) *
             SHRange(RandomCell(element - 1), HerbArray(element - 1, 3, i))
          CellComSH(element - 1, i, 4) = (CellArray(element - 1, 5) / 10000) *
             SHRange(RandomCell(element - 1), HerbArray(element - 1, 4, i))
          CellComSH(element - 1, i, 5) = (CellArray(element - 1, 6) / 10000) *
             SHRange(RandomCell(element - 1), HerbArray(element - 1, 5, i))
          CellComSH(element - 1, i, 6) = (CellArray(element - 1, 7) / 10000) *
             SHRange(RandomCell(element - 1), HerbArray(element - 1, 6, i))
          CellComSH(element - 1, i, 7) = (CellArray(element - 1, 8) / 10000) *
             SHRange(RandomCell(element - 1), HerbArray(element - 1, 7, i))
            'calculate total UB in cell as sum of all community UBs
          CellHerbage(element - 1, i, RunNum) = CellComSH(element - 1, i, 0) +
             CellComSH(element - 1, i, 1) + CellComSH(element - 1, i, 2) +
             CellComSH(element - 1, i, 3) + CellComSH(element - 1, i, 4) +
```

```
          CellComSH(element - 1, i, 5) + CellComSH(element - 1, i, 6) +
          CellComSH(element - 1, i, 7)
       End If
   Next element
   '
   'the standing herbage left in October is the maximum available during the winter
   If i = 6 Then
      For Each element In LandId
         For month = i To 11
            For b = 1 To 7
               CellComSH(element - 1, month, b) = CellComSH(element - 1, 5, b)
            Next b
         Next month
      Next element
   End If
   If i > 5 And i < 11 Then
      'if it is winter and there is no regrowth then grazed herbage cannot be replaced
      'senescence and litterfall continue at the same rate as that under zero grazing
      If ClimateScen = "Baseline" Or ClimateScen = "Warm" Then endmonth = 10
      If ClimateScen = "Extreme Cold" Or ClimateScen = "Cold" Then endmonth = 11
      For Each element In LandId
         For b = 1 To 7
            CellComSH(element - 1, i, b) = (CellComSH(element - 1, i - 1, b) -
          Cell3dKg(element - 1, i - 1, b)) * SenRate(i, b)
            CellHerbage(element - 1, i, RunNum) = CellHerbage(element - 1, i, RunNum) +
          CellComSH(element - 1, i, b)
         Next b
     'if month < April and there is 0 UB in cell then UB for all remaining months is reset to 0
         If i < 11 Then
            If CellHerbage(element - 1, i, RunNum) <= 0 Then
               For month = i To endmonth
                  CellHerbage(element - 1, month, RunNum) = 0
               Next month
            End If
         End If
      Next element
   End If

'Calculate product of palatability and quantity of standing herbage for each cell,
 'and cumulative totals for each landuse type
```

```
    '1) using summer palatability values
  For Each element In LandId
    If i <= 4 Then
      PalProd(element - 1, i) = CellHerbage(element - 1, i, RunNum) *
       SumPArray(element - 1)
      LandPalProd = LandPalProd + PalProd(element - 1, i)
    Else
    'using winter palatability values
      PalProd(element - 1, i) = CellHerbage(element - 1, i, RunNum) *
       WinPArray(element - 1)
      LandPalProd = LandPalProd + PalProd(element - 1, i)
    End If
  Next element
  TotFeedUnits(i) = 0
  For Each element In LandId
    CellFeedUnits(element - 1, i) = 0
    For b = 1 To 7
      'calculate feed units available from each vegetation community in the cell
      CellFeedUnits(element - 1, i) = CellFeedUnits(element - 1, i) +
       (CellComSH(element - 1, i, b) / FUVal(b))
    Next b
    'total feed units available in the land use zone
    TotFeedUnits(i) = TotFeedUnits(i) + CellFeedUnits(element - 1, i)
  Next element

'assign livestock to cells based on landuse type, palatability of vegetation and the amount
‘ of standing herbage in the cell relative to the rest of the landuse zone
  Worksheets("check window").Activate
  Range("Q16").Select
  Selection.Offset(0, 2 * i).Select
  For Each element In LandId
    If LandTotal > 0 And LandPalProd > 0 Then
      CellSheep(element - 1, i, RunNum) = LandTotal * PalProd(element - 1, i) /
       LandPalProd
      'feed units required from cell based on livestock distribution
      CellFeed(i, element - 1) = ((EweYear(landcode, i) + LambYear(landcode, i) +
       YoungYear(landcode, i) + RamYear(landcode, i)) / LandTotal) *
       CellSheep(element - 1, i, RunNum)
      Selection.Offset(element, 0) = CellFeed(i, element - 1)
      Selection.Offset(element, 1) = CellFeedUnits(element - 1, i)
```

```
    Else: CellSheep(element - 1, i, RunNum) = 0
        CellFeed(i, element - 1) = 0
    End If
Next element
TotYear = EweYear(landcode, i) + LambYear(landcode, i) + YoungYear(landcode, i) +
         RamYear(landcode, i)
If TotYear < TotFeedUnits(i) Then
    'check utilisation is not greater than 100%
    'if feed units required > feed units available then livestock are redistributed
    'among cells that still have UB remaining
    Do
        excess = 0
        okcells = 0
        flag = 0
        For Each element In LandId
            If CellFeed(i, element - 1) >= CellFeedUnits(element - 1, i) Then
                excess = excess + (CellFeed(i, element - 1) - CellFeedUnits(element - 1, i))
                CellFeed(i, element - 1) = CellFeedUnits(element - 1, i)
            Else: okcells = okcells + 1
            End If
        Next element
        If okcells > 0 Then
            excesspercell = excess / okcells
        Else: Exit Do
        End If
        For Each element In LandId
            If CellFeed(i, element - 1) < CellFeedUnits(element - 1, i) Then
                CellFeed(i, element - 1) = CellFeed(i, element - 1) + excesspercell
                If CellFeed(i, element - 1) > CellFeedUnits(element - 1, i) Then
                    flag = 1
                End If
            End If
        Next element
    Loop Until flag = 0
        '
    If LandTotal > 0 Then
        For Each element In LandId
            CellSheep(element - 1, i, RunNum) = (CellFeed(i, element - 1) * LandTotal) /
         (EweYear(landcode, i) + LambYear(landcode, i) + YoungYear(landcode, i) +
         RamYear(landcode, i))
```

```
          SumSheep(RunNum, i) = SumSheep(RunNum, i) + CellSheep(element - 1, i,
        RunNum)
        Next element
      End If

For Each element In LandId
        If i <= 4 Then              'in summer
          For b = 1 To 7
            If SumPArray(element - 1) > 0 And LandTotal > 0 Then
            'feed units are removed from each vegetation community in the cell relative
        to their palatability
              Cell3dfu(element - 1, i, b) = CellFeed(i, element - 1) *
        (CellVegScore(element - 1, b) / SumPArray(element - 1))
            Else: Cell3dfu(element - 1, i, b) = 0
            End If
          Next b
        Else                    'in winter
          For b = 1 To 7
            If WinPArray(element - 1) > 0 And LandTotal > 0 Then
              Cell3dfu(element - 1, i, b) = CellFeed(i, element - 1) *
        (WinterVegScore(element - 1, b) / WinPArray(element - 1))
            Else: Cell3dfu(element - 1, i, b) = 0
            End If
          Next b
        End If
      Next element

'for each cell offtake is calculated according to the feed unit value of each vegetation
' community and the feed units consumed from that vegetation community
      For Each element In LandId
        CellKgOff(element - 1, i, RunNum) = 0
        TotalOff = 0
        For b = 1 To 7
          Cell3dKg(element - 1, i, b) = Cell3dfu(element - 1, i, b) * FUVal(b)
          'total offtake from cell
          TotalOff = TotalOff + Cell3dKg(element - 1, i, b)
        Next b
        CellKgOff(element - 1, i, RunNum) = TotalOff
        'total offtake from all cells in landuse zone
```

```
            SumOfftake(element - 1) = SumOfftake(element - 1) + CellKgOff(element - 1, i,
             RunNum)
            Range("B9").Select
            'calculate monthly utilisation of the available utilisable biomass in month i
            If CellKgOff(element - 1, i, RunNum) > 0 And CellHerbage(element - 1, i,
             RunNum) > 0 Then
               CellUtil(element - 1, i, RunNum) = (CellKgOff(element - 1, i, RunNum) /
             CellHerbage(element - 1, i, RunNum)) * 100
            Else: CellUtil(element - 1, i, RunNum) = 0
            End If
            Selection.Offset(RunNum, i) = SumSheep(RunNum, i)
         Next element
         '
         'calculate cumulative utilisation (sum of all offtakes up to month i divided by peak
             utilisable biomass)
         For Each element In LandId
            If SumOfftake(element - 1) > 0 Then
               For month = i To 11
                  CumUtil(element - 1, month, RunNum) = (SumOfftake(element - 1) /
             TotalPeakUB(element - 1)) * 100
               Next month
            Else: CumUtil(element - 1, i, RunNum) = 0
            End If
         Next element

'summer offtake UB feedback loop
         If i <= 4 Then
            For Each element In LandId
               Threshold (element - 1), i, 1, PeakUB(element - 1, 1), 40
               Threshold (element - 1), i, 2, PeakUB(element - 1, 2), 15
               Threshold (element - 1), i, 3, PeakUB(element - 1, 3), 40
               Threshold (element - 1), i, 4, PeakUB(element - 1, 4), 35
               Threshold (element - 1), i, 5, PeakUB(element - 1, 5), 40
               Threshold (element - 1), i, 6, PeakUB(element - 1, 6), 40
               Threshold (element - 1), i, 7, PeakUB(element - 1, 7), 40
            Next element
         End If
      End If
End Sub
```

```
Function SHRange(xx As Variant, herbage As Currency) As Single
'calculate UB from within ±55% envelope around mean UB value
    SHRange = (xx * (herbage * 0.55)) + herbage
End Function
```

```
Function normpick(num)
 'returns a standard normal (0,1) variate given a random number
 'sampled from the standard uniform distribution (0-1)
  If num > 0.5 Then
   tquant = Sqr(-2 * Log(1 - num))
  jj = -(((2.515517 + 0.802853 * tquant + 0.010328 * tquant ^ 2) / (1 + 1.432788 * tquant +
            0.189269 * tquant ^ 2 + 0.001308 * tquant ^ 3)) - tquant)
    Else
   tquant = Sqr(-2 * Log(num))
  jj = ((2.515517 + 0.802853 * tquant + 0.010328 * tquant ^ 2) / (1 + 1.432788 * tquant +
            0.189269 * tquant ^ 2 + 0.001308 * tquant ^ 3)) - tquant
  End If
 normpick = jj
End Function
```

```
Sub Threshold(cell As Variant, j As Integer, vegcomm As Integer, SH As Currency, thresh
            As Currency)
'reduces UB in subsequent months by 20% if vegetation community has been grazed
' beyond threshold of sustainability
    If Cell3dKg(cell, j, vegcomm) > 0 And SH > 0 Then
        If (Cell3dKg(cell, j, vegcomm) / SH * 100) > thresh Then
            For month = j To 4
                HerbArray(cell, vegcomm, month + 1) = HerbArray(cell, vegcomm, month + 1) *
            0.8
            Next month
        End If
    End If
End Sub
```

```
Sub StarvationForm(landcode As String, totreq As Currency)
'for use with single simulation run
    If v = 0 Then mth = "May"
    If v = 1 Then mth = "June"
    If v = 2 Then mth = "July"
    If v = 3 Then mth = "August"
```

```
   If v = 4 Then mth = "September"
   If v = 5 Then mth = "October"
   If v = 6 Then mth = "November"
   If v = 7 Then mth = "December"
   If v = 8 Then mth = "January"
   If v = 9 Then mth = "February"
   If v = 10 Then mth = "March"
   If v = 11 Then mth = "April"
   MsgBox "You are doomed! In the " + landcode + " " + Str(Int(totreq)) + _
   " feed units are required in the month of " + mth + " and there are only " +
          Str(Int(TotFeedUnits(v))) + " available."
End Sub
```

```
Sub FailureSub()
'for use with multiple simulation runs
   For x = v To 11
      FailCount(x) = FailCount(x) + 1
   Next x
End Sub
```

```
Sub ColourCoding(count As Integer)
'colour codes output rows according to the landuse type
   a = 0
   b = 0
   c = 0
   For x = 0 To (NumCells - 1)
      If UpNum > 0 Then
         If Selection.Offset(x, 0) = UpCellId(a) Then
            For y = 0 To count
               With Selection.Offset(x, y).Interior
                  .ColorIndex = 36
                  .Pattern = xlSolid
               End With
            Next y
          If a < UpNum - 1 Then a = a + 1
          End If
      End If
      If OutNum > 0 Then
         If Selection.Offset(x, 0) = OutCellId(b) Then
            For y = 0 To count
```

```
          With Selection.Offset(x, y).Interior
            .ColorIndex = 40
            .Pattern = xlSolid
          End With
        Next y
      If b < OutNum - 1 Then b = b + 1
      End If
    End If
  Next x
End Sub
```

A.6 StatResults macro

```
Option Explicit
'This macro is used with multiple simulation runs and produces simple descriptive
‘statistics for each output parameter. It also records the best and worst run of the
‘simulation set, based on mean April cumulative utilisation.
'
Dim AvgVar() As Single, SumVar() As Single, SDVar() As Single, DiffsVar() As Single
Dim MaxVar() As Currency, MinVar() As Currency
Dim i As Integer, month As Integer, x As Integer, count() As Integer
Dim MeanRunCU() As Single, WorstTest As Single, BestTest As Single, WorstRun As
       Integer, BestRun As Integer
Dim WorstCellHerbage() As Single, WorstCellSheep() As Single, WorstOfftake() As
       Single
Dim WorstMonUtil() As Single, WorstCumUtil() As Single
Dim BestCellHerbage() As Single, BestCellSheep() As Single, BestOfftake() As Single
Dim BestMonUtil() As Single, BestCumUtil() As Single
```

```
Sub Results()
 Application.ScreenUpdating = False
OutResults.Activate
Range("B3").Select
ActiveCell = runcount
Range("B6").Select
For month = 0 To 11
  Selection.Offset(0, month) = FailCount(month)
  Selection.Offset(1, month) = HayFailCount(month)
Next month
'define dynamic arrays based on the number of cells
ReDim AvgVar(NumCells - 1, 11)
```

```
ReDim SumVar(NumCells - 1, 11)
ReDim DiffsVar(NumCells - 1, 11)
ReDim SDVar(NumCells - 1, 11)
ReDim MaxVar(NumCells - 1, 11)
ReDim MinVar(NumCells - 1, 11)
ReDim count(NumCells - 1, 11)
'
ReDim MeanRunCU(runcount)
ReDim WorstCellHerbage(NumCells - 1, 11)
ReDim WorstCellSheep(NumCells - 1, 11)
ReDim WorstOfftake(NumCells - 1, 11)
ReDim WorstMonUtil(NumCells - 1, 11)
ReDim WorstCumUtil(NumCells - 1, 11)
ReDim BestCellHerbage(NumCells - 1, 11)
ReDim BestCellSheep(NumCells - 1, 11)
ReDim BestOfftake(NumCells - 1, 11)
ReDim BestMonUtil(NumCells - 1, 11)
ReDim BestCumUtil(NumCells - 1, 11)
'
For x = 1 To runcount
   MeanRunCU(x) = 0
Next x
'calculate the utilisable biomass statistics
Range("B11").Select
Selection.Offset(-1, -1) = "Available UB in each cell in each month"
StatCalculations CellHerbage()
'calculate the sheep density statistics
Selection.Offset(NumCells + 2, 0).Select
Selection.Offset(-1, -1) = "Number of sheep in each cell in each month"
StatCalculations CellSheep()
'calculate the offtake statistics
Selection.Offset(NumCells + 2, 0).Select
Selection.Offset(-1, -1) = "Offtake from each cell in each month, kg DM"
StatCalculations CellKgOff()
'calculate the monthly utilisation statistics
Selection.Offset(NumCells + 2, 0).Select
Selection.Offset(-1, -1) = "Monthly utilisation from each cell in each month, %"
StatCalculations CellUtil()
'calculate the cumulative utilisation statistics
Selection.Offset(NumCells + 2, 0).Select
```

```
Selection.Offset(-1, -1) = "Cumulative utilisation from each cell in each month, %"
StatCalculations CumUtil()
'
'The next section assumes that the cumulative utilisation calculations were the ones
' carried out immediately previously.
'Extracting the best and worst case scenarios from a set of runs, based upon the
'cumulative utilisation in April.
For x = 1 To runcount
    For i = 0 To (NumCells - 1)
        MeanRunCU(x) = MeanRunCU(x) + CumUtil(i, 11, x)
    Next i
    MeanRunCU(x) = MeanRunCU(x) / NumCells
Next x
'initialise comparison values
WorstTest = MeanRunCU(0)
BestTest = 100000
WorstRun = 1
BestRun = 1
'to find worst run of simulation run
For x = 1 To runcount
    If MeanRunCU(x) >= WorstTest Then
        WorstTest = MeanRunCU(x)
        WorstRun = x
        For i = 0 To (NumCells - 1)
            For month = 0 To 11
                WorstCellHerbage(i, month) = CellHerbage(i, month, x)
                WorstCellSheep(i, month) = CellSheep(i, month, x)
                WorstOfftake(i, month) = CellKgOff(i, month, x)
                WorstMonUtil(i, month) = CellUtil(i, month, x)
                WorstCumUtil(i, month) = CumUtil(i, month, x)
            Next month
        Next i
    End If
Next x
'to find best run of simulation set
For x = 1 To runcount
    If BestTest > MeanRunCU(x) Then
        BestTest = MeanRunCU(x)
        BestRun = x
        For i = 0 To (NumCells - 1)
```

```
          For month = 0 To 11
             BestCellHerbage(i, month) = CellHerbage(i, month, x)
             BestCellSheep(i, month) = CellSheep(i, month, x)
             BestOfftake(i, month) = CellKgOff(i, month, x)
             BestMonUtil(i, month) = CellUtil(i, month, x)
             BestCumUtil(i, month) = CumUtil(i, month, x)
          Next month
       Next i
   End If
Next x
'outputs for worst run
Worksheets("WorstScen").Activate
Range("B3").Select
ActiveCell = WorstRun
Selection.Offset(0, 1) = WorstTest
Range("B7").Select
Selection.Offset(-1, -1) = "Available UB in each cell in each month"
ScenarioOutput WorstCellHerbage()
Selection.Offset(-1, -1) = "Number of sheep in each cell in each month"
ScenarioOutput WorstCellSheep()
Selection.Offset(-1, -1) = "Offtake from each cell in each month, kg DM"
ScenarioOutput WorstOfftake()
Selection.Offset(-1, -1) = "Monthly utilisation from each cell in each month, %"
ScenarioOutput WorstMonUtil()
Selection.Offset(-1, -1) = "Cumulative utilisation from each cell in each month, %"
ScenarioOutput WorstCumUtil()
'outputs for best run
Worksheets("BestScen").Activate
Range("B3").Select
ActiveCell = BestRun
Selection.Offset(0, 1) = BestTest
For x = 1 To runcount
   Selection.Offset(0, x + 1) = MeanRunCU(x)
Next x
Range("B7").Select
Selection.Offset(-1, -1) = "Available UB in each cell in each month"
ScenarioOutput BestCellHerbage()
Selection.Offset(-1, -1) = "Number of sheep in each cell in each month"
ScenarioOutput BestCellSheep()
Selection.Offset(-1, -1) = "Offtake from each cell in each month, kg DM"
```

```
 ScenarioOutput BestOfftake()
 Selection.Offset(-1, -1) = "Monthly utilisation from each cell in each month, %"
 ScenarioOutput BestMonUtil()
 Selection.Offset(-1, -1) = "Cumulative utilisation from each cell in each month, %"
 ScenarioOutput BestCumUtil()
OutResults.Activate
End Sub
```

```
Sub ScenarioOutput(Output)
    With Selection.Offset(-1, -1)
        .HorizontalAlignment = xlLeft
        .VerticalAlignment = xlBottom
        .WrapText = True
        .Font.Bold = True
    End With
    For i = 0 To NumCells - 1
        Selection.Offset(i, -1) = CellIdArray(i)
        For month = 0 To 11
            Selection.Offset(i, month) = Output(i, month)
        Next month
     Next i
    Selection.Offset(NumCells + 2, 0).Select
End Sub
```

```
Sub StatCalculations(InputVar)
With Selection.Offset(-1, -1)
    .HorizontalAlignment = xlLeft
    .VerticalAlignment = xlBottom
    .WrapText = True
    .Font.Bold = True
End With
If OrderRes = "Cell ID" Then
    For i = 0 To NumCells - 1
            Selection.Offset(i, -1) = CellIdArray(i)
            Selection.Offset(i, 26) = CellIdArray(i)
    Next i
Else:
    If UpNum > 0 Then
        For i = 0 To UpNum - 1
            Selection.Offset(i, -1) = UpCellId(i)
```

```
         Selection.Offset(i, 26) = UpCellId(i)
      Next i
   End If
   If OutNum > 0 Then
      For i = 0 To OutNum - 1
         Selection.Offset(i + UpNum, -1) = OutCellId(i)
         Selection.Offset(i + UpNum, 26) = OutCellId(i)
      Next i
   End If
End If
'
Selection.Offset(0, -1).Select
SheepDistribution.ColourCoding (52)
Selection.Offset(0, 1).Select
'
'initialising the arrays
For i = 0 To NumCells - 1
   For month = 0 To 11
      AvgVar(i, month) = 0
      SumVar(i, month) = 0
      DiffsVar(i, month) = 0
      SDVar(i, month) = 0
   Next month
Next i
'
For i = 0 To (NumCells - 1)
   For month = 0 To 11
      count(i, month) = 0
      x = 0
      MaxVar(i, month) = 0
      MinVar(i, month) = 1000000
      For x = 1 To runcount
         If CellHerbage(i, month, x) > 0 Or InputVar(i, month, x) = CumUtil(i, month, x)
          Then
            SumVar(i, month) = SumVar(i, month) + InputVar(i, month, x)
            count(i, month) = count(i, month) + 1
         End If
         If InputVar(i, month, x) > MaxVar(i, month) Then
            MaxVar(i, month) = InputVar(i, month, x)
         End If
```

```
            If InputVar(i, month, x) < MinVar(i, month) Then
                MinVar(i, month) = InputVar(i, month, x)
            End If
        Next x
        If count(i, month) > 0 Then
            AvgVar(i, month) = SumVar(i, month) / count(i, month)
        End If
        'calculating the standard deviation
        For x = 1 To runcount
            If CellHerbage(i, month, x) > 0 Then
                DiffsVar(i, month) = DiffsVar(i, month) + ((InputVar(i, month, x) - AvgVar(i, month)) ^ 2)
            End If
        Next x
        If count(i, month) > 1 Then
            SDVar(i, month) = Sqr(DiffsVar(i, month) / (count(i, month) - 1))
        End If
    Next month
Next i
For month = 0 To 11
    If OrderRes = "Cell ID" Then
        For i = 0 To NumCells - 1
            Selection.Offset(i, month) = AvgVar(i, month)
            Selection.Offset(i, (month) + 13) = SDVar(i, month)
            Selection.Offset(i, (month) + 27) = MinVar(i, month)
            Selection.Offset(i, (month) + 40) = MaxVar(i, month)
        Next i
    Else:
        If UpNum > 0 Then
            For i = 0 To UpNum - 1
                Selection.Offset(i, month) = AvgVar(UpCellId(i) - 1, month)
                Selection.Offset(i, (month) + 13) = SDVar(UpCellId(i) - 1, month)
                Selection.Offset(i, (month) + 27) = MinVar(UpCellId(i) - 1, month)
                Selection.Offset(i, (month) + 40) = MaxVar(UpCellId(i) - 1, month)
            Next i
        End If
        If OutNum > 0 Then
            For i = 0 To OutNum - 1
                Selection.Offset(i + UpNum, month) = AvgVar(OutCellId(i) - 1, month)
                Selection.Offset(i + UpNum, (month) + 13) = SDVar(OutCellId(i) - 1, month)
```

```
                Selection.Offset(i + UpNum, (month) + 27) = MinVar(OutCellId(i) - 1, month)
                Selection.Offset(i + UpNum, (month) + 40) = MaxVar(OutCellId(i) - 1, month)
            Next i
        End If
    End If
Next month
End Sub
```

A.7 Sensitivity macro

```
Option Explicit
'This module is used to carry out sensitivity tests upon Búmodel.
'It must be run from the Tools>Macro>Macros menu in MS Excel.
'You must also make sure the other input parameters are set correctly, that the test
‘ parameter and increments are clearly stated, and that the output workbook, which is
‘ presently testruns1.xls, is open.
'The other Búmodel macros are called from within this macro

Public StatSheet As Worksheet, LiveSheet As Worksheet, VarUB As Worksheet,
             VarSheep As Worksheet
Public VarOfftake As Worksheet, VarMonUtil As Worksheet, VarCumUtil As Worksheet
Dim m As Integer, n As Integer
```

```
Sub SensitivityTest()
    Application.ScreenUpdating = False
    Set StatSheet = Workbooks("Grazing Model 3").Worksheets("Statistical Results")
    Set LiveSheet = Workbooks("Grazing Model 3").Worksheets("Livestock Inputs")
    Set VarUB = Workbooks("testruns1").Worksheets("VarUB")
    Set VarSheep = Workbooks("testruns1").Worksheets("VarSheepNums")
    Set VarOfftake = Workbooks("testruns1").Worksheets("VarOfftake")
    Set VarMonUtil = Workbooks("testruns1").Worksheets("VarMonUtil")
    Set VarCumUtil = Workbooks("testruns1").Worksheets("VarCumUtil")
    '
    n = 0

'To adjust sheep numbers
    For m = 100 To 500 Step 100
        LiveSheet.Activate
        ActiveSheet.Range("B2") = m         'adjust ewe numbers
        'ActiveSheet.Range("B3") = m / 2    'adjust lamb numbers
```

```
'to adjust length of winter feeding
  'For m = 0 To 2 Step 1
    'ActiveSheet.Range("B21").Select
    'ActiveCell.Offset(0, m).Select
    'ActiveCell = "B"

  'adjust sheep weights
  'For m = 25 To 80 Step 5
    'ActiveSheet.Range("B11") = m

  'adjust %bodyweight lost in winter
  'For m = 0 To 40 Step 10
    'ActiveSheet.Range("B14") = m

    'run Búmodel
    BigModule.BigModule
    'This section will only work if there are ten pasture cells only
    'select results from the descriptive statistics worksheet
  '1. copy number of failed runs
    StatSheet.Activate
    ActiveSheet.Rows("6").Select
    Selection.Copy
    VarUB.Activate
    ActiveSheet.Range("A8").Select
    ActiveCell.Offset(n - 2, 0).Select
    ActiveSheet.Paste
  '2. copy UB values
    StatSheet.Activate
    ActiveSheet.Rows("11:15").Select
    Selection.Copy
    VarUB.Activate
    ActiveSheet.Range("A8").Select
    'paste description of sensitivity test increment
    ActiveCell.Offset(n - 3, 0) = "No of ewes"
    'ActiveCell.Offset(n - 3, 0) = "Ewe weight"
    'ActiveCell.Offset(n - 3, 0) = "% of bodyweight lost in winter"
    ActiveCell.Offset(n - 2, 0) = "No. of failed runs"
    ActiveCell.Offset(n - 3, 1) = m
    ActiveCell.Offset(n, 0).Select
    ActiveSheet.Paste
```

```
'3. copy the sheep density values
    StatSheet.Activate
    ActiveSheet.Rows("6").Select
    Selection.Copy
    VarSheep.Activate
    ActiveSheet.Range("A8").Select
    ActiveCell.Offset(n - 2, 0).Select
    ActiveSheet.Paste
    StatSheet.Activate
    ActiveSheet.Rows("18:23").Select
    Selection.Copy
    VarSheep.Activate
    ActiveSheet.Range("A8").Select
    ActiveCell.Offset(n - 3, 0) = "No of ewes"
    'ActiveCell.Offset(n - 3, 0) = "Ewe weight"
    'ActiveCell.Offset(n - 3, 0) = "% of bodyweight lost in winter"
    ActiveCell.Offset(n - 3, 1) = m
    ActiveCell.Offset(n, 0).Select
    ActiveSheet.Paste
'4. copy the offtake values
    StatSheet.Activate
    ActiveSheet.Rows("6").Select
    Selection.Copy
    VarOfftake.Activate
    ActiveSheet.Range("A8").Select
    ActiveCell.Offset(n - 2, 0).Select
    ActiveSheet.Paste
    StatSheet.Activate
    ActiveSheet.Rows("26:30").Select
    Selection.Copy
    VarOfftake.Activate
    ActiveSheet.Range("A8").Select
    ActiveCell.Offset(n - 3, 0) = "No of ewes"
    'ActiveCell.Offset(n - 3, 0) = "Ewe weight"
    'ActiveCell.Offset(n - 3, 0) = "% of bodyweight lost in winter"
    ActiveCell.Offset(n - 3, 1) = m
    ActiveCell.Offset(n, 0).Select
    ActiveSheet.Paste
'5. copy the monthly utilisation values
    StatSheet.Activate
```

```
    ActiveSheet.Rows("6").Select
    Selection.Copy
    VarMonUtil.Activate
    ActiveSheet.Range("A8").Select
    ActiveCell.Offset(n - 2, 0).Select
    ActiveSheet.Paste
    StatSheet.Activate
    ActiveSheet.Rows("33:38").Select
    Selection.Copy
    VarMonUtil.Activate
    ActiveSheet.Range("A8").Select
    ActiveCell.Offset(n - 3, 0) = "No of ewes"
    'ActiveCell.Offset(n - 3, 0) = "Ewe weight"
    'ActiveCell.Offset(n - 3, 0) = "% of bodyweight lost in winter"
    ActiveCell.Offset(n - 3, 1) = m
    ActiveCell.Offset(n, 0).Select
    ActiveSheet.Paste
  '6. copy the cumulative utilisation values
    StatSheet.Activate
    ActiveSheet.Rows("6").Select
    Selection.Copy
    VarCumUtil.Activate
    ActiveSheet.Range("A8").Select
    ActiveCell.Offset(n - 2, 0).Select
    ActiveSheet.Paste
    StatSheet.Activate
    ActiveSheet.Rows("59:68").Select
    Selection.Copy
    VarCumUtil.Activate
    ActiveSheet.Range("A8").Select
    ActiveCell.Offset(n - 3, 0) = "No of ewes"
    ActiveCell.Offset(n - 3, 1) = m
    ActiveCell.Offset(n, 0).Select
    ActiveSheet.Paste
    n = n + 9
  Next m
End Sub
```

Appendix B: Fieldwork data

B.1 2000 botanical composition data

Cover scores from 0 to 9 for each plant type (see Table 4-5 in thesis).

Moss and lichen species not included.

Sites A-G were sampled in Eyjafjallahreppur. Sites L-P were sampled in Mývatn hreppur.

Site	Vegetation community	Total no. of species	Grasses	Sedges and rushes	Dwarf shrubs	Dicot herbs	Moss and lichen	Bare ground or rock	Horsetails & ferns
F1	Birch woodland	16	2	0	9	6	2	0	5
F6	Birch woodland	16	8	1	1	5	2	0	2
A5	Bog or mire	19	3	6	1	2	6	0	1
C8	Bog or mire	12	2	3	3	1	6	4	2
N1	Bog or mire	10	1	7	9	2	9	0	1
N3	Bog or mire	27	4	5	6	4	2	0	1
P2	Bog or mire	14	0	3	7	3	9	0	4
B2	Dwarf shrub heath	16	1	0	6	1	5	3	0
C2	Dwarf shrub heath	15	1	1	9	1	6	1	0
C3	Dwarf shrub heath	17	3	1	9	5	6	0	1
D3	Dwarf shrub heath	14	1	0	9	2	7	0	1
E1	Dwarf shrub heath	30	5	1	8	4	2	0	3
F2	Dwarf shrub heath	28	1	1	6	2	5	1	1
F3	Dwarf shrub heath	24	1	1	9	3	4	1	0
M2	Dwarf shrub heath	16	1	3	9	1	2	2	0
M3	Dwarf shrub heath	20	1	2	9	4	5	0	1
M4	Dwarf shrub heath	15	3	3	7	1	3	0	1
A2	Grassy heath	13	9	1	1	1	6	0	1
A3	Grassy heath	15	8	1	0	2	6	0	2
C1	Grassy heath	9	9	1	0	2	7	0	0
D5	Grassy heath	9	9	3	0	1	4	0	0
F4	Grassy heath	19	3	1	1	2	4	5	1
G1	Grassy heath	12	9	2	2	5	2	0	2
L3	Grassy heath	18	7	3	1	1	3	0	1
P3	Grassy heath	12	9	1	5	1	6	0	0
A1	Hayfield	9	5	0	0	8	0	0	0
F5	Hayfield	7	9	0	0	5	3	0	0
L2	Hayfield	9	5	0	0	1	1	5	1
A4	Moss heath	16	1	1	3	1	7	1	1
A6	Moss heath	14	1	1	2	1	5	6	0
B1	Moss heath	16	1	1	4	2	6	5	0
C5	Moss heath	16	1	1	3	1	6	4	0
C6	Moss heath	21	1	1	6	2	9	1	0
D2	Moss heath	19	3	3	1	2	9	1	1
E3	Moss heath	15	1	1	1	2	5	6	0
E5	Moss heath	16	3	1	1	1	9	1	1
A7	Riverine	12	1	1	3	8	6	0	1
G4	Riverine	33	3	1	2	6	4	2	1

Site	Vegetation community	Total no. of species	Grasses	Sedges and rushes	Dwarf shrubs	Dicot herbs	Moss and lichen	Bare ground or rock	Horsetails & ferns
N2	Riverine	26	7	1	9	9	5	0	2
P1	Riverine	17	3	8	0	9	0	0	1
C4	Sparsely vegetated	7	1	1	1	0	1	9	0
C7	Sparsely vegetated	13	1	1	3	1	3	8	0
D1	Sparsely vegetated	13	1	1	2	1	3	8	0
D4	Sparsely vegetated	8	1	1	1	1	1	9	1
E2	Sparsely vegetated	21	1	1	1	2	2	9	1
E4	Sparsely vegetated	18	1	0	1	2	1	9	0
G2	Sparsely vegetated	12	1	1	0	2	1	8	0
L1	Sparsely vegetated	11	1	1	1	1	1	9	1
M1	Sparsely vegetated	6	0	0	1	1	1	9	0

B.2 2001 botanical composition data

Cover scores from 0 to 9 for each plant type (see Table 4-5 in thesis).

Moss and lichen species not included.

N: Mývatn hreppur study area; S: Eyjafjallahreppur study area

Site	Vegetation community	Total no. of species	Grasses	Sedges and rushes	Dicot herbs	Woody plants	Horsetails and ferns	Moss and lichen	Bare ground or rock
Ngrass14/1	Grassy heath	14	8	4	2	0	1	5	0
Ngrass14/2	Grassy heath	11	7	4	2	5	0	7	0
Ngrass14/3	Grassy heath	18	9	1	4	1	1	6	0
Ngrass14/4	Grassy heath	24	7	4	3	1	1	7	0
Ngrass14/5	Grassy heath	16	5	3	4	2	1	3	0
Ngrass35/1	Grassy heath	5	5	1	0	0	2	4	2
Ngrass35/2	Grassy heath	9	7	3	1	1	1	8	0
Ngrass35/3	Grassy heath	9	4	0	1	6	1	7	0
Ngrass35/4	Grassy heath	7	3	3	1	6	1	4	0
Ngrass35/5	Grassy heath	16	5	2	2	4	1	8	0
Ngrass5/1	Grassy heath	16	6	4	4	2	1	6	0
Ngrass5/2	Grassy heath	19	5	3	8	2	3	4	0
Ngrass5/3	Grassy heath	10	9	1	4	0	1	3	0
Ngrass5/4	Grassy heath	18	6	4	4	0	2	7	0
Ngrass5/5	Grassy heath	6	9	0	4	0	0	2	0
Nriver1/1	Riverine	10	8	0	8	3	1	0	0
Nriver1/10	Riverine	20	6	1	7	8	2	5	0
Nriver1/2	Riverine	11	8	0	7	0	0	0	0
Nriver1/3	Riverine	15	6	0	6	8	0	8	0
Nriver1/4	Riverine	15	4	1	7	5	3	3	0
Nriver1/5	Riverine	9	8	1	8	0	0	0	0
Nriver1/6	Riverine	11	5	1	4	7	5	5	0
Nriver1/7	Riverine	19	4	2	5	4	4	8	0
Nriver1/8	Riverine	15	4	0	8	6	7	8	0

Site	Vegetation community	Total no. of species	Grasses	Sedges and rushes	Dicot herbs	Woody plants	Horsetails and ferns	Moss and lichen	Bare ground or rock
Nriver1/9	Riverine	9	8	0	9	0	7	0	0
Nriver2/1	Riverine	13	4	4	5	8	0	9	0
Nriver2/2	Riverine	9	5	0	8	5	0	3	0
Nriver2/3	Riverine	23	7	3	7	4	0	2	0
Nriver2/4	Riverine	20	9	2	5	1	0	5	0
Nriver2/5	Riverine	14	7	2	6	0	0	5	0
Nsedge20/1	Grassy heath	13	7	6	3	0	1	5	0
Nsedge20/2	Grassy heath	8	3	6	4	0	0	9	0
Nsedge20/3	Grassy heath	14	7	6	5	0	2	5	0
Nsedge20/4	Grassy heath	14	4	4	2	3	1	8	0
Nsedge20/5	Grassy heath	16	8	2	3	0	0	4	0
Nsparse14/1	Sparsely vegetated	12	3	1	2	0	0	1	6
Nsparse14/2	Sparsely vegetated	5	3	0	2	0	0	1	6
Nsparse14/3	Sparsely vegetated	12	3	1	2	0	0	1	6
Nsparse14/4	Sparsely vegetated	6	4	0	2	0	0	1	5
Nsparse14/5	Sparsely vegetated	10	3	1	2	0	0	0	7
Nsparse40/1	Sparsely vegetated	9	1	1	1	2	0	1	8
Nsparse40/2	Sparsely vegetated	7	3	0	1	1	0	1	7
Nsparse40/3	Sparsely vegetated	7	2	0	1	0	1	2	7
Nsparse40/4	Sparsely vegetated	5	2	0	1	0	1	1	9
Nsparse40/5	Sparsely vegetated	6	2	2	2	0	0	3	7
Nsparse50/1	Sparsely vegetated	6	2	1	2	0	2	0	7
Nsparse50/2	Sparsely vegetated	7	1	1	1	0	1	0	9
Nsparse50/3	Sparsely vegetated	7	1	1	1	0	1	0	9
Nsparse50/4	Sparsely vegetated	10	1	1	1	1	1	1	9
Nsparse50/5	Sparsely vegetated	10	1	2	1	1	0	0	8
Nwoodg1/1	Grazed woodland	9	8	0	2	6	2	7	0
Nwoodg1/2	Grazed woodland	7	4	0	1	8	1	8	0
Nwoodg1/3	Grazed woodland	11	5	0	3	7	0	6	0
Nwoodg1/4	Grazed woodland	10	4	1	2	6	0	9	0
Nwoodg1/5	Grazed woodland	14	6	0	2	5	1	0	0
Nwoodg10/1	Grazed woodland	9	2	0	1	8	0	3	0
Nwoodg10/2	Grazed woodland	9	0	5	0	7	1	8	0
Nwoodg10/3	Grazed woodland	6	0	5	0	8	0	8	0
Nwoodg10/4	Grazed woodland	12	0	6	1	8	0	5	0
Nwoodg10/5	Grazed woodland	7	0	5	1	7	0	9	0
Nwoodg12/1	Grazed woodland	15	2	1	1	8	0	2	1
Nwoodg12/2	Grazed woodland	14	2	1	2	6	1	8	0
Nwoodg12/3	Grazed woodland	11	5	0	2	7	0	4	0
Nwoodg12/4	Grazed woodland	12	2	1	1	9	1	2	1
Nwoodg12/5	Grazed woodland	13	7	0	3	5	0	8	0
Nwoodu15/1	Ungrazed woodland	8	9	0	2	1	1	0	0
Nwoodu15/2	Ungrazed woodland	11	1	1	3	6	0	2	2
Nwoodu15/3	Ungrazed woodland	8	3	0	1	8	0	3	0
Nwoodu15/4	Ungrazed woodland	12	9	1	4	0	1	0	0
Nwoodu15/5	Ungrazed woodland	13	5	1	6	1	1	0	0
Nwoodu16/1	Ungrazed woodland	11	3	1	3	7	2	5	0
Nwoodu16/2	Ungrazed woodland	9	7	1	4	1	2	1	0
Nwoodu16/3	Ungrazed woodland	10	5	0	3	8	1	4	0

Site	Vegetation community	Total no. of species	Grasses	Sedges and rushes	Dicot herbs	Woody plants	Horsetails and ferns	Moss and lichen	Bare ground or rock
Nwoodu16/4	Ungrazed woodland	11	6	0	5	6	1	2	0
Nwoodu16/5	Ungrazed woodland	5	1	0	1	3	1	0	2
Nwoodu6/1	Ungrazed woodland	10	4	2	4	2	2	6	0
Nwoodu6/2	Ungrazed woodland	11	4	1	2	8	1	3	0
Nwoodu6/3	Ungrazed woodland	12	7	0	4	2	1	1	0
Nwoodu6/4	Ungrazed woodland	11	4	0	4	0	4	8	0
Nwoodu6/5	Ungrazed woodland	9	2	1	5	4	1	1	0
Sgrass26/1	Grassy heath	15	7	1	6	1	0	6	1
Sgrass26/2	Grassy heath	15	2	3	3	7	1	7	0
Sgrass26/3	Grassy heath	13	9	2	1	2	0	9	0
Sgrass26/4	Grassy heath	16	7	2	2	3	1	8	0
Sgrass26/5	Grassy heath	15	4	2	4	5	0	9	0
Sgrass4/1	Grassy heath	19	6	1	5	2	1	7	1
Sgrass4/2	Grassy heath	14	5	5	6	1	1	3	0
Sgrass4/3	Grassy heath	12	7	1	4	0	5	8	0
Sgrass4/4	Grassy heath	6	9	3	2	0	2	9	0
Sgrass4/5	Grassy heath	4	8	0	4	0	0	9	0
Sgrass43/1	Grassy heath	7	9	0	2	0	0	2	0
Sgrass43/2	Grassy heath	12	9	0	3	0	0	1	0
Sgrass43/3	Grassy heath	11	9	0	2	0	0	1	0
Sgrass43/4	Grassy heath	11	4	5	2	0	1	7	0
Sgrass43/5	Grassy heath	12	6	3	3	0	1	7	0
Sriver1/1	Riverine	9	5	0	4	0	7	2	0
Sriver1/2	Riverine	12	5	2	3	0	6	7	0
Sriver1/3	Riverine	7	2	0	9	0	4	4	0
Sriver1/4	Riverine	11	2	1	5	0	5	3	0
Sriver1/5	Riverine	11	2	0	7	0	5	2	0
Sriver2/1	Riverine	14	4	1	4	1	7	7	1
Sriver2/10	Riverine	12	1	3	2	2	5	9	0
Sriver2/2	Riverine	14	6	1	2	4	1	2	4
Sriver2/3	Riverine	6	1	0	3	0	5	1	5
Sriver2/4	Riverine	10	2	0	2	0	5	3	5
Sriver2/5	Riverine	13	7	2	3	2	2	5	1
Sriver2/6	Riverine	19	5	1	3	0	7	4	0
Sriver2/7	Riverine	20	3	1	4	3	7	8	0
Sriver2/8	Riverine	13	4	1	3	0	7	9	0
Sriver2/9	Riverine	13	3	1	3	0	7	9	0
Ssparse14/1	Sparsely vegetated	7	1	0	1	2	0	2	7
Ssparse14/2	Sparsely vegetated	5	1	0	1	0	1	0	9
Ssparse14/3	Sparsely vegetated	6	2	1	1	0	2	1	8
Ssparse14/4	Sparsely vegetated	16	3	1	4	6	1	2	1
Ssparse14/5	Sparsely vegetated	9	1	1	1	1	0	3	7
Ssparse29/1	Sparsely vegetated	5	1	0	1	1	0	3	7
Ssparse29/2	Sparsely vegetated	3	1	0	1	0	0	1	9
Ssparse29/3	Sparsely vegetated	8	1	1	1	0	0	6	4
Ssparse29/4	Sparsely vegetated	4	1	0	1	0	0	1	9
Ssparse29/5	Sparsely vegetated	6	1	0	1	0	0	1	9
Ssparse31/1	Sparsely vegetated	8	1	1	1	0	1	1	9
Ssparse31/2	Sparsely vegetated	4	1	0	1	0	0	2	8

Site	Vegetation community	Total no. of species	Grasses	Sedges and rushes	Dicot herbs	Woody plants	Horsetails and ferns	Moss and lichen	Bare ground or rock
Ssparse31/3	Sparsely vegetated	8	1	1	1	1	0	3	7
Ssparse31/4	Sparsely vegetated	6	1	1	1	0	0	5	5
Ssparse31/5	Sparsely vegetated	4	1	1	1	0	0	3	7
Swoodu5/1	Ungrazed woodland	16	4	0	3	5	1	6	2
Swoodu5/2	Ungrazed woodland	11	1	0	2	5	1	8	0
Swoodu5/3	Ungrazed woodland	9	5	0	5	0	4	5	0
Swoodu5/4	Ungrazed woodland	12	5	0	5	1	2	4	0
Swoodu5/5	Ungrazed woodland	10	4	1	3	0	4	9	0
Swoodu8/1	Ungrazed woodland	12	7	1	5	4	2	7	0
Swoodu8/2	Ungrazed woodland	10	7	1	3	1	6	5	0
Swoodu8/3	Ungrazed woodland	10	3	1	4	4	1	9	0
Swoodu8/4	Ungrazed woodland	11	3	0	2	8	0	8	0
Swoodu8/5	Ungrazed woodland	10	1	1	1	4	1	8	0
Swoodu9/1	Ungrazed woodland	15	3	1	4	6	0	1	0
Swoodu9/2	Ungrazed woodland	13	2	0	2	8	0	3	1
Swoodu9/3	Ungrazed woodland	14	3	1	3	5	2	8	0
Swoodu9/4	Ungrazed woodland	18	3	0	5	0	4	9	0
Swoodu9/5	Ungrazed woodland	14	3	1	4	2	0	8	2

B.3 2001 utilisable biomass samples

Site ID	Vegetation community	Herbaceous wt, g	Area cut, msq.	Utilisable biomass g/msq.
Ngrass14/1	Grassy heath	18.5	0.04	462.5
Ngrass14/2	Grassy heath	18.7	0.04	467.5
Ngrass14/3	Grassy heath	27.7	0.04	692.5
Ngrass14/4	Grassy heath	6.9	0.04	172.5
Ngrass14/5	Grassy heath	17.2	0.12	143.3
Ngrass35/1	Grassy heath	5.9	0.12	49.2
Ngrass35/2	Grassy heath	5.3	0.04	132.5
Ngrass35/3	Grassy heath	19.5	0.12	162.5
Ngrass35/4	Grassy heath	34.9	0.12	290.8
Ngrass35/5	Grassy heath	27.4	0.12	228.3
Ngrass5/1	Grassy heath	30.3	0.12	252.5
Ngrass5/2	Grassy heath	37.5	0.12	312.5
Ngrass5/3	Grassy heath	26.9	0.04	672.5
Ngrass5/4	Grassy heath	26.3	0.12	219.2
Ngrass5/5	Grassy heath	17.4	0.04	435.0
Nriver1/1	Riverine	21.2	0.04	528.8
Nriver1/10	Riverine	29.4	0.12	245.3
Nriver1/2	Riverine	16.9	0.04	422.8
Nriver1/3	Riverine	21.7	0.04	543.5
Nriver1/4	Riverine	16.9	0.04	423.0
Nriver1/6	Riverine	32.2	0.12	268.5
Nriver1/7	Riverine	19.2	0.12	160.0
Nriver1/8	Riverine	14.7	0.04	366.3
Nriver1/9	Riverine	27.4	0.04	685.3
Nriver2/1	Riverine	15.8	0.04	393.8
Nriver2/2	Riverine	22.6	0.04	565.0

Site ID	Vegetation community	Herbaceous wt, g	Area cut, msq.	Utilisable biomass g/msq.
Nriver2/3	Riverine	42.5	0.12	354.2
Nriver2/4	Riverine	38.0	0.12	316.5
Nriver2/5	Riverine	27.9	0.12	232.3
Nsedge20/1	Grassy heath	9.9	0.04	247.5
Nsedge20/2	Grassy heath	3.7	0.04	92.5
Nsedge20/3	Grassy heath	8.5	0.04	212.5
Nsedge20/4	Grassy heath	4.7	0.04	117.5
Nsedge20/5	Grassy heath	6.6	0.04	165.0
Nsparse14/1	Sparsely vegetated	7.3	0.12	60.8
Nsparse14/2	Sparsely vegetated	6.8	0.12	56.7
Nsparse14/3	Sparsely vegetated	13.0	0.12	108.3
Nsparse14/4	Sparsely vegetated	7.3	0.12	60.8
Nsparse14/5	Sparsely vegetated	6.4	0.12	53.3
Nsparse40/1	Sparsely vegetated	1.7	0.12	14.2
Nsparse40/2	Sparsely vegetated	6.0	0.12	50.0
Nsparse40/3	Sparsely vegetated	0.8	0.12	6.7
Nsparse40/4	Sparsely vegetated	1.3	0.12	10.8
Nsparse40/5	Sparsely vegetated	2.1	0.12	17.5
Nsparse50/1	Sparsely vegetated	3.9	0.12	32.5
Nsparse50/2	Sparsely vegetated	*	*	*
Nsparse50/3	Sparsely vegetated	2.4	1.0	2.4
Nsparse50/4	Sparsely vegetated	11.5	1.0	11.5
Nsparse50/5	Sparsely vegetated	2.3	0.12	19.2
Nwoodg1/1	Grazed woodland	21.2	0.12	176.3
Nwoodg1/2	Grazed woodland	8.6	0.04	214.3
Nwoodg1/3	Grazed woodland	20.2	0.12	168.6
Nwoodg1/4	Grazed woodland	8.3	0.04	208.0
Nwoodg1/5	Grazed woodland	10.2	0.12	84.6
Nwoodg10/1	Grazed woodland	15.2	0.04	379.0
Nwoodg10/2	Grazed woodland	51.6	0.12	430.0
Nwoodg10/3	Grazed woodland	36.8	0.12	307.0
Nwoodg10/4	Grazed woodland	29.2	0.12	243.5
Nwoodg10/5	Grazed woodland	23.4	0.12	195.3
Nwoodg12/1	Grazed woodland	22.3	0.04	556.3
Nwoodg12/2	Grazed woodland	26.5	0.12	220.9
Nwoodg12/3	Grazed woodland	25.1	0.12	209.1
Nwoodg12/4	Grazed woodland	57.7	0.12	481.1
Nwoodg12/5	Grazed woodland	15.0	0.12	125.2
Nwoodu15/1	Ungrazed woodland	9.5	0.04	236.8
Nwoodu15/2	Ungrazed woodland	31.8	0.12	265.0
Nwoodu15/3	Ungrazed woodland	9.2	0.04	230.8
Nwoodu15/4	Ungrazed woodland	6.9	0.04	171.5
Nwoodu15/5	Ungrazed woodland	11.1	0.12	92.1
Nwoodu16/1	Ungrazed woodland	15.2	0.12	126.5
Nwoodu16/2	Ungrazed woodland	13.8	0.12	114.7
Nwoodu16/3	Ungrazed woodland	30.5	0.12	254.0
Nwoodu16/4	Ungrazed woodland	29.4	0.12	245.1
Nwoodu16/5	Ungrazed woodland	26.4	0.12	219.6
Nwoodu6/1	Ungrazed woodland	7.6	0.12	63.3
Nwoodu6/2	Ungrazed woodland	10.7	0.12	89.3
Nwoodu6/3	Ungrazed woodland	8.0	0.12	66.7
Nwoodu6/4	Ungrazed woodland	11.6	0.12	96.8
Nwoodu6/5	Ungrazed woodland	15.3	0.12	127.2
Sgrass26/1	Grassy heath	40.9	0.12	340.4

Site ID	Vegetation community	Herbaceous wt, g	Area cut, msq.	Utilisable biomass g/msq.
Sgrass26/2	Grassy heath	21.6	0.12	180.3
Sgrass26/3	Grassy heath	39.1	0.12	326.0
Sgrass26/4	Grassy heath	26.9	0.12	223.9
Sgrass26/5	Grassy heath	28.1	0.12	234.5
Sgrass4/1	Grassy heath	25.4	0.12	211.8
Sgrass4/2	Grassy heath	26.6	0.12	221.8
Sgrass4/5	Grassy heath	15.2	0.04	380.0
Sgrass43/1	Grassy heath	17.9	0.04	446.8
Sgrass43/2	Grassy heath	21.5	0.04	537.0
Sgrass43/3	Grassy heath	19.6	0.04	488.8
Sgrass43/5	Grassy heath	6.9	0.04	171.5
Sriver1/1	Riverine	19.1	0.04	478.3
Sriver1/2	Riverine	24.8	0.04	620.8
Sriver1/4	Riverine	15.4	0.04	385.5
Sriver1/5	Riverine	20.0	0.04	499.0
Sriver2/1	Riverine	27.4	0.12	228.3
Sriver2/2	Riverine	30.0	0.12	249.9
Sriver2/3	Riverine	17.0	0.12	141.3
Sriver2/4	Riverine	3.9	0.04	97.3
Sriver2/5	Riverine	37.8	0.04	945.8
Sriver2/6	Riverine	31.6	0.12	263.4
Sriver2/8	Riverine	10.9	0.04	272.8
Sriver2/9	Riverine	14.6	0.04	364.3
Ssparse14/1	Sparsely vegetated	13.8	0.12	114.8
Ssparse14/2	Sparsely vegetated	*	*	*
Ssparse14/3	Sparsely vegetated	1.9	0.12	16.2
Ssparse14/4	Sparsely vegetated	28.0	0.12	233.6
Ssparse14/5	Sparsely vegetated	*	*	*
Ssparse29/1	Sparsely vegetated	2.1	1.0	2.1
Ssparse29/2	Sparsely vegetated	*	*	*
Ssparse29/3	Sparsely vegetated	*	*	*
Ssparse29/4	Sparsely vegetated	*	*	*
Ssparse29/5	Sparsely vegetated	*	*	*
Ssparse31/1	Sparsely vegetated	7.2	1.0	7.2
Ssparse31/2	Sparsely vegetated	5.5	1.0	5.5
Ssparse31/3	Sparsely vegetated	8.4	1.0	8.4
Ssparse31/4	Sparsely vegetated	7.8	1.0	7.8
Ssparse31/5	Sparsely vegetated	4.4	1.0	4.4
Swood5/1	Ungrazed woodland	27.4	0.12	228.6
Swood5/2	Ungrazed woodland	10.7	0.04	267.0
Swood5/3	Ungrazed woodland	11.5	0.04	288.5
Swood5/4	Ungrazed woodland	10.2	0.04	255.5
Swood5/5	Ungrazed woodland	8.8	0.04	219.0
Swood8/1	Ungrazed woodland	52.7	0.12	439.3
Swood8/2	Ungrazed woodland	9.5	0.04	237.0
Swood8/3	Ungrazed woodland	18.7	0.04	467.3
Swood8/4	Ungrazed woodland	11.2	0.04	279.0
Swood8/5	Ungrazed woodland	12.0	0.12	99.7
Swood9/1	Ungrazed woodland	46.1	0.12	384.2
Swood9/2	Ungrazed woodland	15.0	0.04	375.0
Swood9/3	Ungrazed woodland	35.1	0.12	292.3
Swood9/4	Ungrazed woodland	19.0	0.12	158.3
Swood9/5	Ungrazed woodland	13.3	0.12	110.6