Modeling Historic Rangeland Management and Grazing Pressures in Landscapes of Settlement

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Abstract Defining historic grazing pressures and rangeland management is vital if early landscape threshold crossing and long–term trajectories of landscape change are to be properly understood. In this paper we use a new environmental simulation model, Búmodel, to assess two contrasting historical grazing landscapes in Mývatnssveit Iceland for two key periods—the colonization period (ca. Landnám, A.D. 872–1000) and the early eighteenth century A.D. Results suggest that there were spatial and temporal variations in productivity and grazing pressure within and between historic grazing areas and indicate that land degradation was not an inevitable consequence of the livestock grazing introduced with settlement. The results also demonstrate the significance of grazing and livestock management strategies in preventing overgrazing, particularly under cooler climatic conditions. The model enables detailed consideration of historic grazing management scenarios and their associated landscape pressures.

Key words Historical ecology. Iceland, agro-ecosystem modelling, rangeland management, grazing pressure

Introduction

Grazing management of domestic livestock is one of the primary ways in which humans can modify landscapes, whether intentionally or unintentionally. Light grazing can alter the species composition of the dominant plant communities while heavy grazing can induce vegetation change, reduce productivity and increase the risk of soil erosion. Overgrazing is one of the main causes of land degradation, a global issue affecting over 40% of the world’s vegetated land surface (Brady and Weil, 1999). It reduces the quality of land resources often resulting in an 'irreversible decline in the capacity of the land to produce' with serious consequences for human subsistence (Biot, 1993). Explanations of land degradation and landscape change associated with grazing pressures have increasingly been derived from holistic analyses that integrate the social and natural sciences. However, human ecological concepts applied to questions of landscape change have frequently lacked historical depth, making it difficult to define long-term trajectories of landscape change and the crossing of thresholds between early landscape stability and grazing-induced landscape change (Blaikie and Brookfield, 1987; Simpson et al., 2001).

The landscape of Iceland has been extensively modified by grazing, and is of particular significance in understanding the historical role of grazing pressure in landscape change as human interaction begins from a well-defined starting point with settlement in the late ninth century A.D. (Landnám; Arnalds et al., 1987; Þorarinsson, 1944, 1961). Since settlement there has been an estimated reduction from 65 to 25% in the vegetation cover (Bjarnarson, 1978; Friðriksson, 1972) with much of the remaining vegetation suffering from depleted productivity (Thorsteinsson, 1986). The ability of a landscape to support livestock, both through grazing and the production of winter fodder, was a key factor in pre-nineteenth century farm sustainability in Iceland. Domestic livestock were a significant part of the economy, with wool, meat, and dairy production essential for subsistence and the payment of rents and tithes (Karlsson, 2000; Magnússon and Vídalín, 1913–1990).
The agricultural system of sedentary pastoralism was introduced by the first settlers of western Scandinavian origin ca. A.D. 872 and remained virtually unchanged through much of Icelandic history. Due to its subarctic location (with short summers and highly variable growing conditions) and mountainous interior, permanent settlement in Iceland is restricted to coastal regions and a few inland areas. There are many examples of overoptimistic settlement and consequent farm abandonment (Sveinbjarnardóttir,

1992), providing the opportunity to investigate the historical grazing factors that contributed to long-term farm sustainability in one location and abandonment and degradation in a neighboring location. This requires the consideration of the physical environment and the management strategies that are possible within this environment. These management strategies may also be influenced by socioeconomic factors, such as the high prevalence of short-term tenancy (Lárusson, 1967), requirements for marriage, and liability to pay tithes and assembly tax (Dennis et al., 2000).

In this paper we reconstruct and model two contrasting historical grazing landscapes, Hofstaðir and Sveigakot, in Mývatnssveit, northeast Iceland, for two key periods, the colonization period (ca. Landnám, A.D. 872–1000) and the early eighteenth century A.D. Within these reconstructed landscapes, the range of possible grazing management strategies are identified and associated landscape pressures evaluated, enabling testing of two hypotheses. The first hypothesis is that there was sufficient natural biomass production to support the numbers of livestock indicated by historical data. The second hypothesis is that alternative land management strategies could have maintained livestock numbers and vegetation biomass, whilst avoiding extensive erosion and landscape degradation. To assess landscape pressures and grazing management strategies the paper introduces a new tool to the field of historical landscape ecology—an environmental simulation model, named Búmodel (bú being the Icelandic term for a farm estate or farming enterprise). This simulation model aims to integrate ecological techniques with a human ecology perspective (Crumley, 1994) for the purposes of investigating past human impacts upon the physical environment in the context of farm management. Such investigations can draw upon many lines of evidence (see for example Barlow et al., 1997). Environmental simulation modeling provides a means of setting these disparate sources of information within a framework representing the real-life human–

environmental system. Understanding of the system can be improved by describing and quantifying the linkages among system elements. Simulation modeling can also stimulate further research by highlighting interesting areas for further investigation, identifying critical data gaps and generating hypotheses that are testable against evidence from archaeological, historical, and environmental sources (McGovern, 1995).

The Mývatnssveit Study Area

Mývatnssveit is located in the northeastern interior of Iceland, surrounding Lake Mývatn (65°36′N, 17°00′W; Fig. 1) and is the only substantial community in Iceland so far inland. It is referred to as a hreppur in historical sources (hreppur being both a community unit of 10–30 farms and the area associated with these farms) and has the modern name of Skútustaðahreppur, referring to Skútustaðir, one of the main settlements in the region. The present boundaries of the hreppur extend south to the edge of the Vatnajökull icefield, covering an area of 4,900 km2, although only the northernmost 20% of this area is vegetated and settled. Several Settlement and Commonwealth Period sites have been excavated in the region (Friðriksson and Vésteinsson, 1998; Lucas, 1999; Vésteinsson, 2004).

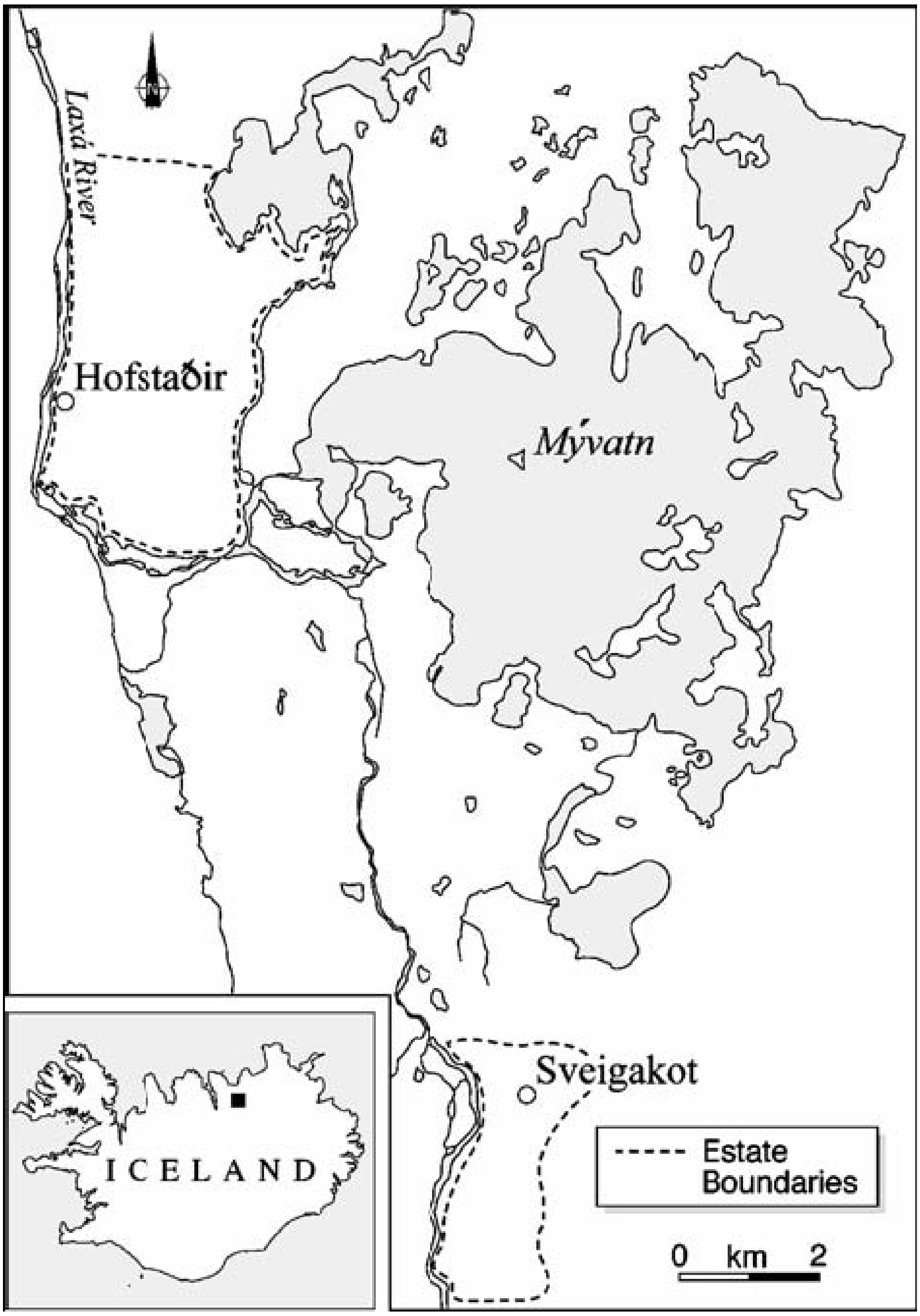


Fig. 1 Location of Hofstaðir and Sveigakot grazing areas,Mývatnssveit, northeast Iceland.

The area immediately surrounding Mývatn consists of flat or gently undulating vegetated land, with large numbers of volcanic features such as lava flows, craters, and pseudocraters. South of the lake are extensive lava fields extending into the barren interior (Ólafsson, 1979). The vegetation cover is dominated by cultivated land, bog/mire vegetation, and heathland. Lake and river islands that are inaccessible to livestock are covered with dense birch scrub and herb-rich vegetation communities, indicating the impact of grazing upon the region’s vegetation cover.

The Mývatn region experiences a more settled, continental climate than most of Iceland (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). The region’s location in the rain shadow of the Vatnajökull icefield results in a relatively dry climate, with annual precipitation between 40 and 100 cm (south to north; Ólafsdóttir and Júlíusson, 2000). The soils in the region are erosion-sensitive Andosols derived from volcanic tephra and aeolian materials of various sources (Soil Survey Staff, 1998). The immediate surroundings of Mývatn experience little or no erosion; however, the extensive barren areas to the east, south, and north of the lake suffer from erosion that is classed as severe or extremely severe (Icelandic Soil Erosion Classification: Arnalds et al., 2001). Studies in the region suggest that there have been several periods of increased erosion activity in the past (Ólafsdóttir and Guðmundsson, 2002; Simpson et al., 2004), both predating and postdating the arrival of Norse settlers in the region.

Two farm estates in Mývatnssveit are modeled: Hofstaðir and Sveigakot (Fig. 1). Hofstaðir is located to the north west of Mývatn, beside the Laxá River (65°37’N, 17°09’W). The farm estate covers approximately 16 km2 between 220–320 m above sea level. Archaeological excavations at Hofstaðir have demonstrated that there has been a farm at this location for over 1,000 years, with the earliest building phase at the site dating from the tenth century A.D. (Friðriksson et al., 2004), immediately postdating a tephra dated to ca. 950 A.D. Sveigakot is located to the south of

Mývatn, between the Kráká river and the now barren 3,800-year-old Laxárhraun lava field (65°31′N, 17°02′W). The farm estate has an area of around 3.5 km2 between 250 and 320 m above sea level. The estate is now extensively eroded, with little or no vegetation. A small Viking-age longhouse and pit house have been excavated at Sveigakot, and tephrochronology and radiocarbon dating indicate that the site was settled shortly after the deposition of the Landnám tephra and had been entirely abandoned by the late twelfth century A.D. (Vésteinsson, 2001).

Model simulations are undertaken for two periods: the Landnám period in the late ninth century A.D. when the region was first settled, and the early eighteenth century, for which detailed and comprehensive farm census records are available. Both farms will be modeled for the Landnám period, but Sveigakot had been abandoned for several centuries by the early eighteenth century so will not be modeled for this period.

Búmodel: A Historical Grazing Management Model

Búmodel is an environmental simulation model that predicts spatial and temporal patterns of vegetation biomass production and utilization (Thomson and Simpson, 2006). It has been developed for the purpose of investigating the interaction between farm management and vegetation degradation in Iceland in the premodern period (pre-1900 A.D.) (Fig. 2). The model is designed to operate at the scale of an individual farm estate, or a group of farms with a common management system, and runs on a monthly basis over a single year. Búmodel uses a fishnet of cells of equal area to model the spatial patterns of vegetation production and utilization. Cell sizes can be between 4–25 ha, depending upon the size of the study area. A larger cell size will give smaller scale patterns but will also reduce computation times. Búmodel is a stochastic

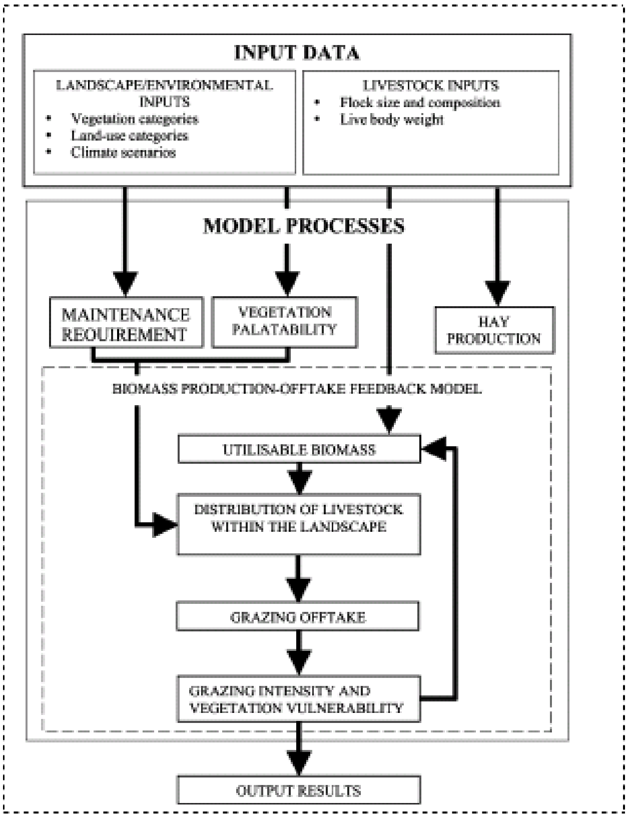


Fig. 2 Structure diagram of Búmodel (Thomson and Simpson, 2006).

spreadsheet-based model that can be loosely coupled with ArcView GIS so that model inputs and outputs can be analyzed both statistically and in map form. The model has been validated using contemporary Icelandic research (Thomson and Simpson, 2006).

Values for the input data are taken from historical and archaeological sources (see below). Eight vegetation categories descriptive of grazing land in Iceland (hayfield, grassy heath, dwarf shrub heath, moss heath, bog, riverine vegetation, birch woodland, and sparsely vegetated land) are used to map the spatial distribution of vegetation within the study area (see Table I for indicative plant species). There are three land-use categories: the cultivated hay meadow area, the uncultivated outfield, which belonged to the farm and was used for livestock grazing and some fodder production, and the rangeland, which was the extensive summer grazing area beyond the limits of the outfield. The climatic scenarios used in Búmodel are based upon air temperature, which is the dominant climatic control upon vegetation growth in Iceland. Four climatic scenarios (baseline, warm, cold, and extreme cold) are defined based upon mean monthly temperature from the long series of meteorological observations (1845–present) at Stykkishólmur on the west coast (Icelandic Meteorological Office, 2001). These scenarios are thought to represent the range of climatic variability in Iceland during the premodern period (Ogilvie, 1984). The scenarios control the starting date and length of the growing season and the production of utilizable vegetation biomass within the growing season. Livestock inputs are composed of the numbers of different livestock types (sheep, cattle, and horses and age cohorts within these categories) and their live body weights, which are used to calculate basic nutritional requirements. Livestock are distributed within the Búmodel land-use categories on a monthly basis.

Model process submodels have been developed from contemporary agricultural research (Thomson and Simpson, 2006) from Icelandic sources. The maintenance requirements submodel predicts the nutritional requirements of the grazing livestock and the amount of vegetation that will be removed by grazing. The vegetation palatability submodel predicts which vegetation communities will be preferred for grazing (which can change seasonally), which, together with the maintenance requirements submodel, determines the distribution of livestock across the study area and the grazing offtake from each cell. The hay production submodel predicts the amount of fodder produced from the hayfield, based upon its area, the climate scenario, and the quantity of fertilizer available (from manure).

The biomass production-offtake feedback model predicts the spatial and temporal patterns of vegetation biomass production and removal by grazing across the study area. The quantity of utilizable biomass (UB, the vegetation that is available to grazing animals) available at any time depends upon the amount of vegetation growth and decay previous to that time and upon the intensity of grazing. The level of biomass cumulative utilization by livestock may be calculated from the amount of UB that is removed from a cell by grazing as a percentage of the peak growing season UB (a proxy for annual production; Friðriksson, 1972). Over-grazing occurs when utilization exceeds a threshold value, which varies between vegetation communities (Thorsteinsson, 1980). A 40% utilization threshold is used for the grassy heath, moss heath, riverine, birch woodland and sparsely vegetated communities; a threshold of 15% for dwarf shrub heath, and a threshold of 35% for bog/mire (RALA, 1978a, b, 1979, 1980, 1981). Overgrazing of UB during the growing season affects growth in subsequent months, while overgrazing outside the growing season may affect growth in subsequent seasons (Archer and Tiezen, 1980). The cumulative utilization value in April represents the annual utilization of vegetation biomass.

Model Data Requirements: Environmental Reconstruction

A reconstruction of the historical landscape is required for modeling, both in terms of vegetation cover and land use zones. Palaeoenvironmental evidence (pollen, soils) and

Table I Indicative Plant Species in Búmodel Vegetation Categories

Búmodel vegetation category	Typical plant species
Hayfield	Species of *Agrostis*, *Festuca*, *Poa* and *Deschampsia* grasses.
Grassy heath	*Agrostis* sp., *Festuca rubra*, *Deschampsia caespitosa*, *D. flexuosa*, *Thymus praecox*, *Alchemilla alpina*, *Galium* sp.
Dwarf shrub heath	*Vaccinium* sp., *Empetrum nigrum*, *Salix herbacea*
Moss heath	*Racomitrium lanigonosum*, *Silene acaulis*, *Thymus praecox*
Bog	*Carex nigra*, *C. bigelowii*, *Eriophorum angustifolium*, *Juncus* sp., *Equisetum* sp.
Riverine vegetation	*Angelica archangelica*, *Ranunculus* sp., *Salix phylicifolia*, *S. lanata*
Birch woodland	*Betula pubescens*, *Salix* sp., *Geranium sylvaticum*, *Alchemilla vulgaris*
Sparsely vegetated land	Over 70% bare ground with scattered mosses, herbs and grasses

documentary evidence may be used to estimate the historical vegetation cover. These sources may be augmented by extrapolation from modern vegetation maps and aerial photographs and knowledge of regional ecological dynamics. The resulting broad picture of the historical vegetation patterns includes the relative areas and distribution of the key vegetation types. In cases of uncertainty simulations could be undertaken with several different vegetation reconstructions. Reconstruction of historical land use zones may use historical property boundaries or evidence from archaeological survey.

Farm Estate Reconstructions: Hofstaðir

The outfield pastures of Hofstaðir are defined by historical property boundaries and turf-based earthwork dykes (one of which predates an A.D. 1300 tephra fall from Hekla; Einarsson et al., 2002). A detailed regional pollen record is not yet available for Mývatnssveit but palynological and other environmental research at the regional and national scale (Steindórsson, 1962; Thorsteinsson and Arnalds, 1992) suggests that two alternative vegetation maps can be reconstructed for the Hofstaðir estate at the time of Landnám (Fig. 3). The first reconstruction assumes that birch woodland dominated the landscape, but with varying understory botanical composition depending upon drainage and topographical conditions. The Búmodel birch woodland category does not distinguish understory composition, so the vegetation was described in mosaics of woodland, grassy heath, dwarf shrub heath, riverine vegetation, and bog. This reconstruction is based upon the assumption that most of the lowlands in Iceland (below 300–400 m) were covered in birch woodland at the time of Landnám (Kristinsson, 1995; Thorsteinsson and Arnalds, 1992). Hofstaðir lies below this estimated tree line, and woodland on the western side of the Laxá valley still exists today. Archaeological evidence from the excavation of the Vikingage site at Hofstaðir (birch tree bark, twigs, wood fuel residues and evidence of smelting activity; Simpson et al., 2003) indicates that there was woodland in the vicinity of the farm. The second Landnám reconstruction for Hofstaðir assumes fewer trees and greater dominance of heathland. Areas above 300 m are covered by dwarf shrub heath and boggy areas beside watercourses and are assumed to be unwooded. Evidence for such a reconstruction is provided by vegetative predictive modeling (Ólafsdóttir et al., 2001), which did not predict birch forest (trees over 2 m) in this region at the time of Landnám, and if bog areas were very wet tree growth would have been discouraged. The vegetation cover at Hofstaðir in the eighteenth century (Fig. 3) has been extrapolated from twentieth century vegetation maps and fieldwork survey. It is assumed that the vegetation was less degraded than in the twentieth century and that drainage and exposure were the primary influences upon vegetation cover with a small infield area beside the farmstead and dwarf shrub heath restricted to high exposed sites.

Farm Estate Reconstruction: Sveigakot

The outfield pastures of Sveigakot are defined by interpolation between adjacent historical farm areas (Vésteinsson,

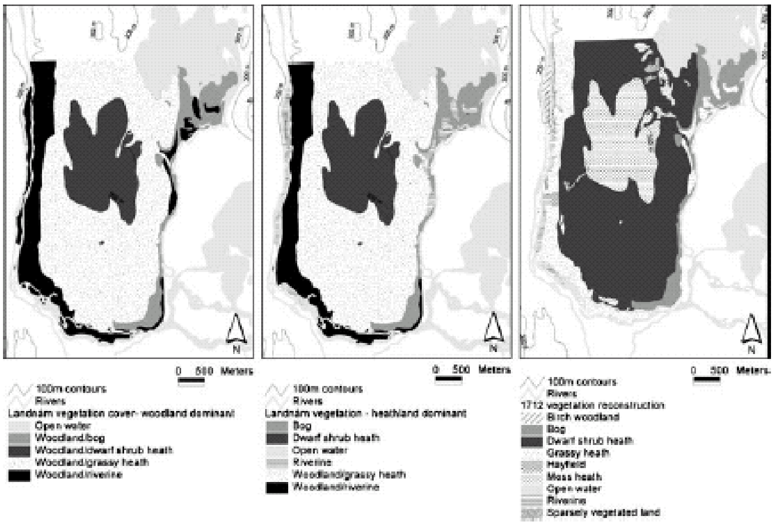


Fig. 3 Vegetation cover reconstructions for Hofstaðir: (I) Landnám birch woodland dominated, (II) Landnám heathland dominated, (III) eighteenth-century vegetation cover.

2001). The area is heavily eroded today, but geoarchaeological analysis has indicated that the land surface was stable and well-vegetated in the period immediately preceding Landnám (Simpson et al., 2004). Sveigakot means 'cottage of the swathes (of grassland)' but it has been suggested that this name reflects the vegetation cover in more recent centuries, rather than being related to the original farmstead (Vésteinsson, 2001). Fuel residue analysis at Sveigakot has shown that both birch and willow were used for fuel (Simpson et al., 2003), and were presumably sourced from the farm locality. Two vegetation cover maps can be constructed for Sveigakot (Fig. 4), in a similar manner to Hofstaðir. In both reconstructions wet meadow vegetation would have covered the banks of the Kráká, but either birch woodland or grassy heath vegetation cover can be hypothesized on the higher ground. Table II shows each Búmodel vegetation category by area for the different reconstructions.

Model Data Requirements: Management Inputs

In order to model the impact of farm management Búmodel requires information on livestock (types, numbers, and weights), livestock management (seasonal distribution between land-use zones, slaughtering) and fodder production. Values for these inputs may be available from direct sources, such as farm records, or estimated from indirect forms of evidence. For example byre sizes and configurations may indicate the number of dairy cows, and zooarchaeology can indicate animal sizes, the stocking mix, and certain management practices. The present version of the model is confined to the examination of the relative impacts of livestock on levels of vegetation biomass. Additional effects, such as those of different methods of grazing ('clipping' vs. 'pulling') or trampling, are not considered here. Goats and pigs are not considered in the current version of Búmodel, so these animals are not included in the Landnám simulations. Information on the Icelandic breed of these species is very limited, and they have different ways of feeding (browsing and rooting). While never a major component of the farm herd, goats and pigs may have had a noticeable local impact, particularly on the birch woodland, and could be incorporated into future applications of the model.

Management Reconstructions: Landnám

The early farm at Hofstaðir had an economy based on cattle, sheep, goats, and pigs, supplemented by fish and

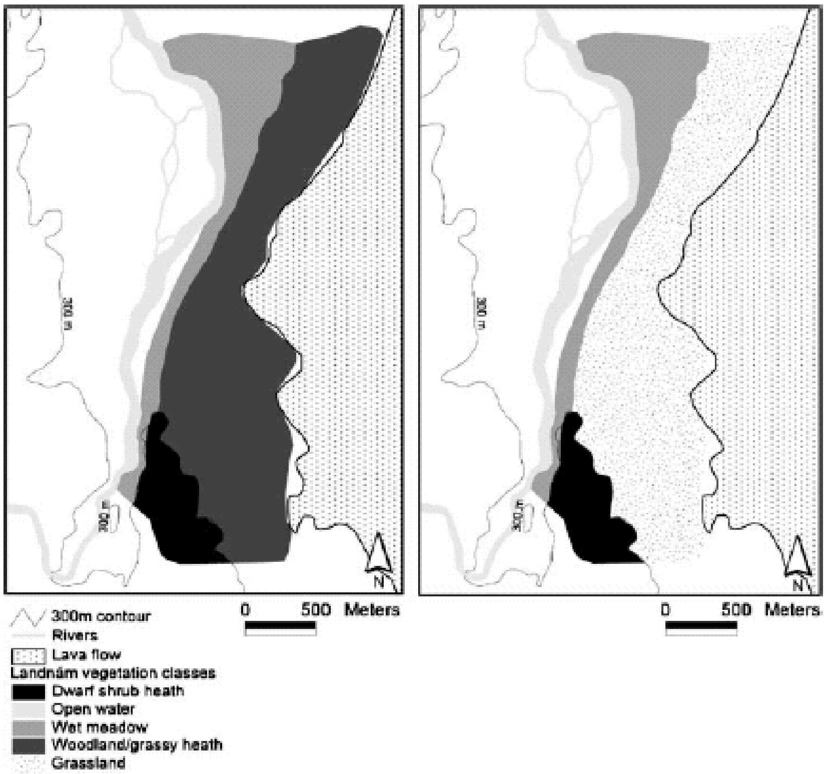


Fig. 4 Vegetation cover reconstructions for Sveigakot at Landnám: (left) birch woodland dominated, (right) grassland dominated.

Table II Area (ha) of Búmodel Vegetation Categories for the Different Landscape Reconstructions

Vegetation category	Hofstaðir Landnám birch reconstruction	Hofstaðir Landnám heath reconstruction	Sveigakot Landnám birch reconstruction	Sveigakot Landnám heath reconstruction	Hofstaðir 1712 reconstruction
Hayfield	0	0	0	0	5
Grassy heath	422	422	116	232	216
Dwarf shrub heath	122	245	35	35	810
Moss heath	0	0	0	0	266
Bog	62	123	0	0	124
Riverine vegetation	133	164	77	77	32
Birch woodland	739	523	116	0	14
Sparsely vegetated land	0	0	0	0	10

wild bird eggs (Vésteinsson et al., 2002). Small amounts of horse bone have also been found. The NISP (number of identified species) counts from zooarchaeological analysis record one cow for every 6.8 caprines (sheep or goats but most probably sheep) in the late tenth century, rising to one cow for every 2.5 caprines in the eleventh century (McGovern, 2003). Estimation of live weight from radii bones (O'Connor, 1989) gives sheep live weights in the range of 37–40 kg (McGovern, 2003). Landnám livestock numbers were estimated for Hofstaðir based upon a household size of 10–15 people (Table III). It is assumed, based on the archaeofauna (McGovern, 2003), that the Landnám farm at Hofstaðir was following a dairy strategy with their cattle (neonatal slaughter of calves and high numbers of adult cattle) and a meat/wool production strategy with their sheep, with wethers being kept for wool production and lambs killed in the autumn or at the start of their second summer.

It is unlikely that Sveigakot, with its smaller farm estate, would have been able to support as large a household as Hofstaðir. The household size in the eleventh-early twelfth century A.D., as estimated from the hall size, was around 7–10 people (McGovern, 2003), although 3–5 people may be more realistic. Zooarchaeological evidence indicates that the caprine/cattle ratio increased from the ninth to the eleventh centuries, and that this ratio was around 1.6 caprines for every cow in the Landnám period. It appears that Sveigakot was pursuing a dairying strategy for its cattle and a wool production strategy for its sheep, possibly with some ewe dairy production. Sveigakot culled their lambs in the autumn of their first summer, possibly after they had returned from grazing on the summer pastures. The estimated livestock numbers for Sveigakot in the Landnám period are given in Table IV, based on a household of seven people.

Management Reconstructions: 1712 A.D.

Livestock numbers and management for the early eighteenth century period are available in the farm census Jarðabók (Magnússon and Vídalín, 1913–1990). Mývatnssveit was surveyed for this census in August 1712, when 19 farms were recorded. Livestock numbers for the eighteenth century simulations for Hofstaðir are taken directly from this source (Table V). Livestock weights were estimated from the carcass weights given in Aðalsteinsson (1990). In 1712 the value of the Hofstaðir estate was the highest

Table III Estimated Livestock Numbers for Hofstaðir at Landnám

Livestock type	Number of animals	Estimated live weight (kg)	Management information
Dairy cattle	7	350	Kept for milk production
Calves	7	23 kg at birth	Culled in May
Immature cattle	2	270	Kept for meat production
Ewes	29	37	Some milk production
Lambs	19*	3 kg at birth	11 retained after autumn cull
Immature sheep	15	35	5 retained after spring cull
Wethers/rams	21	40	Kept for wool production
Horses	4	350	Kept for transport purposes

* Assumes some prenatal/neonatal mortality.

Table IV Estimated Livestock Numbers for Sveigakot at Landnám

Livestock type	Number of animals	Estimated live weight (kg)	Management information
Dairy cattle	12	350	Kept for milk production
Calves	10	14 kg at birth	Culled in May
Ewes	13	35	Some milk production
Lambs	9*	3 kg at birth	4 retained after autumn cull
Immature sheep	10	35	3 retained after autumn cull
Wethers/rams	4	40	Kept for wool production
Horses	1	350	Kept for transport purposes

* Assumes some prenatal/neonatal mortality.

valuation in the hreppur, at 40 ‘hundreds’. The land rent is listed as being paid in fish and the cattle rent in butter. 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 Jarðabók record also notes that there was sufficient dwarf birch and willow for fuel and for bulking out hay supplies. It seems likely that at least some of the livestock were grazed on the common land south of Mývatn during the summer months, most likely the wethers and possibly the lambs. The cattle would have been kept indoors over winter and fed hay, while the sheep were grazed out of doors with a little hay feeding when weather conditions prevented grazing (Aðalsteinsson, 1990). The horses were sent away from the estate in winter to Mývatnsöræfi (an area to the east of the lake) and left to graze without supervision. 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 55 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 39 lambs).

Búmodel Simulation Results

Firstly, for the Landnám vegetation reconstructions, simulation runs without any livestock were undertaken for the four climatic scenarios. For the initial set of simulations with livestock (for both time periods) it was assumed that no hay was given to the animals in winter, that all livestock were grazed on the farm estate throughout the year and that snow cover did not prevent grazing in the winter months. These simulations act as control datasets, indicating the grazing pressure on the farm under different climate scenarios and the potential for expanding livestock numbers. Additional simulations were then undertaken to assess the capacity of the estates to cope with adverse climatic conditions, such as cold summers and long periods of snow cover. The occurrence of persistent snow and ice cover would have prevented grazing on large areas of the estate. In Mývatnssveit in winter the dominant wind direction is from the south, and southern facing or exposed areas would have had only very thin or no 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.

Hofstaðir: Landnám Period

The utilizable biomass (UB) with zero grazing in summer, autumn and winter for the two Landnám vegetation reconstructions (B: birch woodland dominant, H: heathland dominant) is shown in Fig. 5. The average UB for both reconstructions is broadly similar, although the woodland reconstruction has on average 100 kg ha-1 more UB than the heathland reconstruction in the summer months, although the margin declines in the winter months. There is an average of 18.9 ha of grazeable vegetation per 25 ha cell (open water and land outside the estate boundaries are excluded).

For the initial set of grazing simulations, the model suggests that the Hofstaðir estate could have comfortably

Table V Modeled Livestock at Hofstaðir in 1712 A.D. (Magnússon and Vídalín, 1913–1990; Aðalsteinsson, 1990)

Livestock type	1712 (2 households)	Estimated live weight (kg)
Dairy cows	4	350
Milk ewes	55	45
Lambs	25	3.7 kg at birth
Wethers	34	65
Horses	5	350

supported a Landnám farm of 10–15 people with either vegetation reconstruction. There was sufficient vegetation biomass throughout the year to support the estimated livestock numbers without grazing damage (Fig. 6). However, this assumes that all the vegetation on the estate was accessible to grazing throughout the year. The introduction of winter snow cover will reduce grazing pressure on some cells and increase pressure on others. In order to assess these changes in grazing pressure, snow cover between November and March was assumed on the densely vegetated areas on the valley sides. There was still sufficient vegetation biomass to support the estimated livestock numbers (with culling) without grazing damage in both vegetation reconstructions under all the climate scenarios.

Hofstaðir could evidently have supported more livestock on its estate in the Landnám period, and therefore more people, without incurring grazing damage. Livestock numbers could have been tripled without mishap under the warmer scenarios with the B (birch-dominated) reconstruction, but under this scenario eight cells were liable to shrub grazing damage with the H (heath-dominated) reconstruction and the baseline scenario. Under the colder scenarios, with winter snow cover, and with triple livestock numbers, up to two-fifths of the estate would have been subject to shrub grazing damage with either vegetation reconstruction: cold scenario (B: 7 cells > 15%, H: 8 cells > 15%), extreme cold scenario (B: 32 cells > 15%, H: 29 cells > 15%; Fig. 7). This shrub grazing damage could be avoided if certain winter management actions were applied, either through winter feeding of livestock, or culling of animals in the autumn. A dairy cow is estimated to require 180.15 kg of hay per month when kept indoors (based on one cow having the feed requirements of six ewes; a ewe is estimated to require 30.03 kg of hay per month when kept indoors). The mean amount of fodder that could be harvested from the riverine vegetation communities in the extreme cold scenario was 1,533 kg/ha (with a harvesting efficiency of 70% of the August UB). In order to feed the dairy cattle it would be necessary to harvest an area of 5.8 ha (for seven cows) or 17 ha for the triple numbers of livestock. In the extreme cold scenarios, for the B reconstruction, overgrazing could have been avoided if the dairy cattle were fed indoors throughout the winter (October–April), and either the immature cattle, ewes, and lambs were also fed for 2–3 months, or if all lambs and immature sheep were culled in September and the ewes were fed for two months. This would have required fodder to be harvested from 26 ha. For the H reconstruction, overgrazing could only be avoided if all lambs and immature sheep were culled in September, all dairy cows and ewes were fed indoors over the winter, and the immature cattle were also fed indoors for three months. This would have required the harvest of 31 ha.

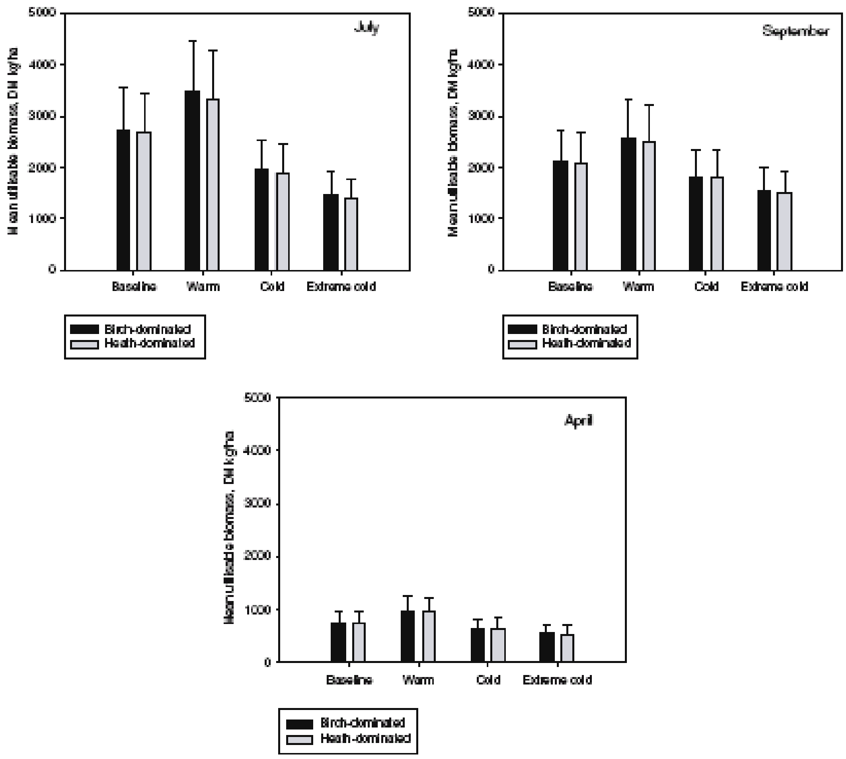


Fig. 5 Mean utilizable biomass in July, September and April at Hofstaðir with zero grazing (Landnám vegetation reconstructions).

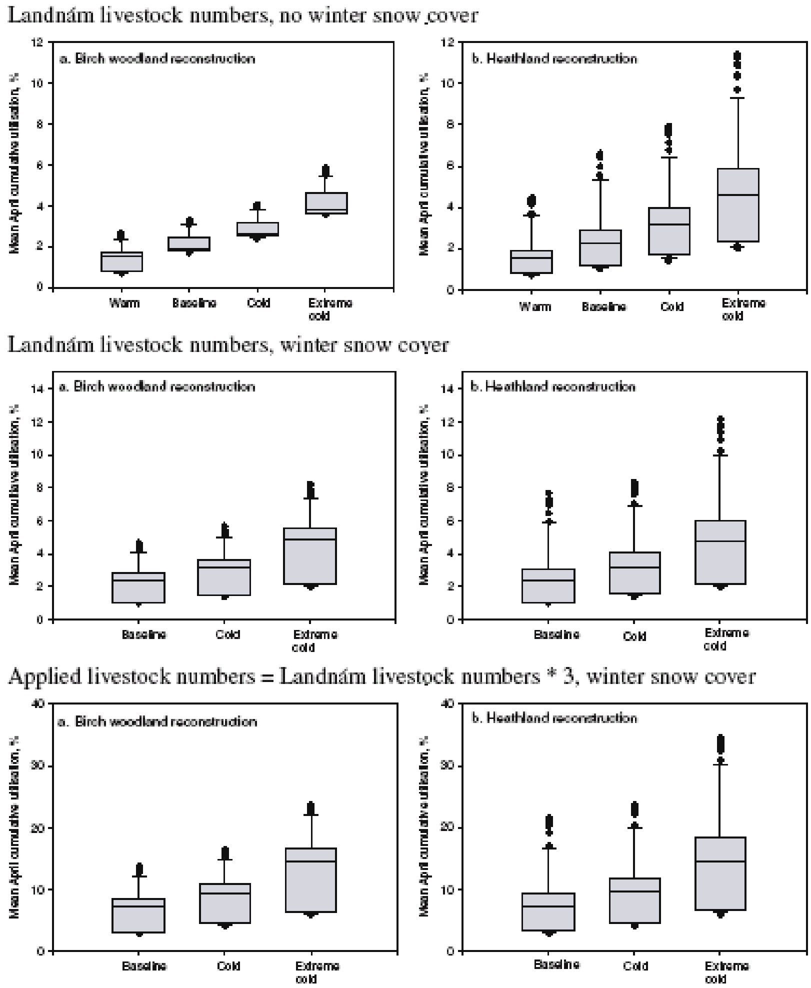


Fig. 6 Box plots of grazing pressure at Hofstaðir with Landnám vegetation reconstructions.

Sveigakot: Landnám Period

The utilizable biomass (UB) for the two vegetation reconstructions (B: Birch woodland dominated, G: grassland dominated) with zero grazing are shown in Fig. 8. The mean cell UB for both reconstructions are similar, although the differences in UB between the climatic scenarios are most marked in the summer months. Two sets of model simulations were undertaken with all-year grazing and no snow cover: one using the livestock numbers given in Table IV and one using the same livestock numbers as the

Landnám farm at Hofstaðir (Table III). From these simulations it would appear that Sveigakot could have supported a household of a similar size to Hofstaðir (10–15 people) but grazing damage was likely in the southwestern corner of the estate where there are areas of dwarf shrub heath, represented by the two outlying points in Fig. 9. With the Hofstaðir stocking numbers under the extreme cold scenario over 75% of the estate was being grazed at rates high enough to cause shrub damage.

In winter half of the estate is assumed to be covered by snow between November and March. The addition of snow cover intensifies the grazing pressure on exposed areas. This increase in intensity is greatest in those cells in the southwest of the estate that are already overgrazed, but does not push the remaining cells over the threshold of shrub grazing damage except in the extreme cold scenario. These areas of dwarf shrub vegetation remain vulnerable to overgrazing even when the numbers of winter grazing livestock are greatly reduced.

Landnám livestock numbers could have been increased by 50% if winter management strategies were also implemented. In the warmer scenarios, overgrazing could be avoided if the dairy cattle were fed indoors in the winter months (October–April). In the cold scenario, it would also have been necessary to feed the ewes and lambs for two months. In the extreme cold scenario it would have been necessary to feed the ewes for a third month and to cull all the lambs and immature sheep in the autumn in order to avoid overgrazing the shrub areas. This would have required 16 ha to be harvested for hay. Shepherding might also have reduced grazing damage by encouraging a more even grazing pattern.

If the dwarf shrub heath community is replaced by the sparsely vegetated land (SVL) community (which is possible with consistent overgrazing) then grazing pressures fall on the areas of SVL but increase in the other cells (Fig. 10). Even with indoor feeding of cattle in the winter months the majority of the snow-free area remains at risk of further shrub grazing damage under the extreme cold scenario.

Hofstaðir: Early Eighteenth Century

Modeling suggests that the vegetation on the Hofstaðir estate in the early eighteenth century was capable of supporting the recorded livestock numbers grazing throughout the year without risk of vegetation damage in all but the coldest climate scenario (Fig. 11), assuming no winter snow cover. Under the extreme cold scenario, an average of two cells had April cumulative utilization 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 13 cells, 17% of the estate area, were at risk of grazing damage.

Winter snow cover puts additional grazing pressure on the land that is still grazeable (Fig. 12). There is a risk of grazing damage under the extreme cold scenario (23 cells) and up to 13 cells are approaching the shrub damage threshold in the cold scenario. However, cumulative utilization does not exceed 40% under any of the climate

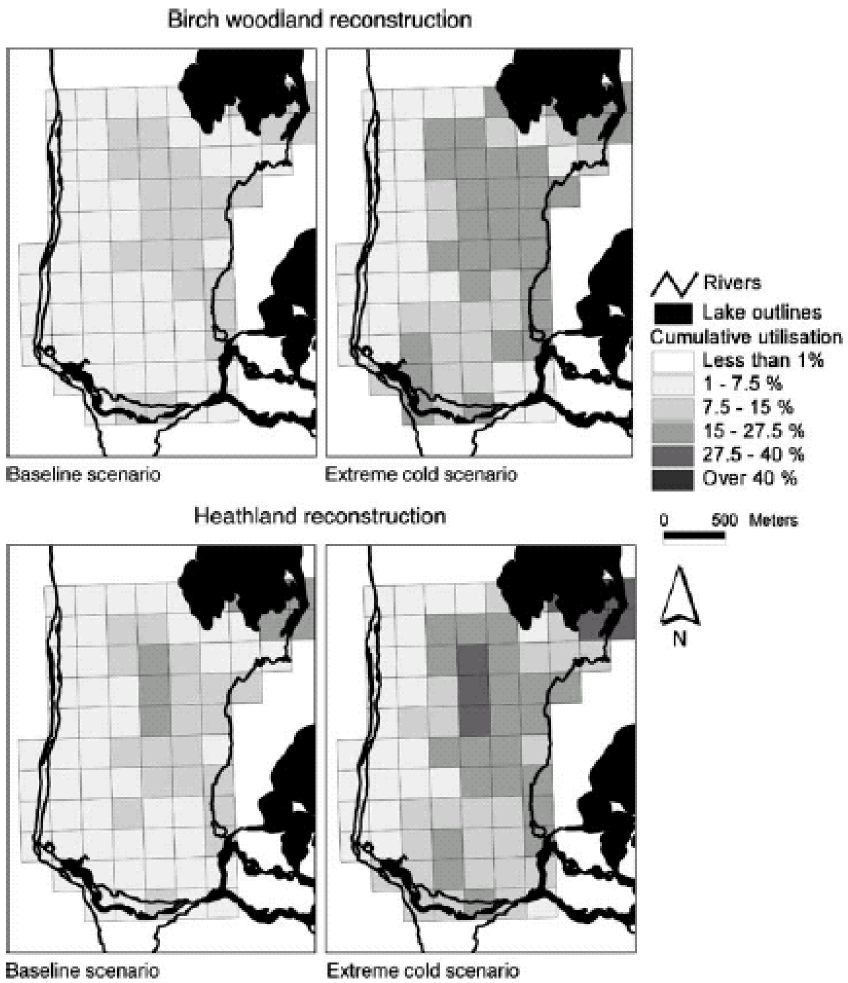


Fig. 7 Mean April cumulative utilization on the Hofstaðir estate with treble livestock numbers.

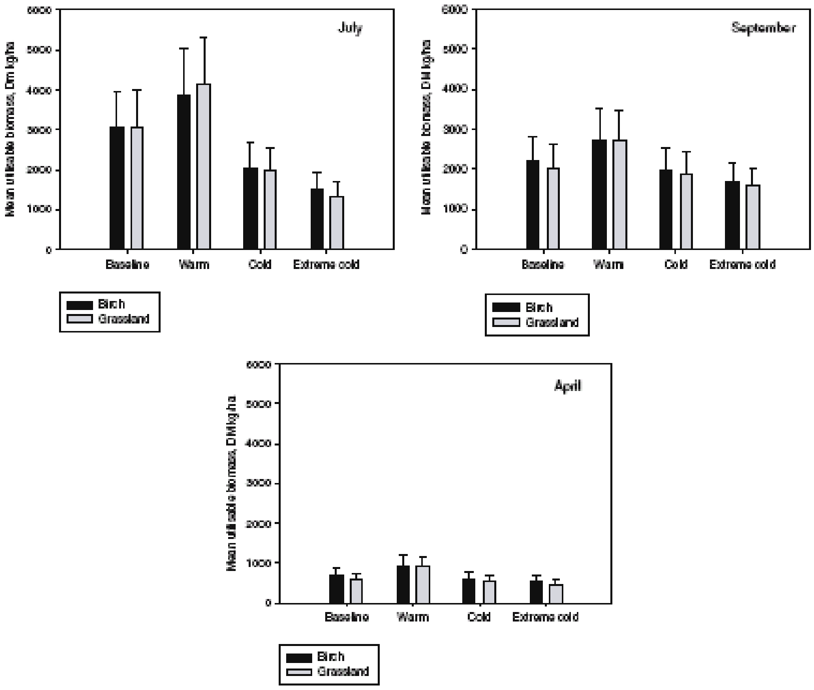


Fig. 8 Mean utilizable biomass in July, September and April at Sveigakot with zero grazing (Landnám vegetation reconstructions).

scenarios, so grazing damage to the grass-based vegetation communities is unlikely. Potentially, Hofstaðir could have increased its livestock numbers under the warmer climate scenarios. A 25% increase in livestock numbers would not cause grazing damage during the summer months. However, during the winter, with the valley vegetation ungrazeable due to snow cover, there is an increased risk of grazing damage under the baseline (1 cell), cold (14 cells), and extreme cold (29 cells) climate scenarios.

The implementation of winter management strategies reduces the risk of grazing damage. Culling lambs and wethers by 30–50% in the autumn reduces the grazing pressure on the estate. Used in combination with winter feeding (for 1 month or more) during extremely cold years, this could avoid grazing damage to vegetation entirely. It is estimated that 3.2 ha of outfield meadow would need to be harvested for fodder in order to feed the Hofstaðir sheep flock for one month in such a situation.

The calculation of hay production in Búmodel depends upon the area of hayfield, the mean summer and winter temperatures, and the amount of fertilizer applied. The bulk of the fertilizer 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. Feeding four cows indoors from October to May would have produced 88.32 kg of effective nitrogen fertilizer. 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 twentieth 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. The increase in predicted hay production between the 19.5 kg ha fertilizer input and the 45 kg ha input was between 26% (warm scenario) and 42% (extreme cold scenario).

The cultivated hayfield of 4.5 ha at Hofstaðir was capable of producing fodder for 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 fertilizer regime (Fig. 13). Under the extreme cold scenario and low fertilizer input, 42 ewes could be supported on hay for a single month. In contrast, under the warm scenario with high fertilizer input, 283 ewes could be supported for a single month, or approximately all of Hofstaðir's sheep flock could be supported for 2 1/2 months.

Discussion and Conclusions

Búmodel has been used to test two hypotheses concerning the management of livestock grazing in premodern Iceland. The first hypothesis was that natural biomass production during the premodern period was sufficient to support the

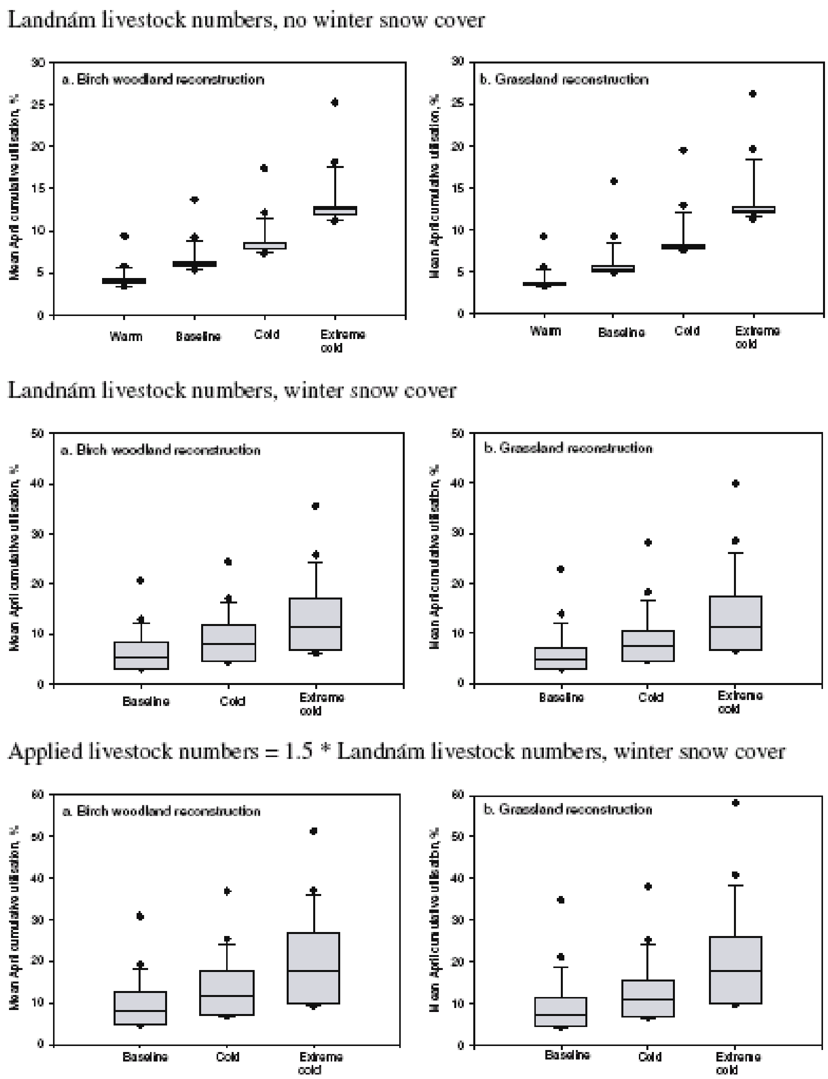


Fig. 9 Box plots of grazing pressure at Sveigakot with Landnám vegetation reconstructions.

numbers of livestock indicated by archaeological and historical data. The second hypothesis was that grazing management strategies could have maintained livestock numbers and vegetation cover, whilst avoiding extensive erosion and land degradation. On both estates and in both time periods modeling indicates that there was likely to be sufficient vegetation to support the inferred (Landnám) and reported (eighteenth century) livestock numbers throughout the year and suggests that land degradation was not an inevitable consequence of introducing domestic livestock grazing at Settlement. However, under the coldest climatic scenarios shrub grazing damage was likely to occur unless winter grazing management strategies were implemented. On average the growing season in Iceland lasts for 5 months (May to September) in the lowlands, during which time sufficient utilizable 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).

Management strategies that may have maintained grazing resources can be identified in the historical literature and included reducing the numbers of livestock in winter, supplementary feeding of livestock with fodder from the hayfield or from the outfield and shepherding. Reducing

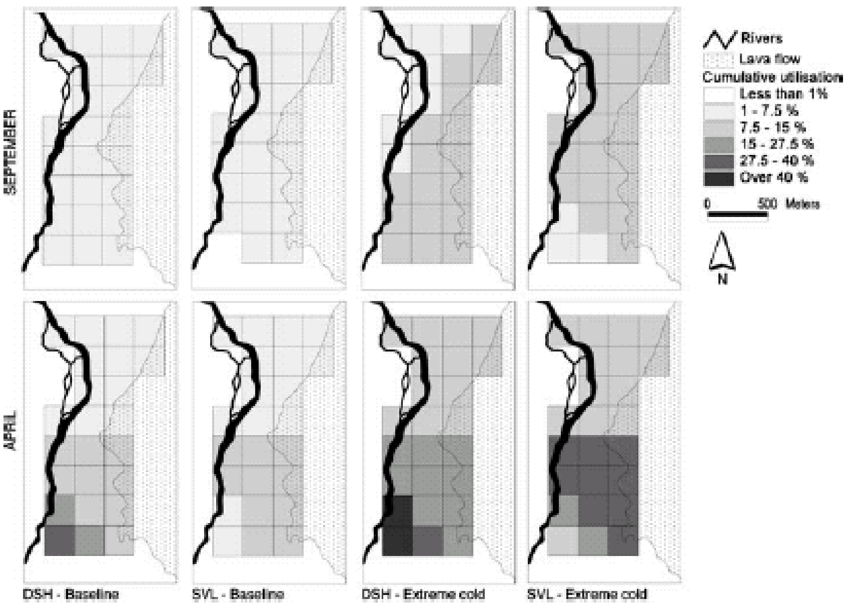
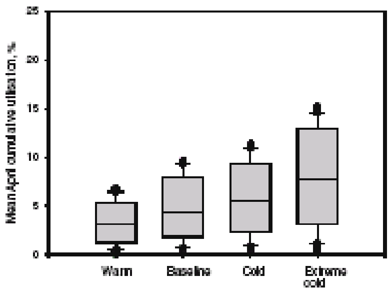
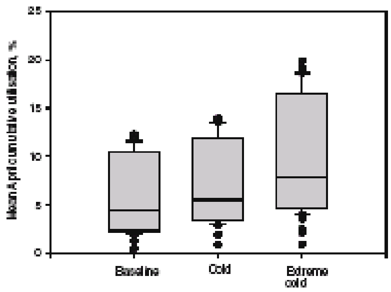


Fig. 10 Changes in grazing pressures on the Sveigakot estate when dwarf shrub heath degrades to sparsely vegetated land.

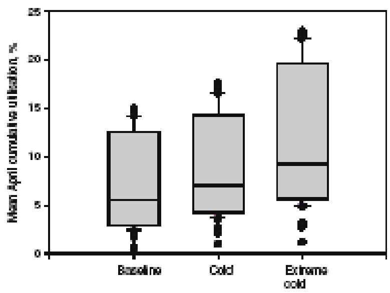
livestock numbers in the autumn ensured that there were sufficient grazing and fodder stocks for the remaining animals. They were then likely to survive winter in better condition: in the case of pregnant ewes, this would result in a higher spring birth and lamb survival rates, so that overall herd size was maintained. Livestock might be fed fodder from the hayfield or the outfield in addition to winter grazing. This was essential in the case of dairy cattle in order to maintain milk yields. However, hay harvesting was labor intensive and the nutritional value of hay declines with age, reducing the incentive to harvest more than was necessary, as any surplus would not keep well until the



18thC livestock numbers, no snow cover



18thC livestock numbers, winter snow cover



1.25 * 18thC livestock numbers, winter snow cover

Fig. 11 Box plots of grazing pressure at Hofstaðir with the eighteenth century vegetation reconstruction.

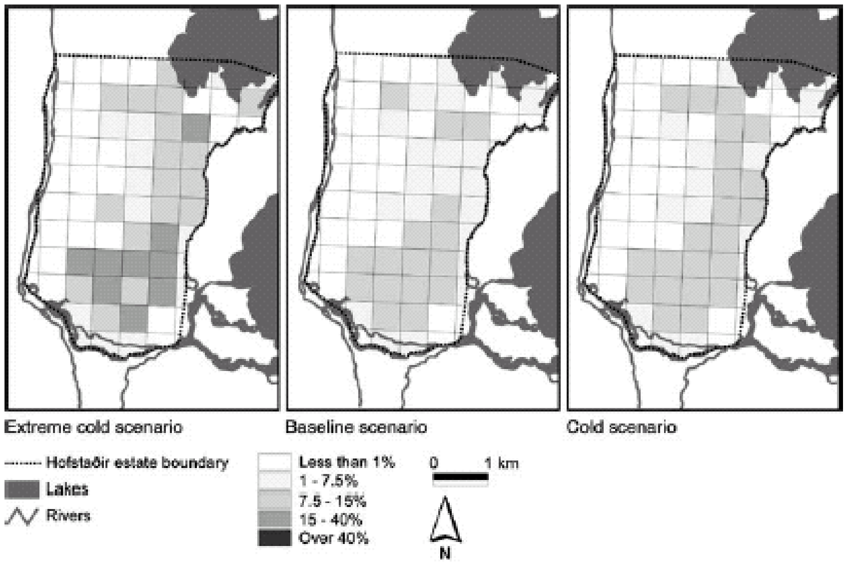


Fig. 12 Mean April cumulative utilization on the Hofstaðir estate with the eighteenth century vegetation reconstruction and snow cover.

following winter. Eggertsson (1998) describes the hreppur system of mutual support, where hay considered to be surplus was required to be sold on to those short of hay, as being a disincentive to farmers stockpiling hay for cold winters. Fodder from the outfield would also have been of poorer quality than that from the hayfield, 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.

There are notable contrasts in the relative abilities of Hofstaðir and Sveigakot to support a large household and large numbers of livestock in the Landnám period. Hofstaðir had natural advantages in its large estate, with large areas of vegetation cover that were valuable for both summer and winter grazing. As a result, Hofstaðir could have supported a Landnám household of 10–15 people with ample room for expansion. The large areas of wet meadow vegetation along the banks of the river Laxá would have provided fodder for winter storage whilst the hay meadow was being created. This wet meadow fodder could have supported large numbers of cattle, perhaps supplying beef for feasting at the large tenth century longhouse found at the site. Grazing pressures, even if a fairly large household is assumed, were sufficiently low to avoid grazing damage to vegetation in the warm and baseline climate scenarios. In the coldest scenarios, damage to shrub vegetation was possible but could have been avoided with increased hay feeding or culling of young animals (see above). It is interesting to note that the areas of dwarf shrub heath, which have the highest levels of grazing pressure (principally as a result of winter grazing), are the same areas that show signs of soil instability in the medieval period (Simpson et al., 2004). This suggests that grazing management at Hofstaðir was not always sufficiently responsive to

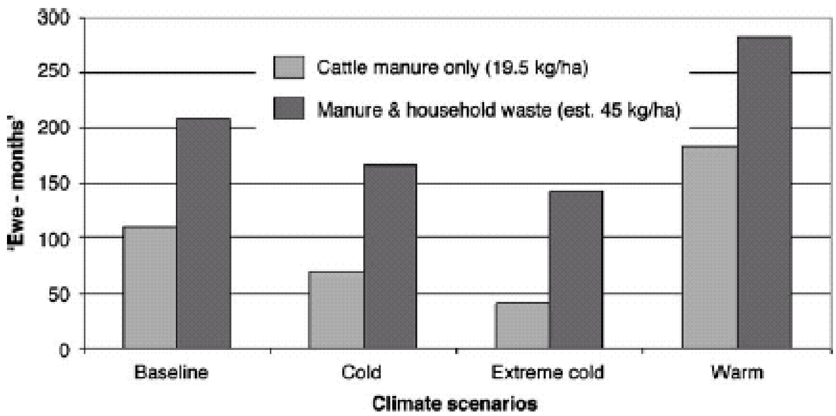


Fig. 13 Number of ewes that can be supported by hay feeding at Hofstaðir in 1712.

avoid overgrazing in adverse winters, but the absence of soil instability across a wider area infers that, on the whole, grazing management at Hofstaðir managed to avoid overgrazing and land degradation.

The Landnám farm at Sveigakot was operating with lower margins of vegetation biomass in order to maintain a reasonable household size. Nevertheless, either of the two Landnám vegetation reconstructions could have supported sufficient livestock for the postulated household size. The principle constraint was the small area of the estate, bounded by the supposedly barren lava field to the east, and by larger farm estates to the west, bordered by the channel of the river Kráká, and to the north and south. The household would have been left with little room for maneuver if river channel change destroyed the wet meadow pastures essential for winter fodder production. Such a loss of pasture might have been one of the factors behind the shift from a cattleintensive strategy at Sveigakot in the Landnám period to a sheep-intensive strategy in the twelfth century. The Búmodel simulations indicated that any areas of dwarf shrub heath on the estate would have been rapidly overgrazed and subject to vegetation degradation and soil erosion. The only way to avoid this would have been the unrealistic option of hay feeding of all livestock during the winter months or careful shepherding, although this may have been restricted by winter snow cover. The conversion of these heath areas to sparsely vegetated or bare ground would have increased winter grazing pressure on the rest of the estate but not to a sufficient degree that these areas immediately became overgrazed.

The favorable situation of Hofstaðir during the Landnám period seems to have been sustainable in the long-term. The Jarðabók record for Hofstaðir gives a general impression of a farm that was not experiencing difficulties in supporting its livestock and inhabitants. Sedimentary analysis for this period (Simpson et al., 2004) has demonstrated that the landscape of the Hofstaðir estate was stable, with lower levels of inferred erosion than the regional average (Ólafsdóttir and Guðmundsson, 2002). Compare this situation with that of Vestur-Eyjafjallahreppur in southern Iceland (Thomson and Simpson, 2006) where both the outfield and rangeland pastures were being grazed much closer to the degradation threshold in the same period of the early eighteenth century.

Inevitably there are potential pitfalls in the use of simulation modeling in historical ecology. There is a risk of being overly deterministic when interpreting modeling results, as the environmental processes are the most welldefined parts of the model. Historical documentary evidence must be analyzed carefully, in order to avoid errors of misinterpretation, such as seasonal bias and underreporting of livestock numbers. It is also impossible to fully assess the accuracy of inputs when modeling the distant past. This is particularly the case when estimating the extent and productivity of vegetation communities during the Landnám period, as there are no areas of vegetation in Iceland that can be said to have been truly free of any anthropogenic impact and so could be representative of the vegetation cover at Landnám. Palynological research indicates a much more extensive and heterogeneous cover of woodland and higher levels of biomass production in the absence of grazing. Given this, both estates may have been able to support higher numbers of livestock and people than estimated in this paper and could have supported lower numbers without difficulty. However, uncertainties in the landscape and management reconstructions can be assessed by undertaking simulations with different reconstructions that cover the range of probable values, as in this paper. The stochastic elements in the model processes also result in a range of possible outputs from a single set of inputs: validation tests of Búmodel with modern datasets have indicated that the actual values (for biomass production and offtake) will fall within the range of predicted values (Thomson and Simpson, 2006).

Búmodel is a new tool for the investigation of human and environmental interactions in a livestock-based agricultural setting, providing time depth and quantitative assessment of grazing pressures in historic landscapes. It provides a means of synthesizing 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). The model can now be developed further, to more closely integrate human aspects of land management with the biophysical environment. Examples may include population changes due to epidemics of smallpox and plague in the thirteenth and fifteenth centuries, impacts of devastating volcanic eruptions, and different management strategies that may be related to the social position of households and the wider political economy of settlement. In the Icelandic study areas considered, Búmodel demonstrates spatial and temporal variations in productivity and grazing pressure within and between historic grazing areas. It also suggests that land degradation was not an inevitable consequence of livestock grazing and the significance of grazing and livestock management in preventing overgrazing, particularly under cooler climatic conditions. Búmodel now has the potential for application in other areas of Iceland and the North Atlantic (it has already been applied in the Faroe Islands; Thomson et al., 2005), and the methodology and model framework could also be applied to understanding the historical dimensions of other extensive livestock-based agricultural systems and their landscapes.

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