Chapter 7

Land: Its Organisation and Management at Norse Hofstaðir

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Introduction

Land, its organisation and management as well as its intrinsic quality are little understood aspects of the settlement process in Iceland. Yet an understanding of the concept and significance of land is vital if we are to recognise the way in which environmental resources were used to create and maintain social structures, the role of management decisions in setting new directions of environmental change, and the adoption and adaptation of land management strategies to sustain food production. Organisation of land was needed to ensure the requirements of grazing domestic livestock (dominantly sheep, cattle and cows) and access to fuel resources were met in order to provide foundations for subsistence and local economies.

One key aspect of this organisation included different areas of land being used for winter and summer grazing. Winter grazing areas were generally recognised as being within the boundaries of farm estates, although occasionally shared and partitioned, and could be up to several hundred hectares in extent. Sheep were gathered and brought to these areas from upland summer pastures in September and grazed outdoors as far as was possible through to May. Across Iceland, arrangements for summer grazing were complex and varied widely from region to region; they included the use of farm estates for summer as well as winter grazing, the development of shielings within estate boundaries to graze milking livestock, and the extensive grazing of regulated common land areas (Simpson *et al.* 2001; Thomson and Simpson 2007). Management of livestock in this way allowed exploitation of the widest range of plant biomass while conserving hay resources harvested from the fertilised home-field and from wetland areas within the farm estate, and which were generally allocated to cows held in byres over the winter (Borchgrevink 1977; Aðalsteinsson 1991; Sveinbjarnardóttir 1992; Amorosi *et al.* 1998; Dennis *et al.* 2000).

Successful introduction of livestock-based land organisation and management during colonisation of Iceland required overcoming challenges presented by a natural environment sensitive to human impact. Soils in Iceland are predominantly classified as Andosols (Jóhannesson 1960; IUSS Working Group WRB 2006; Andisols: Soil Survey Staff 1998) derived from volcanic ejecta. The soils silt-sized textures, low bulk densities, and low clay and organic contents make them highly susceptible to erosion

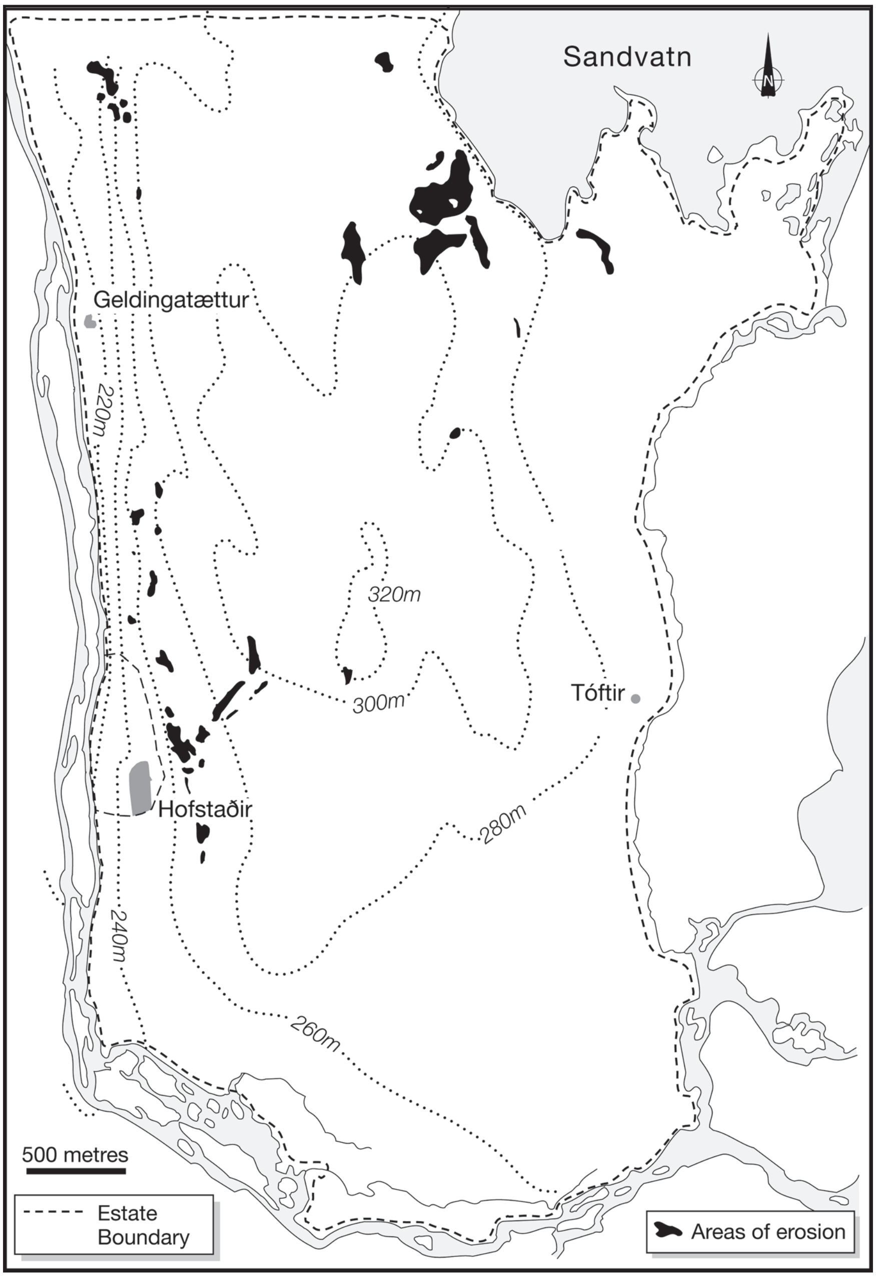

Figure 7.1 The Hofstaðir estate, Mývatnssveit. The estate is bounded by natural barriers on most sides and by a pre-1300s boundary wall on the northern side.

(Wada *et al.* 1992; Arnalds *et al.* 1995; Arnalds 2000). Historical assessments suggest that at least 40% of topsoils have been lost from Iceland since settlement (Thorsteinsson *et al.* 1971; Friðriksson 1972) with a consensus view that the introduction of grazing management regimes on soils inherently susceptible to erosion was the major cause of degradation. Cutting and burning of woodlands may also have contributed to an environmental imbalance between human demands and landscape sustainability, reinforced by climate change from warmer conditions at the time of settlement to consistent cooler conditions by the 13th century (Arnalds *et al.* 1987; McGovern *et al.* 1988; Buckland *et al.* 1991; Archer and Stokes 2000; Ogilvie 1984; Ogilvie *et al.* 2000). Adaptation of land organisation and careful management was essential to sustain food and fuel resource production from land that was easily degraded.

The nature of land organisation and management at Norse Hofstaðir is considered in this chapter, assessing the implications that this had for land productivities, land degradation, and the long term sustainability of the farm estate. Four aspects of the ca. 16km^2 estate are considered within a geoarchaeological and environmental history framework (fig.7.1): grazing regimes and the pressures that these brought to bear on the landscape (Thomson and Simpson 2007); homefield management and productivities (Adderley *et al.* 2008), fuel resource utilisation (Simpson *et al.* 2003; 1999), and landscape responses (Simpson *et al.* 2004). In integrating these aspects of an Icelandic farm estate, new understandings of how land in a sensitive environment was sustained by inherent land qualities, land organisation and land management are achieved.

Grazing pressures

Assessment of grazing pressures during the settlement and colonization period at Hofstaðir is made through integrative modelling of vegetation, livestock and climatic elements of estate reconstruction to predict biomass productivities and utilization; we have created an environmental simulation model for this purpose (Búmodel: *bú* - farm estate or farming enterprise; Thomson and Simpson 2006). Climate scenarios used in Búmodel are based on air temperature, the dominant climate control on vegetation growth in Iceland; four climate scenarios (baseline, warm, cold and extreme cold) are defined on the mean monthly temperature from the long series of meteorological observations (1845 – present) at Stykkishólmur (Icelandic Meteorological Office, 2001). These scenarios are considered to represent the range of climatic variability in Iceland during the pre-modern period (Ogilvie 1984). Vegetation and management input data are derived from the locality of the study area. The model is designed to operate at the scale of an individual farm estate or a group of farms and runs on a monthly basis over a single year. It is a stochastic 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 agricultural Icelandic research (Thomson and Simpson 2006).

Hofstaðir estate reconstruction

Palynological and other environmental research at the regional scale (Steindórsson 1962, Thorsteinsson and Arnalds 1992; Lawson, this volume) suggests that two alternative vegetation maps can be reconstructed for the Hofstaðir estate at the time of *Landnám* (fig.7.2; table 7.1). The first reconstruction assumes that birch woodland dominated the landscape, but with varying under-story botanical composition depending upon drainage and topographical conditions. This reconstruction is based upon the assumption that most of the lowlands in Iceland (below 300-400m) were covered in birch woodland at the time of *Landnám* (Thorsteinsson and Arnalds 1992, Kristinsson 1995). Archaeological evidence from excavation of the Viking-age 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 derived from predictive vegetation modelling (Ólafsdóttir *et al.* 2001) suggests fewer trees and greater dominance of heathland. Areas above 300m are covered by dwarf shrub heath and bog beside watercourses is assumed to be unwooded.

From zoo-archaeological analyses, supported by archaeological observation, the earliest farm at Hofstaðir had an economy based on cattle, sheep, goats and pigs, supplemented by fish and wild bird eggs with small amounts of horse bone also found (Vésteinsson *et al.* 2002). The number of identified species (NISP) counts record 1 cow for every 6.8 caprines (almost certainly sheep) in the late 10th century, rising

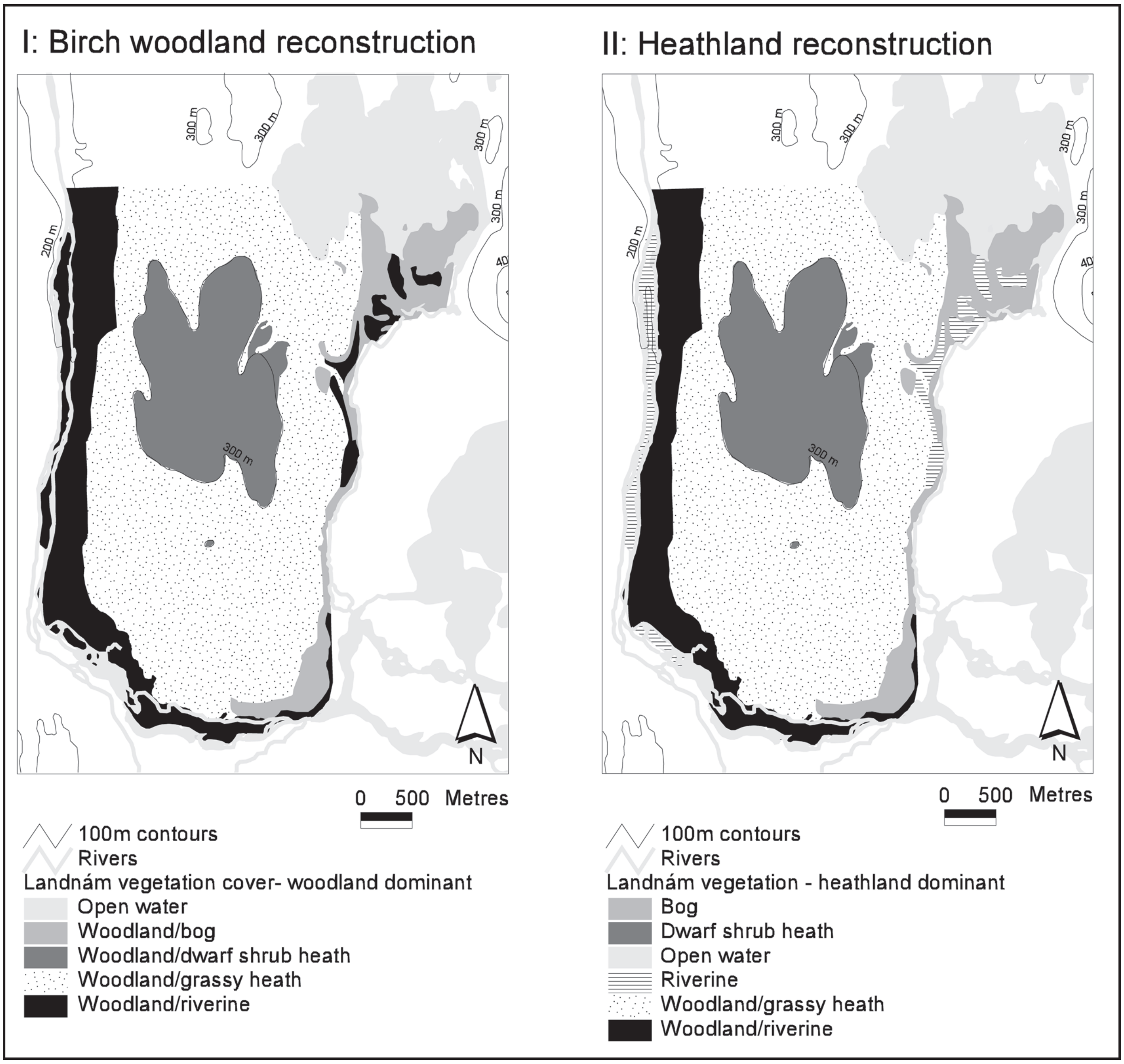

Figure 7.2 Alternative vegetation reconstructions for the Hofstaðir estate at *Landnám*

Vegetation category	**Hofstaðir *Landnám* birch woodland reconstruction (ha)**	**Hofstaðir *Landnám* heath-land reconstruction (ha)**
Grassy heath	422	422
Dwarf shrub heath	122	245
Moss heath	0	0
Bog	62	123
Riverine vegetation	133	164
Birch woodland	739	523
Sparsely vegetated land	0	0

Table 7.1 Area of Búmodel vegetation categories for different vegetation cover reconstructions.

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	38	Kept for wool production
Horses	4	350	Kept for transport purposes

*Assumes some pre-natal/neonatal mortality.

Table 7.2 Estimated livestock numbers for Hofstaðir at Landnám.

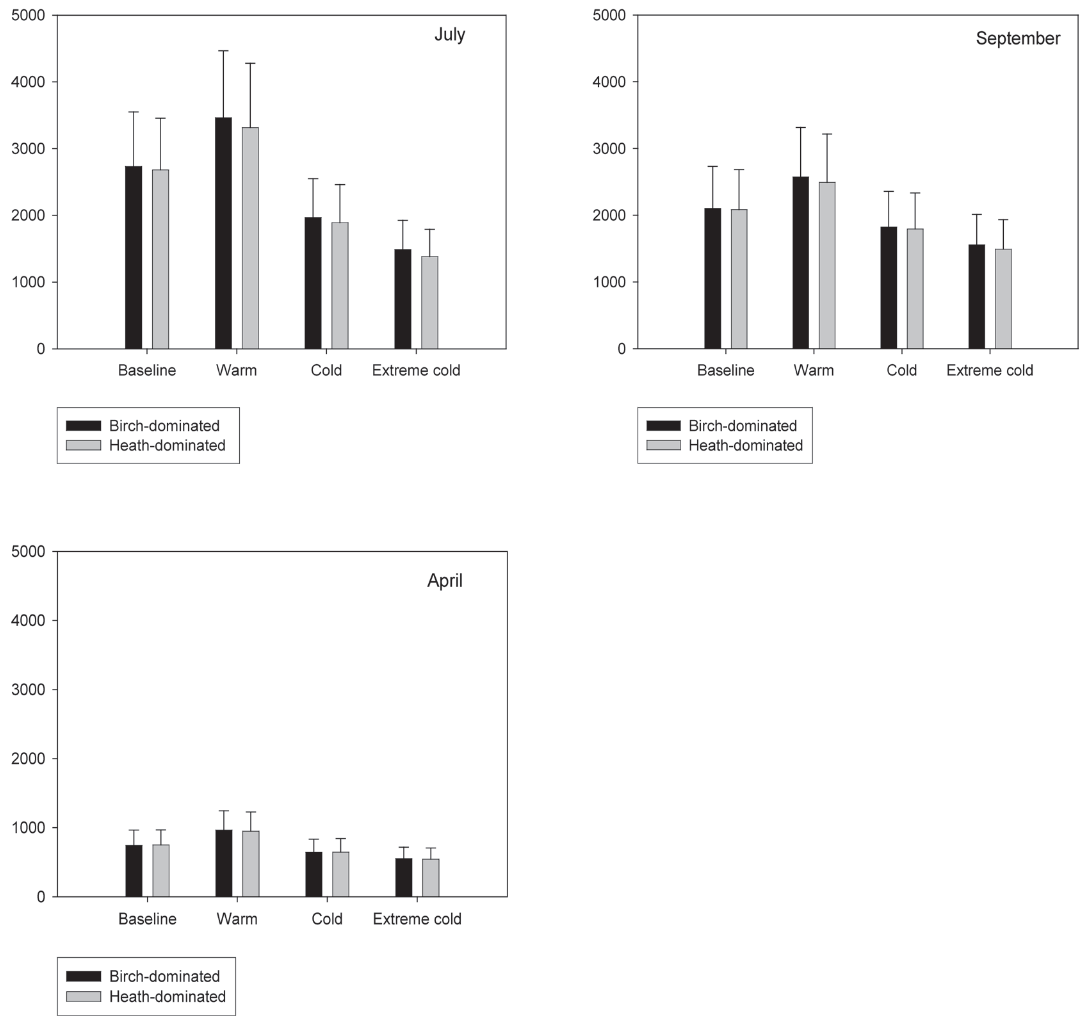

Figure 7.3 Mean utilizable biomass (kg/ha) in July, September and April at Hofstaðir with zero grazing (*landnám* vegetation reconstructions).

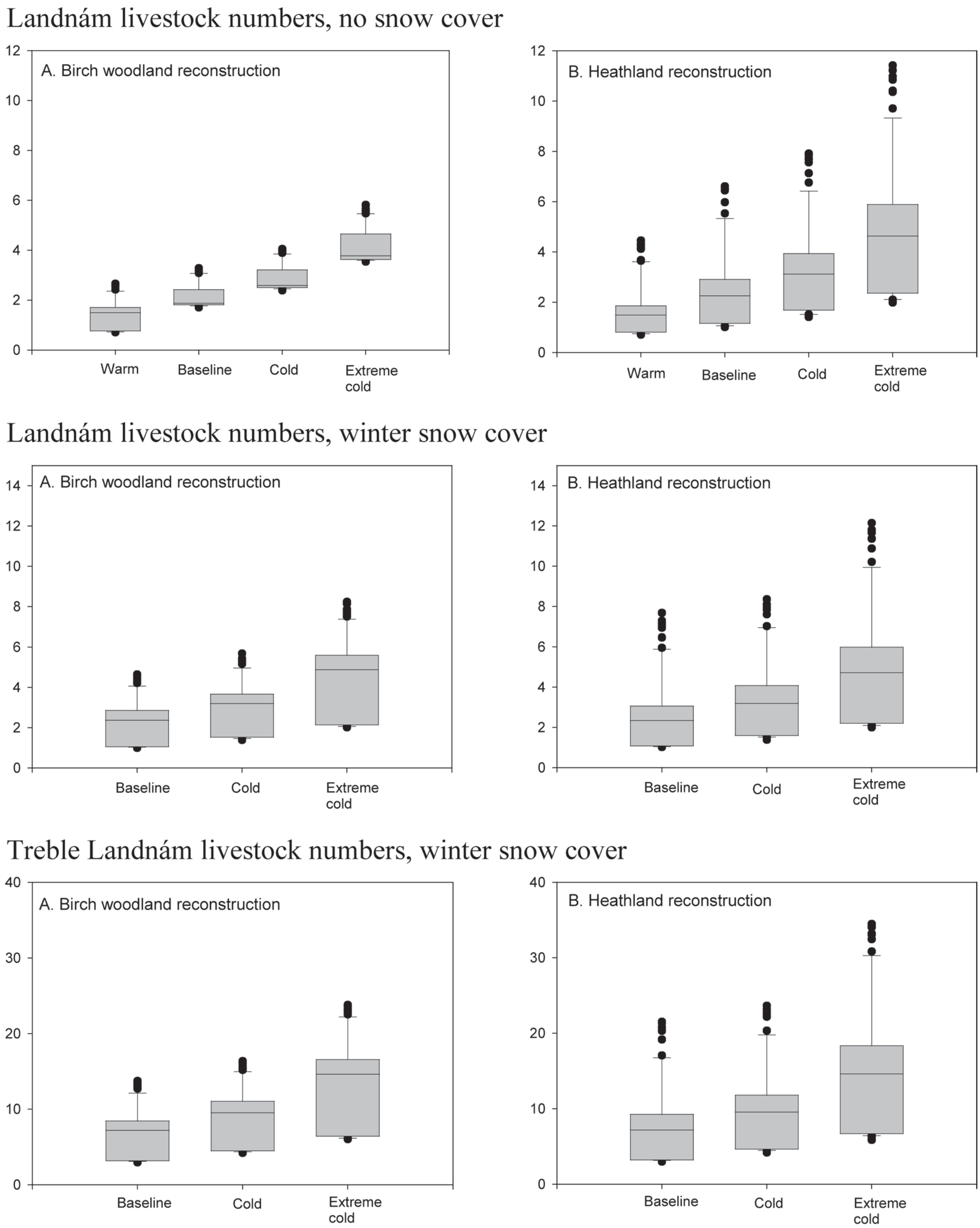

Figure 7.4 Búmodel results: Box plots of grazing pressure at Hofstaðir with *Landnám* vegetation reconstructions. Vertical axis is percentage vegetation utilisation in different areas of the estate.

to 1 cow for every 2.5 caprines in the 11th century (McGovern, this volume). Estimation of live weight from bone radii (O'Connor 1989) suggests caprine live weights in the range of 35-38 kg (McGovern, this volume). *Landnám* livestock numbers were estimated for Hofstaðir based upon a household size of 10-15 people for modelling purposes (table 7.2). It is assumed, based on the archaeofauna that the *landnám* farm at Hofstaðir was following a dairy and beef production 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.

Modelled biomass productivities and utilisations

The modelled scenarios for utilizable biomass with zero grazing in July, September and April for the two *landnám* vegetation reconstructions are shown in figure 7.3. The average utilizable biomass for both reconstructions is broadly similar, although the woodland reconstruction has on average 100 kg/ha more utilizable biomass than the heathland reconstruction in the summer months, with the margin declining in the winter months.

For the initial set of grazing simulations, with either vegetation reconstruction, the model outputs suggest that there was sufficient vegetation biomass throughout the year to support the estimated livestock numbers without grazing damage (fig.7.4). 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 locations 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. Even then 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. On this basis the model suggests that the Hofstaðir estate could have comfortably supported a *landnám* farm of between 10-15 people.

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 birch-dominated reconstruction, but some areas were liable to shrub grazing damage with the heathland 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 (fig.7.5).

Discussion

Modelling indicates that there was sufficient vegetation to support the suggested *landnám* 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 five 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 could include reducing the numbers of livestock in winter, supplementary feeding of livestock with fodder from the hayfield or from the outfield and shepherding. 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. Livestock might be fed fodder from the hayfield or the outfield in addition to winter grazing. Provision of high quality hayfield fodder was essential in the case of dairy cattle in order to maintain milk yields; fodder from the out-

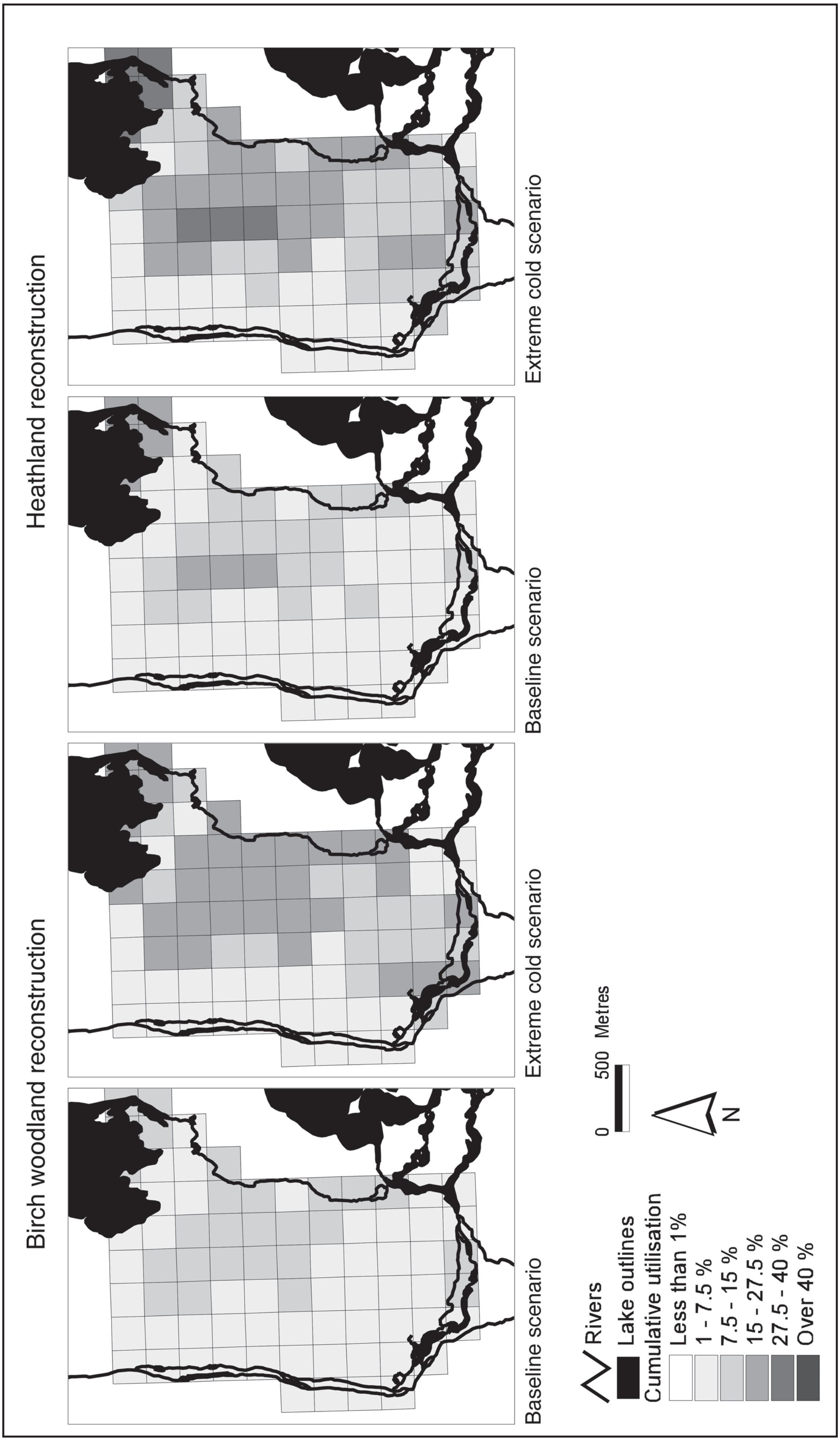

Figure 7.5 Mean April cumulative utilization on the Hofstaðir estate with treble livestock numbers.

field would 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.

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 10th 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.

Home-field management and productivities

The home-field, the managed field area adjacent and surrounding the farm site, was a key element of land organisation since in many locations it produced much of the high quality fodder required to over-winter livestock. Creation, management and productivity of home-field areas has been considered a key part of the initial success and long-term sustainability of early settlements across the North Atlantic region (Adderley and Simpson, 2005; 2006; Simpson *et al.* 2002). In this analysis we identify the contributions of climate, soil, altitude, aspect and adaptive management influencing home-field grassland productivities at Hofstaðir, focusing on the Norse settlement period from ca. AD 872 but running our analyses through to onset of intensive modern farm management ca. AD 1950. We integrate contributory factors within the CENTURY agro-ecosystem model (Parton *et al.* 1998; Metherell *et al.* 1993), a model well verified through both soil analyses and use of historical data in North Atlantic contexts (Adderley *et al.* 2000; Simpson *et al.* 2002; Adderley and Simpson 2005). In our discussion we highlight the way in which model-based analyses permit assessments to be made of the relative importance of these contributory factors over extended periods of time and for different Norse and later historic management scenarios.

Climate reconstructions

Contemporary high-resolution data-sets from weather stations along the Laxá valley and around Lake Mývatn have been used. The modelling study requires proxy records of climate including palaeo-temperatures and, where possible, palaeo-precipitation. Climatic conditions have been assessed by considering both long-term fluctuations at a regional level and by examining local variations. It is widely noted that climatic conditions were generally warmer at the time of the Norse settlement (AD 874 onwards) with cooler conditions becoming established in the 13th century (Ogilvie 1984; Ogilvie *et al.* 2000). At the regional North Atlantic level, a strong relationship between the Greenland ice core record and historical evidence of climate has been previously demonstrated and whilst anomalies around AD 1500 and AD 1700 have been described, historical climatic evidence for the time of settlement is consistent with these long-term trends (Guðmundsson1997; Sveinbjörnsdóttir 1993).

Examining instrumental data from the 20th Century onwards it is clear that the rainfall pattern in north eastern Iceland is distinctly different to that elsewhere in Iceland. Since the whole region is in the rain shadow for prevailing wind directions created by the Vatnajökull glacier, total annual precipitation is low (~ 400 $mm.a^{-1}$) relative to southern and western Iceland (1000-4000 $mm.a^{-1}$) (Einarsson 1979). Likewise the period of highest rainfall in this region is in mid-late summer, whilst in south and west Iceland this is in early-winter. Over longer periods the interaction of temperature and precipitation is seen in the strong negative rainfall anomalies reported for Stykkishólmur in west Iceland during prolonged cold periods. From empirical observations, winter season temperatures are related to vegetation growth the following year, with cold winters reported to reduce vegetation growth through the following season (Bergþórsson 1988). For model input, local climate information has been collated from published and unpublished datasets for five measurement sites in the Mývatn and Laxá valley area (Veðurstofa Íslands 2005, pers. comm.). These sites are at Sandur (65°57'N, 17°33'W; 3 m Above Sea Level), Staðarhóll (65°49.2'N, 17°20.8'W; 42 m ASL), Hólasandur (65°42'N, 17°06'W; 350 m ASL), Mývatnsheiði (65°36.9'N, 17°13.0'W; 350 m ASL) and Reykjahlið (65°39'N, 16°55'W, 285 m ASL). For the purposes of modelling early-Norse hay meadow management, reconstructed annual temperatures based on historical sea-ice data and other sources (Bergþórsson 1969), have been scaled to instrumental data. For each site, modern temperature measurements have been used to scale these longer term regional temperature trends to localised conditions. In the absence of either long-term proxy records of snow and rainfall for the modelling study, rather than generate a stochastic variable, the local short-term precipitation data have been used by rewinding and repeating these throughout the modelled period.

Home-field soils

Auger coring across the Hofstaðir home-field (Bolender unpublished, and by the authors) indicated that soil horizons and tephra layers were well preserved and cultural material was recovered from most core locations including all occupation layers from settlement to present day. Cultural deposits were generally deeper on the southern side of the site with much of the activity associated with medieval activity and predating the 1477 tephra. In the northern part of the site, associated with Viking age occupation, cultural material was restricted to fewer layers and cultural deposits were generally shallower than in the southern part of the site.

Two representative soil profiles were exposed in the Hofstaðir home-field (fig.7.6), with one selected for more detailed analyses (profile F; Adderley *et al.* 2008). Bulk soil samples were used for physical and chemical analyses. Bulk density was measured on volumetric samples following drying at 105°C. Air-dried and sieved sub-samples were used for other analyses. Following wet oxidation to remove organic matter, particle size distribution was measured using a Coulter laser-granulometry apparatus. Organic matter was measured by the Walkley-Black method (Klute 1986), total nitrogen by a modified Kjeldahl method (Nelson and Sommers 1973), and total phosphorus by an acid-persulphate digestion and colorimetric measurement (AOAC, 2000). Total carbon was measured by a Dumas technique using total-combustion gas chromatography (AOAC, 2000). Soil thin-sections were prepared at the University of Stirling Thin Section Micromorphology Laboratory (see www.thin.stir.ac.uk) using standard procedures adapted from the method described by Murphy (1986). Acetone replacement in the liquid phase was followed by impregnation in a polyester resin system applied under vacuum. Following curing, blocks were cut, mounted, ground and polished to 30 µm thickness on glass slides (110 mm x 75 mm x 3 mm). Slide thickness was monitored optically and through calliper measurement (Adderley *et al.* 2002).

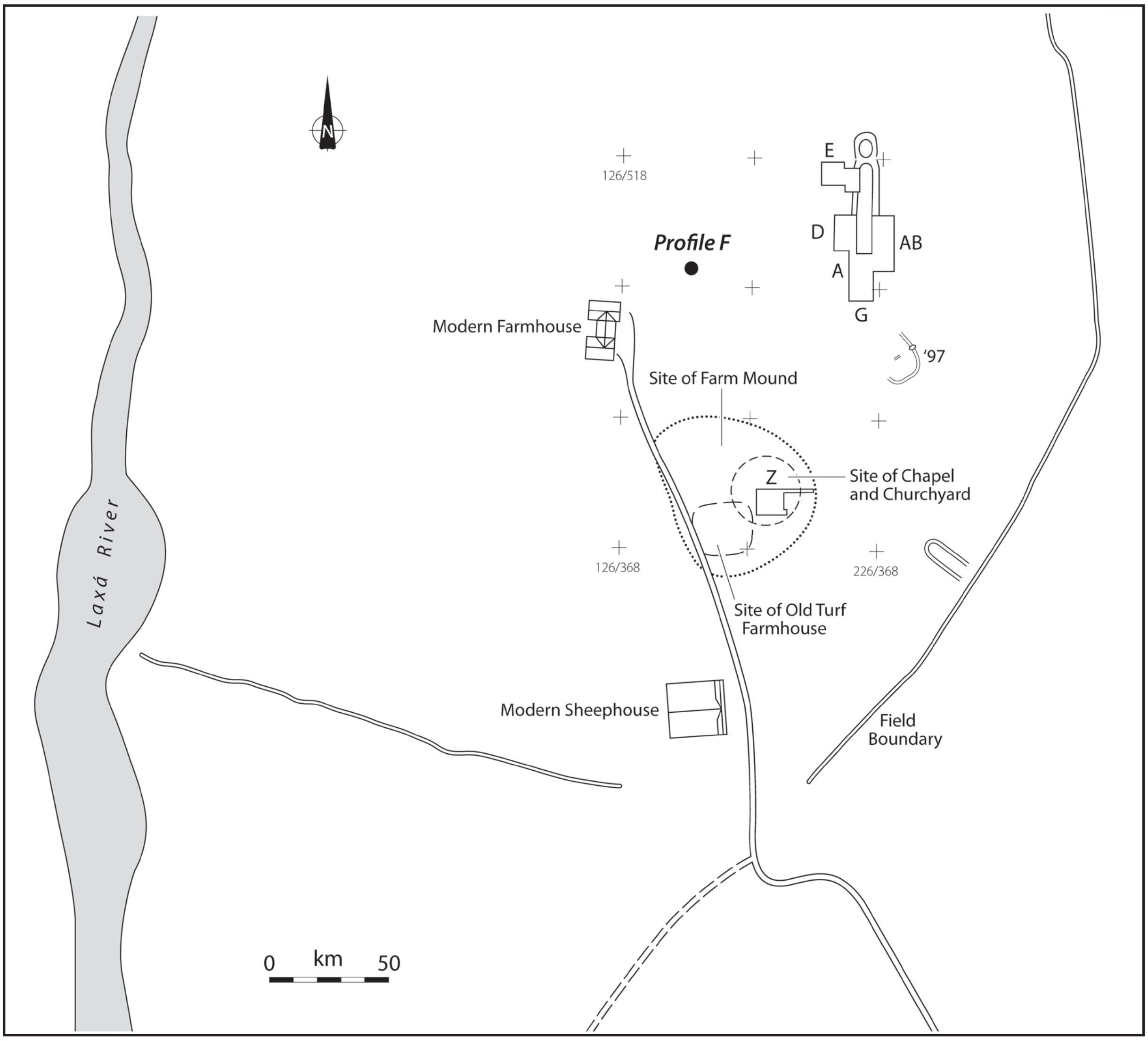

Figure 7.6 The Hofstaðir home-field, showing field boundaries, locations of archaeological sites and profile F.

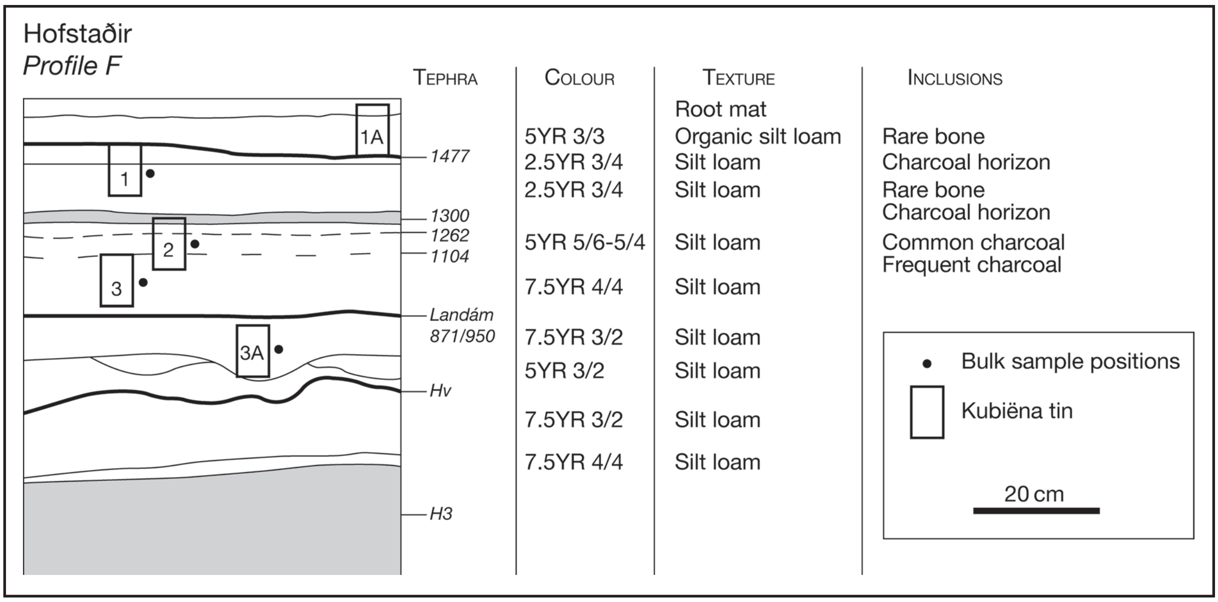

Figure 7.7 Representative home-field soil profile showing tephrochronologies and soil accumulations.

Site	Sample	OM (%w/w)	Total N (% w/w)	Tot P (mg/100g)	Tot C (%w/w)	Texture Classification (Hodgson, 1976)
Hofstaðir	F1	10.4	0.41	447	5.91	Sandy silt Loam
	F2	28.3	0.63	459	9.24	Sandy silt Loam
	F3	11.5	0.44	204	6.48	Sandy silt Loam
	F3a	25.6	0.65	195	9.17	Sandy silt Loam

Table 7.3 Soil properties from the representative home-field soil profile at Hofstaðir; summary of laboratory and field measurements.

Description of the soil thin sections has followed the International System (Bullock *et al.* 1985; Stoops 2003). A range of magnifications (x10 – x400) and constant light sources (plane polarised - ppl, cross-polars - xpl, circular polarized – cpl, and oblique incident - oil) were used to obtain detailed descriptions, and these were recorded in semi-quantitative summary tables. The field profile at Hofstaðir (fig.7.7) is characterised by dark brown colours beneath and dark reddish brown above the V~950 tephra. Above the V~950 tephra, rare fine bone fragments become evident together with common to frequent charcoal occurrences sometimes organised as thin horizons. Total phosphorus and total nitrogen concentrations are enhanced in the horizons above the V~950 tephra; while the total phosphorus concentrations are enhanced in the stratigraphy between the V~950 tephra and H-1104/1158, major increases come between H-1104/1158 and H-1300, maintained through to V-1477 (table 7.3). In thin section (table 7.4), soils prior to *landnám* and continuing just above the V~950 tephra have common pale brown to reddish brown organomineral material with few to frequent coarse mineral materials of different types; microstructures are crack and channel and chamber. Fine organic materials are few to frequent and include amorphous black and brown materials. Few reddish amorphous and cryptocrystalline features are evident together with depletion pedofeatures indicating imperfectly drained conditions. These characteristics continue immediately above the V~950 tephra to a microstratigraphic sequence of contrasting silt and fine sand accumulation indicative of landscape disturbance (fig.7.8); this sequence is also evident in the corresponding thin section from the second profile exposed in the home-field, indicating that disturbance impacted across the area that became the Hofstaðir home-field. Above the silt and fine sand accumulation sequence, soil characteristics revert to

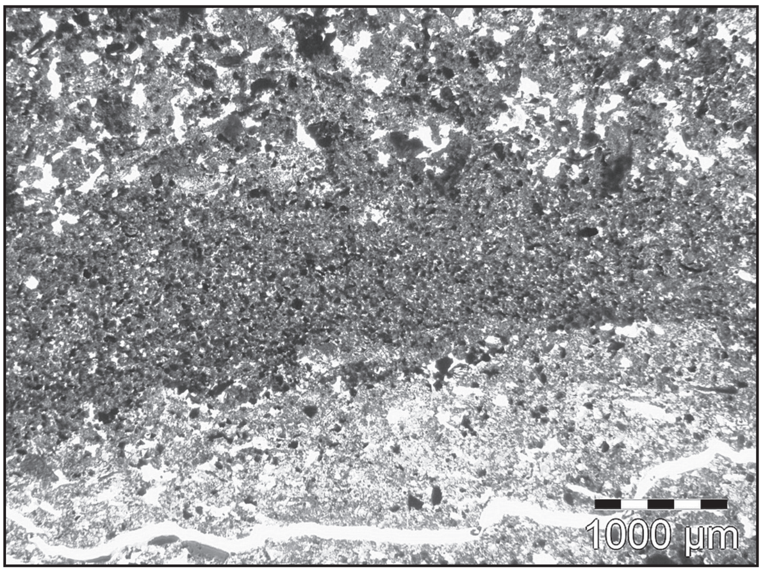

Figure 7.8 Linear silt and fine sand accumulations between *Landnám* and 1104 tephra, Hofstaðir profile F4 sample3, micro-horizon c. Indicative of landscape disturbance.

Hofstaðir Profile F

Thin Section sample	Micro-horizon	COARSE MINERAL MATERIAL >63µm: TEPHRA: Unknown	Vö 1477	Hekla 1300	Katla 1262	Hekla 1104	Landnám 871	Hekla (H3)	Brown	Pale brown	Grey	Black	Igneous rock	Phytoliths	Diatoms	Bone	Rubified mineral	FINE MINERAL MATERIAL	COARSE ORGANIC MATERIAL: Charcoal	Parenchymatic	Fungal Sclerotia	FINE ORGANIC MATERIAL: Cell residue	Amorphous (black)	Amorphous (brown)	PEDOFEATURES: Silt infills	Amorphous crypto - crystalline (reddish brown)	Depletion	Excremental (mammillate)	Excremental (spheroidal)	Calcium spherulites	MICROSTRUCTURE	COARSE MATERIAL ARRANGEMENT	GROUNDMASS b FABRIC	RELATED DISTRIBUTION
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Frequency class refers to the appropriate area of section (Bullock *et al.*, 1985) *t* Trace • Very few •• few ••• Frequent/common •••• Dominant/very dominant.
Frequency class for textural pedofeatures (Bullock *et al.*, 1985) *t* Trace * Rare ** occasional *** Many

Table 7.4 Summary of micromorphology observations from the representative home-field soil profile at Hofstaðir.

the micromorphological features observed before and immediately after the V~950 tephra with no evidence of cultural amendment. It is clear that there was an initial impact followed by a hiatus after which cultural amendment of the soil began. Micromorphological features indicating substantial cultural amendments of the imperfectly drained and organic silt loam soil are evident in the sedimentary sequence before H-1104/1158 and through to the V-1477 tephra. Amendments include domestic waste evidenced as bone fragments (fig.7.9), fuel residues including woods (charcoal and crystallitic fine mineral material) and peats (rubified fragments; fig.7.10) and animal manures (calcium spherulites, very rare and degraded but partially preserved beside bone fragments). These features vary in occurrence and are at their most frequent between the H-1104/1158 and H-1300 tephras. Above the V-1477 tephra indicators of cultural amendment are absent indicating a curtailing of attempts to maintain home-field fertility, a change in home-field focus or, in light of the reduced impact on upland grazing areas, there may have been a temporary abandonment of the home-field area.

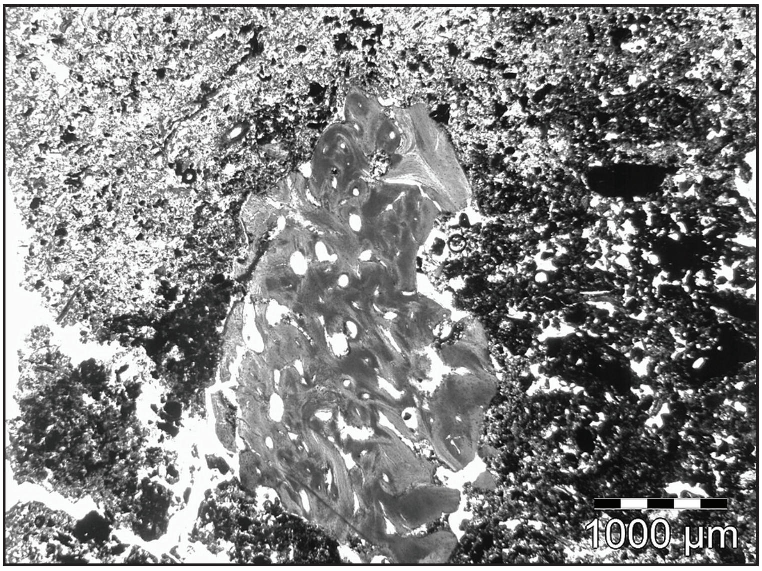

Figure 7.9 Bone and domestic debris located above silt and fine sand accumulations and below 1104 tephra, Hofstaðir profile F4, sample 3, micro-horizon a. Indicative of soil amendment.

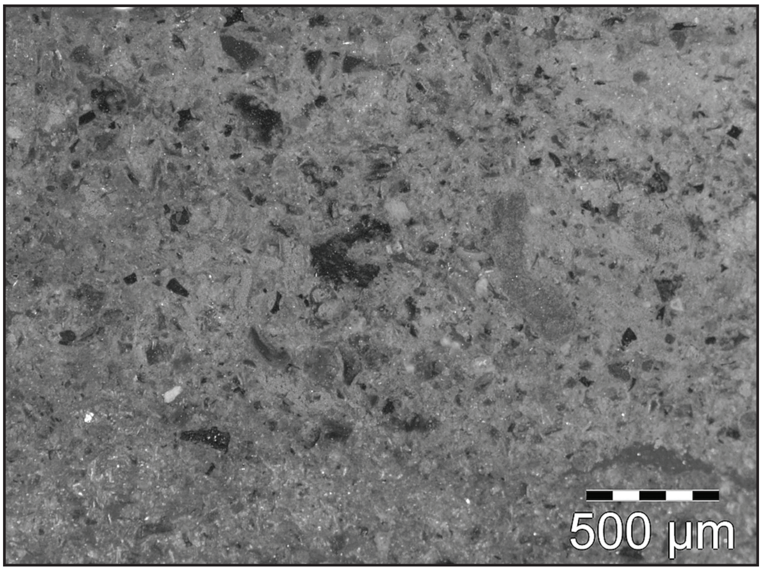

Figure 7.10 Rubified fine material (red coloured when observed in oblique incident light) with fine black charcoals interpreted as peat fuel residues. Located above silt and fine sand accumulations and below 1104 tephra, Hofstaðir profile F4, sample 3, micro-horizon a. Indicative of soil amendment.

Modelling home-field productivity

The well-verified CENTURY agroecosystem model (Parton, *et al*, 1998; Metherell *et al.* 1993) is based on turnover of soil organic carbon, initialized after considering the available palaeoecological evidence for vegetation (Dugmore, *et al.* 2005) and with starting values of soil nutrient concentrations based on the measured values obtained from samples below the *landnám* tephra and considered undisturbed (Adderley and Simpson 2005; Adderley *et al.* 2002; Kelly *et al.* 1997). The carbon pools in the model were initialised assuming that the

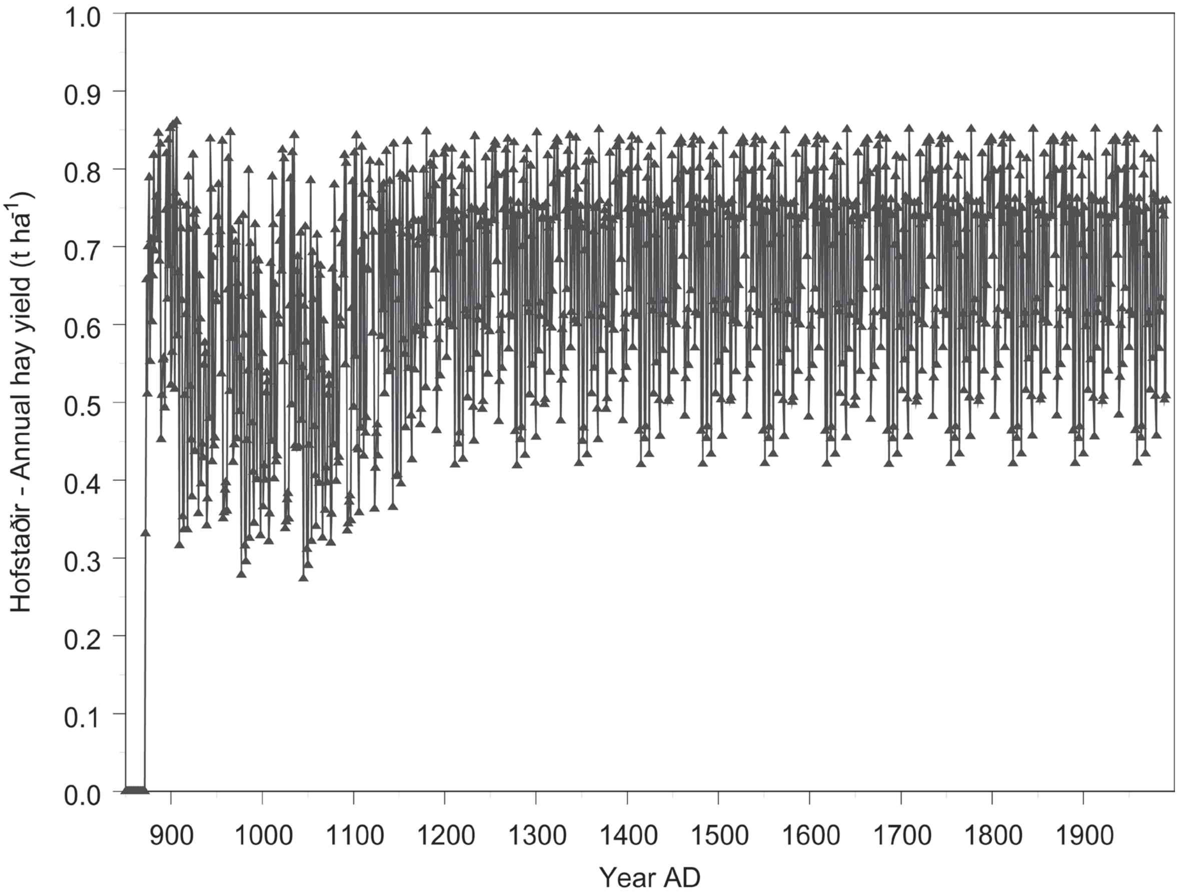

Figure 7.11 Results of Hofstaðir home-field CENTURY modelling incorporating soil-based evidence of changes in land management.

pre-*landnám* land cover in the Laxá Valley and Mývatn region was a grass and woody shrub mixture. The contribution of the shrub components prior to the creation of the home-field is based on observations of similar vegetation in the UK (Ovington and Madgwick 1959) and Greenland (Elkington and Jones 1974). The dry matter and carbon and nitrogen composition of the removed plant material is based on typical native grasses. These and grass-growth parameters were based on previous experimental studies in Iceland (Thorvaldsson *et al.* 2000; Thorvaldsson and Martin 2004) and from long-term field trials in the British Isles (Shiel and Hopkins 1991). These allow the maximum annual hay yield before storm, storage and other losses to be predicted.

Application of this modelling paradigm with monthly time-steps to historical and archaeological contexts places high demands on the data available, but offers a key advantage in that the integration of multiple data-sources potentially minimises the models sensitivity to individual factors. The sensitivity of the model to different climate factors has been tested individually. The home-field area at Hofstaðir has been modelled for hay production; this includes the unique climate reconstruction and soil properties for the site. Both the hay yields and the accumulation or loss of soil organic matter have been considered. The latter has been previously demonstrated (Adderley and Simpson 2005) to provide a buffer for the Norse farmer against year-to-year climate changes.

Three sets of circumstances have been considered: First, the chronologies of soil management activities examined by soil micromorphology (above) are incorporated into the model. Using these micromorphology and tephrochronology data, clear differences in ma-

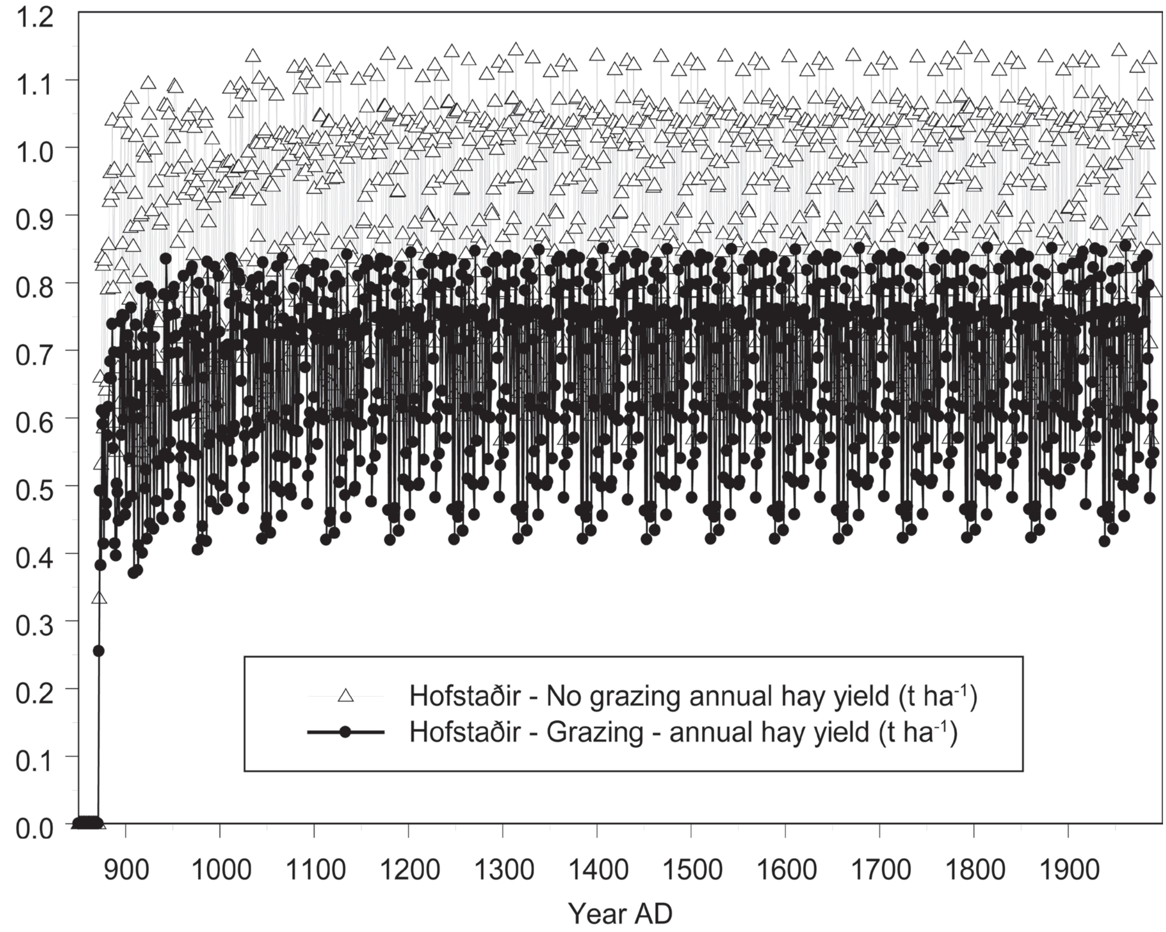

Figure 7.12 Results of Hofstaðir home-field CENTURY modelling; grazing – no grazing scenarios.

nure inputs are found with periods of different relative manuring rates, as well as periods with no observed input. Using the baseline or "normal" input of carbon from manure has been considered at a rate of 100 g C m^{-2} $application^{-1}$. For periods of high manure input an input of 200 g C m^{-2} $application^{-1}$ i.e. "double" input has been modelled. The 100 g C m^{-2} $application^{-1}$ value mirrors practices seen elsewhere in Iceland (Simpson *et al.* 2002) but is a relatively low input when considered to the sustainability of traditional Shetland farming practices (Adderley, *et al.* 2000). On this basis the home-field at Hofstaðir received "normal" inputs from AD 872-1104, "double" input for AD 1104-1477 and "normal" input post AD 1477. Second, the effects of grazing in the home-field is considered; scenarios with no grazing whatsoever are compared to a grazing scenario where grazing for one month before leaving the grass for the hay crop and grazing of the aftermath for two months are incorporated in the model. Third, scenarios of continuous uniform 'high' inputs are considered.

In the period after *landnám*, Hofstaðir shows rapid rises in hay yield from the commencement of farming and reaches a plateau in yield after c.75 years (fig.7.11). The modelled results reveal early erratic year-on-year hay yields and relatively low hay yields compared to other locations that have been considered in the North Atlantic (Adderley and Simpson 2005). Where changes in manure inputs are observed in the soils-based evidence, these are apparent in the modelled outputs. As would be expected, lower manure inputs lead to lower yields and vice versa, with rapid response to changes in input. The 'double' manure scenario (fig.7.12) shows a

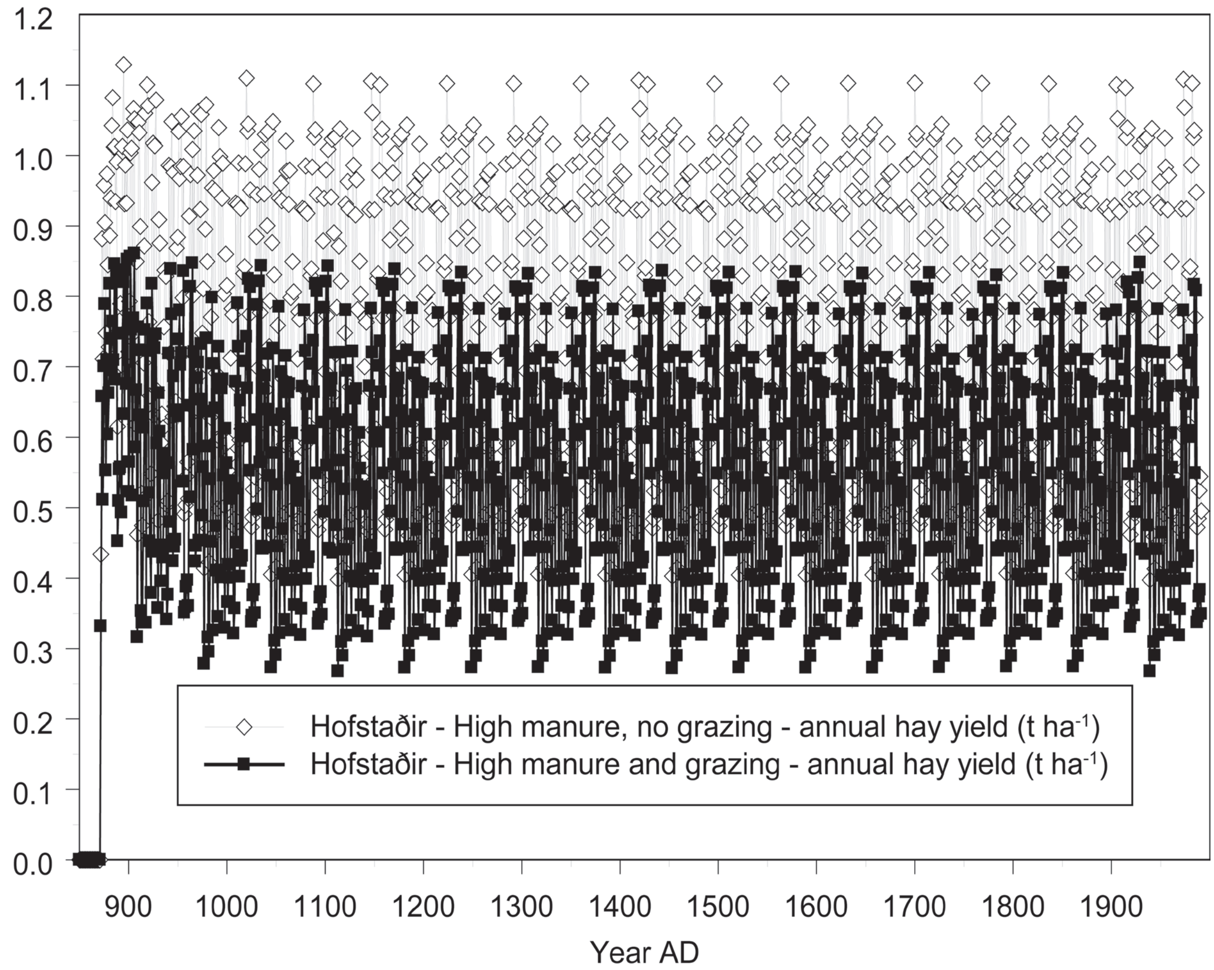

Figure 7.13 Results of Hofstaðir home-field CENTURY modelling; 'high' manure scenarios.

markedly higher initial yield relative to the normal scenario before declining slightly to reach a plateau after 75-100 years. Once this plateau is reached the maximum yields are very similar to the 'normal' scenario. The effect of aftermath grazing can be seen by considering the difference between grazing scenarios and where this factor is removed; similarly "double" manuring with no grazing (fig.7.13) shows increased maximum yields relative to the scenarios with grazing. Both of these no-grazing scenarios show yields reaching plateaux within 75 years of home-field establishment.

Discussion

It is evident that the maximum levels of productivity, regardless of the management strategy adopted, are generally no better than subsistence with little possibility for carrying over fodder material year-on-year to create a storage buffer for years with poor yield. This provides an imperative to developing understandings of different possible land management strategies and their relationship to past climatic variations. All the scenarios modelled have considered the same dates for manuring, hay harvesting and grazing. In respect of climate and site differences, the actual hay yield the Norse farmer obtained, rather than the maximum hay yield as sought through the modelling, will have been lower due to loss through storms and poor drying conditions for hay-making. For all the scenarios modelled short-term, *i.e.* year-to-year, variabilities in hay yield are common and may be explained by region-wide climatic fluctuations. Especially important appear to be prolonged cold periods in either spring or autumn or both, all of which limit the plant growth period. In the more extreme conditions of Greenland, it has been demonstrated that irrigation of the home-field was required by the Norse settlers in some locations to promote grass growth due to summer drought following cold winter periods (Adderley and Simpson 2006). With the model outputs appearing insensitive to increases in precipitation, water availability at Hofstaðir does not appear to be a limiting factor to grassland production.

The contrast between the modelled outputs that incorporate changes in manure input, when compared to fixed continuous manure inputs, reveals that maintaining the intensity of land management was fundamental to maintaining hay yield. This is especially the case at Hofstaðir, which is both sensitive to change and shows erratic yields when manure inputs are low. These results demonstrate the extent to which a single exogenous or site-related factor can be considered limiting to production, and emphasise the need to understand the issues related to different land management strategies by the Norse farmers and on site selection by the first *landnám* settlers. This particularly concerns Hofstaðir, an undoubtedly high-status settlement but with what appears to be a home-field area that was inherently of limited productivity at settlement. This suggests that other strategic elements played a rôle in decisions relating to initial site settlement rather than the initial yield per unit area from the home-field and that different land management strategies were developed, in the case of Hofstaðir rapidly and successfully, to sustain agriculture (Adderley *et al.* 2008). When the rôle of land management is considered beyond the initial settlement period, it is clear that the hay yields reach a plateau and suggests that sustained management over the first three centuries of settlement could produce a home-field area that offered a nutrient buffer. This has been demonstrated in Faroese contexts as potentially mitigating some of the year-to-year climatic variation (Adderley and Simpson 2005).

Fuel resource utilisation

Fuel resources were a basic necessity of life for early societies, providing light, warmth, the possibility of cooking food and allowing a range of metalworking processes. Fuel ash residues associated with these activities are frequently found in archaeological site stratigraphies, and their analyses offers the opportunity to consider the role of fuel resources in discussions of site function and landscape resource utilisation in changing social and environmental contexts (Schiegl *et al.* 1996; Pierce *et al.* 1998). Despite the significance of fuel ash residues in archaeological site contexts, the identification of materials used as fuels from fuel ash residues found in site stratigraphies remains a major challenge to archaeologists. Such residues are frequently from multiple sources, are mixed with other forms of occupational debris and have been subjected to a range of post-depositional processes including bioturbation, freeze-thaw and wetting-drying (Pierce *et al.* 1998).

Sediment thin-section micromorphology analyses of undisturbed samples does however have the potential to discriminate between different fuel ash residues in mixed sedimentary environments at the microscopic scale (Davidson and Simpson 2001). Micromorphological indicators of fuel ash residues may include colour, indicative of iron immobilisation when heated (Courty *et al.* 1989); charcoal material (February 1991; Umbanhower and McGrath 1998); calcitic pseudomorph crystals (Brochier *et al.* 1992; Brochier and Thinon 2003); and silica phytoliths and diatoms (Courty *et al.* 1989). Such analyses of fuel residues have, in a range of environmental contexts, permitted distinctions to be made between wood sources, including burning temperature, and between grass, sedge and animal manure sources. While these general observations are helpful in interpreting fuel residue features observed in thin sections, our approach is to provide controlled micromorphological observation against which features from archaeological sites can be assessed. To do so we integrate Icelandic historical documentary sources identifying the types and range of materials used as fuel resources with experimental combustion of these material found in the present day landscape, and manufacture of the residues produced as thin sections.

The first objective is to establish whether experimentally combusted historically defined Icelandic fuel materials have distinctive residue attributes and features that can be observed in thin section. This provides a controlled basis for a second objective, the identification of fuel residues in the temporally constrained midden stratigraphies at Hofstaðir. In doing so, such analyses can make a critical contribution to debate on the historical ecology of *landnám* in Iceland, with its implications for understanding human settlement processes and environmental change. This includes discussion on the selection of materials as fuel resources for different activities, social and environmental regulation of fuel resource utilisation, and the contribution that fuel resource availability may have made to the success or failure of early settlement sites.

Historically defined fuel resource control materials

Identification of appropriate materials for experimental combustion was made through analyses of the Land Register of Árni Magnússon and Páll Vídalín (*JÁM*). The Land Register was systematically compiled between 1702 and 1714 for each farm property in Iceland by several scribes, and normally lists all resources present including materials used as fuels. In Þingeyjarsýslur, the counties covering north-eastern Iceland, and including Mývatnssveit, the Land Register was compiled in 1712. Here the scribe had a consistent approach to asking about fuel, not only noting if there were resources such as wood or shrub, but also if dung or driftwood was used as supplements; in this region only 12 entries out of 347 fail to mention fuel. Categorising these, 141 of the farms had access to woodland fuel resources and in coastal localities where woodland was not found, driftwood was an important fuel resource. Shrub is mentioned in 106 farms and was found in all environments including coastal; in 93 cases there was shrub but no wood. In all, 83% of the farms in Þingeyjarsýslur had access to wood or shrub as a fuel resource. Peat and turf were only cut at 2 farms and one of them also had shrub, so only one farm relied entirely upon peat. However 48 farms were said to have cut peat in earlier times. Of these, 27 also had recourse to shrubland, and 12 had recourse to woodland, suggesting that the peat had not been cut because no other fuel was available, but from choice. On the remaining farms, most had adopted domestic livestock dung burning. Dung is mentioned as fuel in 116 farms, but in only 26 cases was it the only fuel source available. The use of dung was widespread throughout the region as a supplementary fuel, but was more commonly used where wood was scarce.

Review of the Land Register for Þingeyjarsýslur suggests fuel resources included, in order of importance: birch, willow, peat, turf and domestic livestock dung as the principal fuels, with driftwood, seaweed, and fish-bones as subsidiary or very localised fuel resources. Accordingly, samples of the historically defined principal fuel resource materials were collected from the Mývatnssveit district. Separate samples of moderately humified peat material, well humified mineral-rich turf material, sheep dung, cow dung, birch wood (*Betula pubescens*) and willow wood (*Salix lanata*) were air dried and then combusted in a muffle furnace at 400°C and 800°C for 60 minutes, and the ash residues

	Peats	Mineral-based Turf	Willow Wood (*Salix lanata*)	Birch Wood (*Betula pubescens*)	Cow Dung	Sheep Dung
400°C	Course mineral material Frequent silica phyoliths, few silica diatoms; very few red heated minerals, very few tephra; very few quartz; very few irregular calcites.	Course mineral material Very few silica phytoliths (all grass); very few silica diatoms; few red heated minerals; few tephra; few quartz; very few irregular calcites.	Course mineral material None Observed.	Course mineral material None observed.	Course mineral material None observed.	Course mineral material Very few heated red minerals; very few tephra; very few irregular calcites.
	Fine mineral material Dominant dark brown (ppl.) and red (oil).	Fine mineral material Frequent brown (ppl.) and red/orange (oil.).	Fine mineral material Dominant grey and dark brown (ppl.); grey and orange (oil.).	Fine mineral material Very dominant grey (ppl.)' grey and orange (oil.).	Fine mineral material None observed.	Fine mineral material Very dominant, light brown (ppl.); grey crystallitic with few black materials (oil.); fragmented.
	Organic material Occasional black (ppl. and oil.); carbonised.	Organic material Occasional black and dark brown (ppl.) and (oil.); carbonised.	Organic material Frequent black, various shapes, with occasional porous structures, carbonised; and frequent, linear fibrous brown (ppl. and oil.), partially carbonised.	Organic material Frequent, black (ppl. and oil.), rod-like and subrounded, carbonised.	Organic material Very dominant, black (ppl. and oil.); common internal void space, smooth and rough serrate; fibrous and fragmented.	Organic material None observed.
	Groundmass b fabric Faintly stipple speckled.	Groundmass b fabric Faintly stipple speckled.	Groundmass b fabric Crystallitic micro-fine.	Groundmass b fabric Crystallitic micro-medium.	Groundmass b fabric Isotropic, black.	Groundmass b fabric Stipple speckled.
800°C	Course mineral material Dominant silica phytoliths, few silica diatoms; frequent red heated minerals; very few irregular calcites.	Course mineral material Very few silica phytoliths (all grass); very few silica diatoms; frequent red heated minerals; very few irregular calcites.	Course mineral material None observed.	Course mineral material None observed.	Course mineral material Very few red heated mineral; very few tephra; very few irregular calcites.	Course mineral material Very few heated minerals.
	Fine mineral material Frequent light brown (ppl.) and yellow (oil.).	Fine mineral material Frequent light brown (ppl.) and yellow (oil.).	Fine mineral material Very dominant; pale brown (ppl.) and light grey (oil.).	Fine mineral material Very dominant; dark brown (ppl.) and light grey (oil.).	Fine mineral material Very dominant, grey (ppl.) and white/grey (oil.); fibrous.	Fine mineral material Very dominant, grey (ppl.); white/grey (oil.); fragmented.
	Organic material None observed.	Organic material None observed.	Organic material None observed	Organic material None observed	Organic material None observed.	Organic material None observed.
	Groundmass b fabric Faintly stipple speckled.	Groundmass b fabric Faintly stipple speckled.	Groundmass b fabric Crystallitic micro-fine clustered.	Groundmass b fabric Crystallitic micro-fine clustered.	Groundmass b fabric Faintly stipple speckled.	Groundmass b fabric Stipple speckled.

Table 7.5 Micromorphological descriptions of ash residues from historical fuel resources – wood, turves and animal manures – combusted at 400°C and 800°C

collected and prepared as thin sections. (For soil-thin section preparation and description see home-field soils, above). These combustion temperatures represent two situations; high temperature complete combustion (800ºC) as would be routinely found in 'industrial' metal working activity, and low temperature, incomplete combustion (400ºC) as would be more often associated with 'domestic' hearths.

Micromorphology of experimentally combusted materials

Residues from combusting peat and mineral-based turf material at 400ºC are clearly characterised in thin section by rubified (reddened) fine mineral material observed in oblique incident light (table 7.5; Courty *et al.* 1989). Discrimination between peat and mineral-based turf is evident in the very few and few occurrences respectively, of rubified coarse mineral material. Such rubification of coarse and fine mineral material is caused by structural disruption during heating and resulting segregation of iron oxides. The few, meso-sized charcoal fragments is also indicative and accords with the recent experimental observations of Umbanhower and McGrath (1998) highlighting distinctions between wood, leaf and grass charcoals. Silica phytolith and diatom attributes can also be used to discriminate between peat turf and mineral-based turf. In peat, frequent phytoliths and few diatoms are observed, contrasting with the very few phytoliths and very few diatoms of the mineral-rich turf material. At 800ºC, organic material has completely combusted in both peat and mineral-based turf materials and the fine mineral material is characteristically yellow in oblique incident light. The very few silica phytoliths and diatoms are, however, more obvious in peat residues.

At combustion temperatures of 400ºC wood material can be distinguished from other materials by its distinctive crystallitic groundmass birefringent (b) fabric dominated by calcite and by the frequent occurrence of macro-sized black charcoal fragments (table 7.5; Prior and Williams 1985; February 1991). The calcite crystals, which are grey in oblique incident light, have irregular surfaces, are poorly preserved and do not retain structural characteristics. These, although likely to be calcitic pseudomorphs derived from plant-source calcium oxalates, cannot be used as a species indicator (Brochier 2002; Canti 2003). A distinction between willow (*Salix lanata*) and birch (*Betula pubescens*) wood material is, however, hinted at by their related distribution to charcoal materials. Willow crystallitic b fabric material is classified as micro-medium with clustering of calcites along the edges of the dark brown fibrous charcoal material, with birch classified as micro-coarse, but not directly interfacing with charcoal. Further distinctions between willow and birch ash residues combusted at 400ºC are suggested, with willow ash residue contains brown fibrous charcoals that are absent from birch ash residues. At 800ºC crystallitic b fabrics are still in evidence as a distinguishing characteristic of wood ash, although paler and clustered, perhaps fused; there is however, no visually observable distinction between willow and birch materials.

Animal dungs combusted at 400ºC also exhibit distinctive micromorphological characteristics (table 7.5). Burnt residues of cow dung are characterised by black, isotropic organic material with surfaces that range from smooth to rough serrated. In contrast, burnt sheep dung residues are characterised by fine mineral material, which is light brown (plane polarised light) and grey (oblique incident light) in colour. Very few coarse mineral grains are evident in the sheep dung ash residues, reflecting rangeland grazing; very few calcitic spherulites are also evident, with a concentric pattern distinct from the calcitic material found in much of the wood ash residues. After combustion at 800ºC cow dung and sheep dung residues are simi-

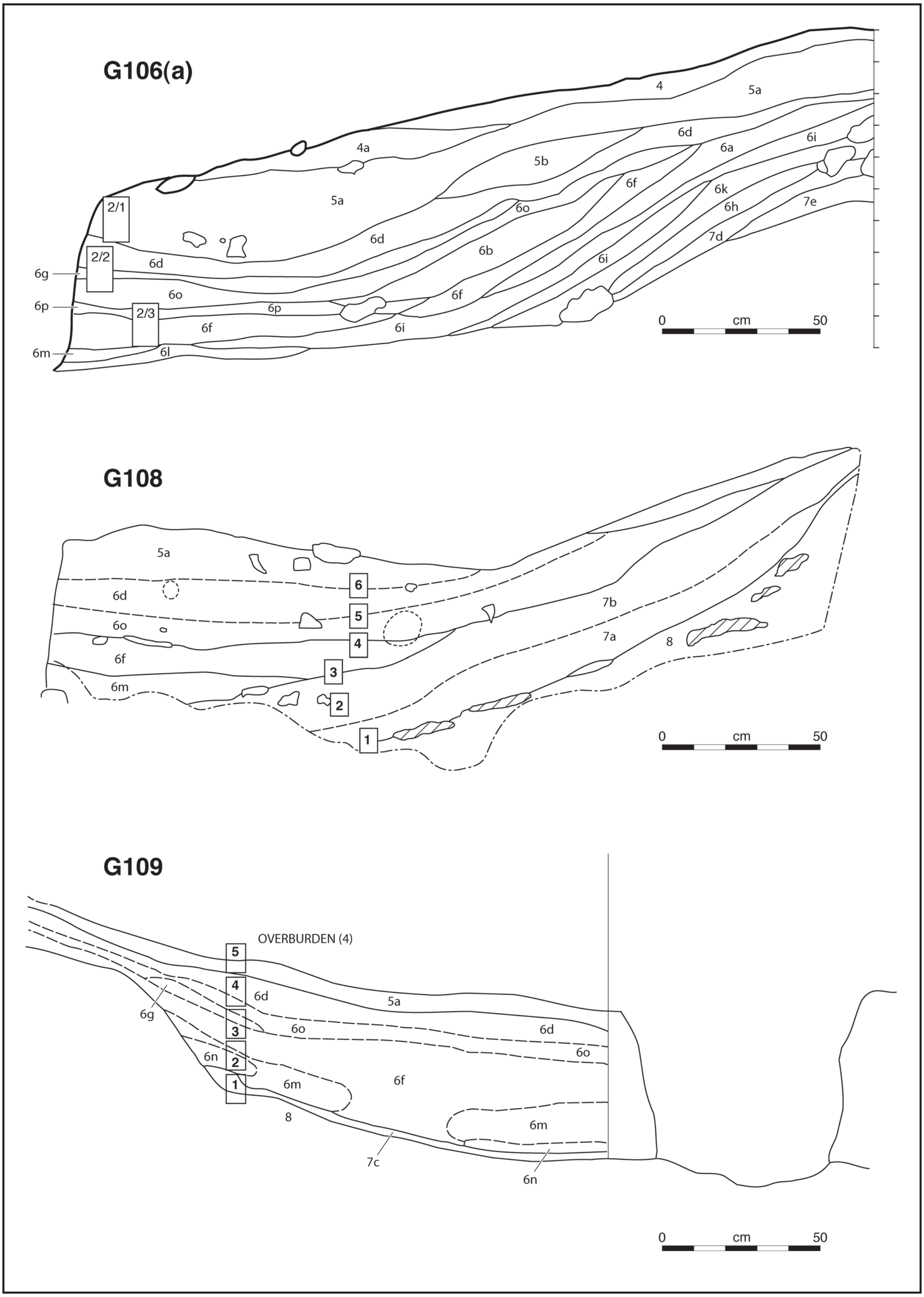

Figure 7.14 Midden stratigraphies of Area G, Hofstaðir showing contexts and thin section sample locations.

Section	Micro-horizon	Coarse mineral material						Fine mineral material (oil)				Organic material			Groundmass b fabric
		Quartz	Calcite	Tephra and silts	Diatoms	Phytoliths	Heated mineral	Red	Yellow	Grey (crystallitic)	Brown	Charcoal (undiff.)	Amorphous (black)	Amorphous (brown)	
108 / 6	1	•	•	•		•	•	•				••		•••	Stipple
	2	••	•	•			••	••	•			•		•	Stipple
	3	•	•	•			•	•				•••		•••	Stipple
	4	•	••	•		••	••	••••	•				•	•	Stipple
	5	•	•	•		•	••	•••				•••	•		Stipple
108 / 5	1	•	•	•		•	••	••				••	•	•••	Stipple
	2	•	•	•		••	•	•				•••	•	••••	Stipple
	3	•	•			•	••	•				••	•	•••	Stipple
108 / 4	1	•	•	•		•	••	•••				•••	•		Stipple
108 / 3	1	•	•	•		•	••	•••				•••	•		Stipple
	2	•		••••											—
	3	•	•	•		•	•	•••				••	•	•••	Stipple
	4	•	•	•		•	•	••				•	•	•••	Stipple
108 / 2	1	•	•	•		•	••	••				••		••	Stipple
	2	•	•	•		•	••	•••	•				•	•	Stipple
	3	•	•	•		•	••	••				••	•	•••	Stipple
	4	•	•	•		•	••	••••					•		Stipple
108 / 1	1	•	•	••							•••			•	Stipple
	2	•	•	•		•	••	••••				••	••		Stipple
	3	•	•	••••											—
	4	•	•	••							•••				Stipple
	5	•	•	••			••	•••	•		•••			•	Stipple
	6	•	•	•			•••	••••	•••					•	Stipple
	7	•	•	•			••	••••	•					•	Stipple
	8	•	•	••••											—

Section	Micro-horizon	Coarse mineral material						Fine mineral material (oil)				Organic material			Groundmass b fabric
		Quartz	Calcite	Tephra and silts	Diatoms	Phytoliths	Heated mineral	Red	Yellow	Grey (crystallitic)	Brown	Charcoal (undiff.)	Amorphous (black)	Amorphous (brown)	
109 / 5	1	•	•	•		•	••	•••	•			•	•	•	Stipple
	2	•	•	•		•	•	•				•••	•	•••	Stipple
109 / 4	1	•	•	•		•	••	•				•••	•	•••	Stipple and Crystallitic
	2	•	•	•••		•	••	•••	••				•	•	Stipple
	3	•	•	••		•	••	••	••			••	•	••	Stipple and Crystallitic
109 / 3	1	•	••				•	•••	•••	••••				•	Crystallitic
	2	•	•	•		•	••	••		•		•••	•	•••	Stipple and Crystallitic
109 / 2	1	•	••	•		•	•	••	•	••		•••	•	•••	Stipple and Crystallitic
	2	•	•	•••				•	•						—
	3	•	•	•		•	•	••	•	•		•••	•	•••	Stipple and Crystallitic
	4	•	•	•		•	••	•••	••	•		•	•	•	Stipple and Crystallitic
109 / 1	1	•	••	•		•	••	•••	•	•		•	•	•	Stipple and Crystallitic
	2	•	•	•		•	•••	•••	••	••		•		•	Crystallitic
	3	•	•	•		•	•	•••	•••	•			•		Stipple and Crystallitic

Section	Micro-horizon	Quartz	Calcite	Tephra and silts	Diatoms	Phytoliths	Heated mineral	Red	Yellow	Grey (crystallitic)	Brown	Charcoal (undiff.)	Amorphous (black)	Amorphous (brown)	Groundmass b fabric
106a / 1	1	•	•	•		•	•	•••				••			Stipple
106a / 2	1	•	•	•		•	••	••	•		•••	•••	•		Stipple and Crystallitic
106a / 3	1	•	•	•		•	••	••	•		•••	••	••		Stipple and Crystallitic
	2	•	•	•		•	••	••	•		•••	•••	•		Stipple and Crystallitic

Frequency class refers to the area of section (Bullock *et al., 1985)*
• Very few •• few ••• Frequent/common •••• Dominant/very dominant.

Table 7.6 Summary micromorphological descriptions of thin sections from Hofstaðir, Area G profiles 108,109 and 106a.

lar, with fine mineral material of grey colours in plane polarised light and white/grey colours in oblique incident light very dominant. Subtle distinctions in fine mineral material are evident however; fibrous in cow dung ash residues and more fragmented and crystallitic in sheep dung ash residues that may reflect differences in animal diet.

Micromorphology of fuel residues in midden deposits

Representative, undisturbed sediment samples from the midden stratigraphies within the pit-house G at Hofstaðir (McGovern 1998; Simpson, Milek *et al.* 1999; Lucas 1999; Vésteinsson 1999) were collected in Kubiëna tins. Vertical samples from Hofstaðir were obtained from profile faces in three separate sections (G106a – three samples, G108 – 6 samples and G109 – five samples; fig.7.14), giving a total of fourteen samples from the cultural deposits. (For thin section manufacture and description, see home-field soils, above).

Table 7.6 provides summary micromorphology descriptions of thin sections from Hofstaðir midden stratigraphies. Preliminary observation of these thin sections established coarse mineral material, fine mineral material, organic material and groundmass b fabrics as having the same type of micromorphological attributes as the experimentally combusted material, although there is mixing of different ash residue attributes. The experimental analyses provide, therefore, a basis from which to interpret fuel utilisation at the study sites, with micromorphology of the sediments enabling the separation and quantification of mixed ash residue deposits.

Care is required in differentiating between fuel ash residues and other debris within the midden, which may resemble ash residues. Calcitic material (very few) derived from shell is evident in the midden thin sections, but apart from ash residues, the main constituents of the midden stratigraphy are uncarbonised amorphous brown organic materials (very few to dominant) – interpreted as turf construction waste – and animal and fish bone fragments (very few to frequent). Preliminary observation of midden deposit thin sections also demonstrates the relatively undisturbed nature of the deposits at Hofstaðir; evidence of bioturbation and cryoturbation is rare or non-existent, reflected in the finely stratified nature of the deposits, while evidence of aeolian deposition is limited (table 7.6).

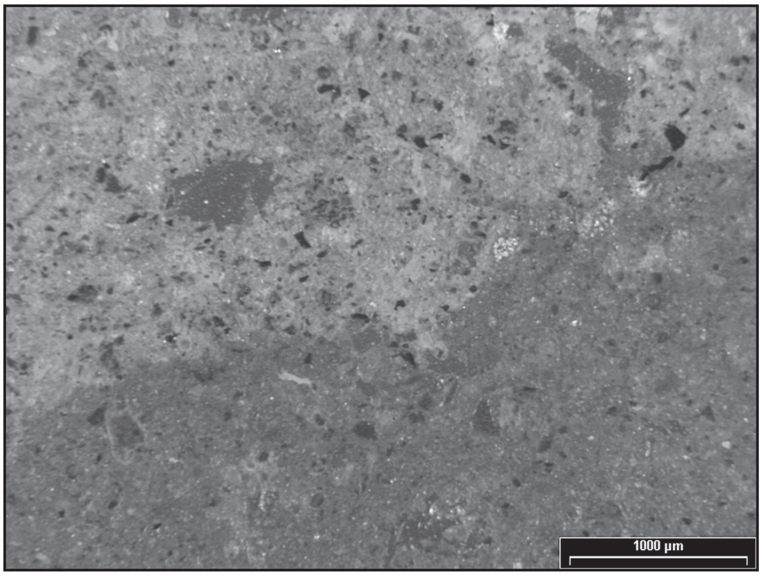

Figure 7.15 Rubified and yellowed fine mineral material with rubified coarse mineral material under oblique incident light, Hofstaðir section G108, thin section sample 1; interpreted as residues of mineral based turf combustion at high temperatures (upper, light grey) and low temperatures (lower, mid grey).

Red (rubified), fine mineral material colours (observed under oblique incident light) associated with carbonised organic materials and phytoliths can be interpreted as peat and mineral-based turf ash residues from low temperature combustion. Very few and few occurrences of heated coarse mineral material, associated with the red fine mineral material, can separate peat and mineral based turf residues respectively (table 7.6; fig.7.15). At Hofstaðir, there is evidence of low-temperature residues of mineral-rich turf material throughout the midden stratigraphies, from the beginning of deposition to its cessation, but particularly in the lower horizons where there are a relatively large number of rubified coarse minerals. As there is no micromorphological evidence to suggest that mineral-based turf material was combusted at high temperatures, it is possible to suggest that this was a staple fuel resource during the settlement and consolidation period, and was likely to have been exploited for domestic

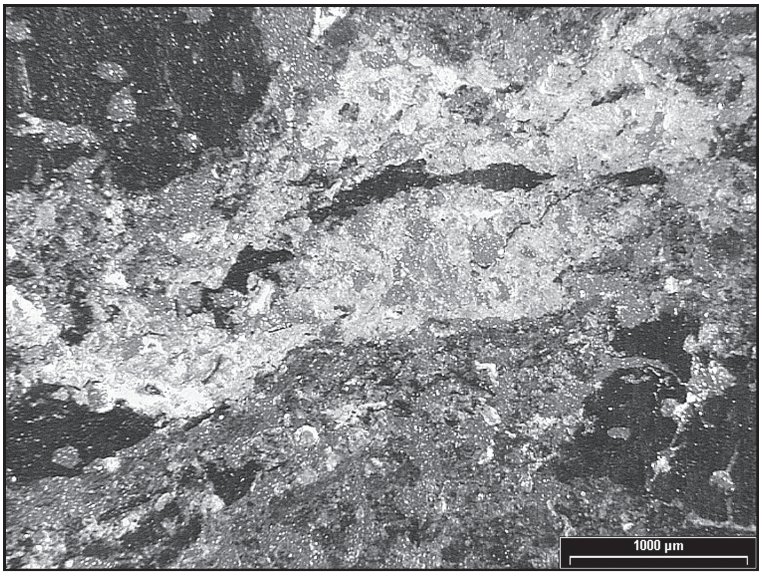

Figure 7.16 Yellow fine mineral material under oblique incident light (upper light grey micro-horizon in black and white image), Hofstaðir section G108, thin section sample 5; interpreted as residues of peat combusted at high temperatures.

heating, lighting and cooking activity. Evidence of low temperature peat combustion is limited and is more consistently evident in the middle and upper horizons of the Hofstaðir midden stratigraphies. In contrast, the less frequently occurring yellow matrix colours, that lack rubified coarse mineral materials, are particularly evident in section G109 and G106 and indicating that peats were combusted at high temperatures throughout the formation of the midden (fig.7.16). These observations suggest that much of the peat brought to the site as a fuel resource was primarily for 'industrial' activity

Thin section samples have frequently occurring crystallitic groundmass b fabrics and discrete very few, calcitic coarse mineral material; these features are also associated with charcoals that have distinct pore spaces (table 7.6 fig.7.17). Together, these fabrics and features are interpreted as wood fuel ash residues. Wood fuel ash residues, both calcitic materials and charcoals, are found throughout the midden deposits, but are more common in later phases of accumulation, suggesting a greater intensity of wood use for fuel in the later part of the settlement period. Less frequent clustering of the crystallitic material in b fabrics suggests that some of the wood material used as fuel was combusted at high ('industrial') temperatures, and is also found throughout the stratigraphy, again becoming more frequent in upper horizons. Evidence for the use of animal manures as fuel sources is entirely lacking from the micromorphological evidence at Hofstaðir.

Discussion

This research has established that there are distinctive micromorphological attributes in historically defined and experimentally combusted fuel materials that can be used to help interpret fuel residues found in settlement age archaeological site stratigraphies in Iceland. Furthermore, thin section micromorphology has permitted a range of fuel ash residues to be identified and discriminated from other debris evident in midden deposits. For the people occupying Hofstaðir, fuel resources included peat, mineral-based turf and birch wood used throughout the period of midden formation, but with distinct trends in their utilisation. Residues from low temperature combustion of mineral-based turf are evident throughout the stratigraphy, although more concentrated during the earliest phases of midden formation. In contrast wood ash residues from low and high temperature combustion become more prevalent during later phases of midden formation. Peat utilisation is almost entirely associated with high temperature combustion and evident throughout the stratigraphy.

We suggest that the first settlers in Iceland arrived fully understanding the fuel resource potential of their inherent landscapes and focussed on the extraction of wood, peat and turf material - although further work is required to define the origin of fuel resource selection in Norse society. Furthermore, we suggest that shortly after settlement, the mix of different fuel resources at different locations may have been influenced by cultural factors. Peat and wood resources are clearly of importance in high temperature, iron smelting and smithing activity (McDonnell and MacLean, this volume) at the high status Hofstaðir site, and it is possible to suggest that Hofstaðir had ample access to these resources. It is significant in this context that there are no known peat mines on the Hofstaðir property and peat would therefore presumably have to be sought elsewhere. The nearest known peat mines are to the south in the land of Helluvað. Regulation of resources to maintain social hierarchy is a common social phenomenon in Iron Age society and the issue remains of whether social elites were regulating peat availability in the north of Iceland as a means of retaining and enhancing power and authority. Not only was the emerging legal framework and religious observances being

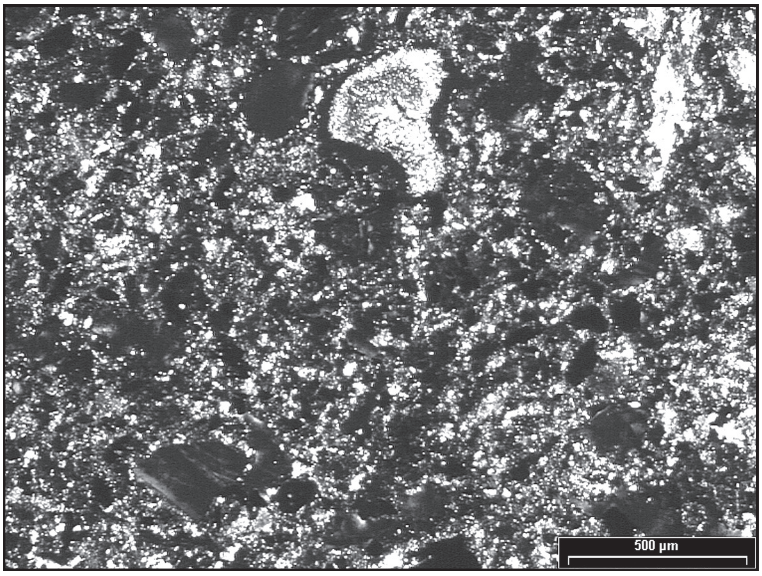

Figure 7.17 Crystallitic b fabric under cross polars, Hofstaðir section G109, thin section sample 3; interpreted as ash residues from wood combustion.

used to enhance chieftain power, land resources - of which fuel resources were a part - may also have been used in this manner. Evidence for fuel resource regulation is further hinted at in the Hofstaðir stratigraphy where increases in the proportion of wood utilisation are seen. This suggests that woodland management may have occurred (see also Lawson, this volume). Such a possibility is in contrast to the prevailing view of an Icelandic settlement period characterised by major woodland loss and land degradation (Hállsdóttir 1987; McGovern *et al.* 1988, Simpson *et al.* 2001) and may emphasise the significant role that large scale land management may have played in the successful maintenance of high status settlement-age sites.

Landscape responses

Assessment of landscape responses to farm estate colonization and settlement activities given in the earlier sections of this chapter is made through local sediment accumulation rates based on tephrochronology as a proxy record for soil erosion (Dugmore and Erskine 1994; Dugmore *et al.* 2000; Simpson *et al.* 2004). These field based analyses are supported by thin section micromorphology of organic and mineral features to characterize sediment (or soil) accumulation and allowing identification of periods when there was no accumulation ('standstill' phases; Simpson *et al.* 2004). Sediment accumulation rates at Hofstaðir can be compared and assessed against pre-*Landnám* (pre–human settlement) and regional indicators of soil erosion using the work of Ólafsdóttir and Guðmundsson (2002).

Three transects were randomly placed in the estate area, each running from east to west across the valley landscape. On each transect, 12 randomly located soil pits were excavated down to the thick horizon of white, siliceous, fine-grained Hekla tephra (H_3 - 2,800 yr B.P.), providing a total of 36 soil profiles. Tephrochronologies were based on the regional framework of Þórarinsson (1944, 1952), local studies associated with the archaeological investigations at Hofstaðir (Sigurgeirsson 1995; 2001; Sigurgeirsson, personal communication), and the land degradation study of Ólafsdóttir and Guðmundsson (2002). Five tephra horizons were consistently identified in each profile and used as isochrones (table 7.7). Note that tephra identified as *Landnám* 872±2 (Grönvold *et al.* 1995) was subsequently identified as V~950. Other historical tephra horizons are found in the region (notably Veiðivötn [AD 1717] and Hekla [AD 1104/1158]), but could not be consistently identified in examined profiles and, therefore, were not used in this analysis. Munsell colour, field texture and field structure were recorded and soil thicknesses between tephra horizons were carefully measured to an accuracy of ± 1 mm, providing soil accumulation rates.

Tephra	Origin and age	Type	Field colour and texture	Micromorphology description
"a"	Veiðivötn (AD 1477)	Basic	10YR 3/2; fine sand	Brown and black; fine sand; isotropic, glass; smooth, angular and subangular; common vesicular; common 1 degree of irregular line alteration and few 3° of pellicular core alteration
V-950	Veiðivötn (AD 871 ±2) (Landnám)	Basic/Acid	2.5YR 3/3; silt loam	Brown; fine sand; isotopic glass; smooth angular; rodlike to blocky
b/c	Uncertain (c. AD 600 and AD 700)	Basic	7.5YR N2/0 – 7.5 YR N3/0; fine sand	Black; fine sand; isotropic; smooth subangular
H	Hverfjall (c. 2,500 BP)	Basic	7.5 YR N2/0; coarse sand	Pale brown; coarse sand; anisotropic speckled with rodlike and tabular inclusions; smooth subangular blocky; common vesicular; few 1° of linear alteration
H_3	Hekla 3 (c. 2,800 BP)	Acid	10YR 5/5; silt loam	Yellow; silt; isotropic glass; smooth angular lenticellular, few fibrous; 1° of pellicular alteration

Table 7.7 Generalised tephrochronology for the Hofstaðir estate with field and thin section micromorphology description.

Temporal phase	Mean soil accumulation rate mm / yr : Hofstaðir	Mean soil accumulation rate mm / yr : Regional *(after Ólafsdóttir and Gudmundsson, 2002)*
'a' (A.D. 1477) - Present day (2000)	0.14	0.35
Landnám (A.D. 871) - 'a' (A.D. 1477)	0.17	0.15
h (2,500 yr. B.P.) - Landnám (A.D. 871)	0.04	0.05
H_3 (2,800 yr. B.P.) - h (2,500 yr. B.P.)	0.13	0.05

Table 7.8 Regional and Hofstaðir estate grazing area soil accumulation rates.

The term soil, rather than sediment, accumulation rate is used here, as it is the term used by Ólafsdóttir and Guðmundsson (2002) whose work forms the baseline for this investigation.

Soil accumulation rates are set in a wider, regional, land-degradation context by comparison with work by Ólafsdóttir and Guðmundsson (2002). Their work is an analysis of spatial and temporal patterns of land degradation based on Landsat TM satellite imagery and soil accumulation measured in sixty-seven soil profiles. Soil accumulation data were collected from five transects, also running from east to west across the valley landscape, within a *c*. 750 km^2 area of Mývatnsheiði, between the river Skálfandafljót and Mývatn. Data are given on vegetation cover and soil accumulation rates at different altitudes, with data from altitudes less than 300 m comparable with the Hofstaðir estate. The analyses by Ólafsdóttir and Guðmundsson (2002) emphasise the role of climate in long-term patterns of land degradation and provide a regional and temporal baseline against which evidence of land degradation in the Hofstaðir estate can be assessed.

Undisturbed soils were collected in Kubiëna tins from between tephra horizons from three randomly selected profiles on Transect 3 at Hofstaðir (transect 3/profile 9 – four samples; transect 3/profile 6 – five samples; transect 3/profile 4 – five samples). (For thin section manufacture and description, see home-field soils, above). Additionally, point counting was used to quantify particle size classes determined by graticule eyepiece. Interpretation of the features observed in thin section was assisted by reference to Fitzpatrick (1993) and Courty *et al*. (1989), with distinctive pedofeatures and microstructures associated with Icelandic andosols considered in relation to Romans *et al.* (1980), Arnalds *et al.* (1995), and Simpson *et al*. (1999).

In soil profiles, depths to the H_3 tephra within the Hofstaðir estate ranged from 25 cm to 141 cm. The lower part of the profiles, beneath *Landnám* tephra, are typically sandy silt loam with Munsell colours ranging from 10YR 3/5 (dark yellowish brown) to 7.5 YR 3/4 (dark brown). Above *Landnám* tephra, the soils are typically silty loams with Munsell colours ranging from 10YR 3/6 (dark yellowish brown) to 10YR 3/3 (dark brown). Field soil structure is typically weakly developed granular throughout these profiles. In thin section, soils typically comprise a range of coarse (50-500 µm) tephra materials, and sorting varies from moderate to

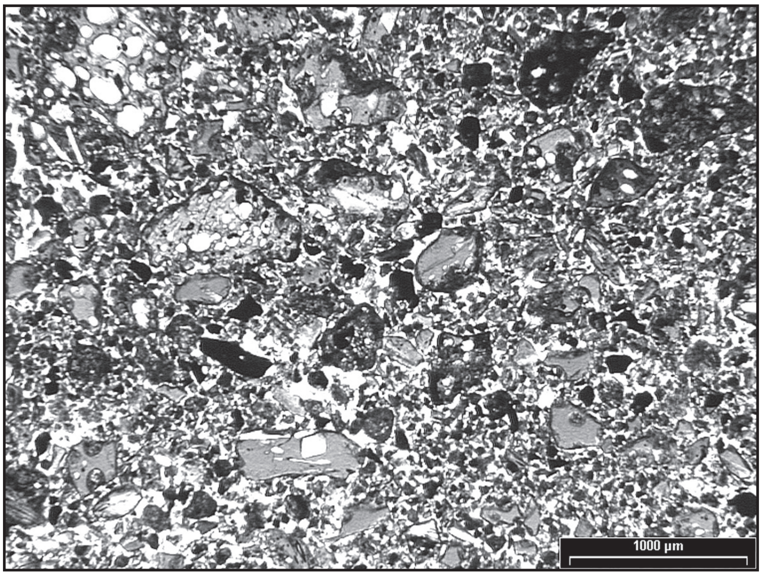

Figure 7.18 Porphyric related distribution with coarse material surrounded by fine organo-mineral material; between H3 and h tephra bands. Hofstaðir transect 3, profile 6, sample 5a.

of the mineral soil, below the vegetation root mat.

H_3 Tephra (2,800 yr. B.P.) – h Tephra (2,500 yr. B.P.)

Soils between the H_3 and h tephras are typically 10YR 3/5 (dark yellowish brown) sandy silt loams with weakly developed, fine-granular structures. Soil accumulation rates across the Hofstaðir estate have a mean of 0.13 mm/yr and a range of 0.04 to 0.47 mm/yr (table 7.8). These accumulation rates are considerably higher than the regional accumulation rate of 0.05 mm/yr within the < 300 m altitude range, although comparable with prehistoric accumulation rates of 0.1-0.3 mm/yr in southern Iceland (Dugmore *et al.* 2000). This suggests that the Hofstaðir estate may have had an above average susceptibility to soil movement in the centuries after the major H_3 volcanic activity, although the variations identified serve to emphasis the localised nature of soil erosion and accumulation. Furthermore, micromorphology indicates that down-slope movement of soil materials was a likely dominant local erosion process and that accumulation was greatest in the western side of the study site where it may have been more sheltered.

In thin section (tables 7.9, 7.10, 7.11), coarse mineral material is characterised by frequent and common pale brown angular and sub-angular h tephra with a mean size of ca. 250 µm (fig.7.18). Point counting indicates that the coarse material comprises on average 36% of the accumulated soil. Fine mineral material is characterised as brown organo-mineral and examination of this material with scanning electron microscopy indicates that it is often comprised of discrete fine, angular and sub-angular mineral grains. Phytoliths are few or

well sorted. Fine mineral materials are organo-minerals and dark brown, brown, and reddish brown in colour; groundmass b-fabrics are consistently isotropic and related distributions are dominantly porphyric. Coarse and fine organic materials include fungal spores, lignified tissues, and amorphous fine materials. Microstructures within the Hofstaðir profiles are dominantly granular, with laminar microstructures (Fitz-Patrick 1993) also evident in the historic, post-*Landnám* phases of soil accumulation.

Based on tephrochronology, soil accumulations in profiles across the Hofstaðir estate and in the regional profiles can be considered in four phases (table 7.8). Two of the phases are pre-settlement: one occurs between H3 tephra (2,800 B.P.) and h tephra (2,500 B.P.), the second occurs between h (2,500 B.P.) and V~950 (*Landnám* tephra, AD 871±2). Using thin section micromorphology, attention is also given to the sequences of accumulation between the b/c tephra (ca. AD 600-700) and the V~950 tephra (*Landnám* tephra, AD 871±2). Post settlement phases are between V~950 (*Landnám* tephra, AD 871±2) and the 'a' tephra (AD 1477) and between 'a' tephra (AD 1477) and the top very few within the organo-mineral material. A range of fine and coarse organic materials is evident in thin section, including fungal spores and few brown amorphous materials; rare and occasional excremental pedofeatures are also evident.

The observations suggest that soil accumulation between 2,800 and 2,500 B.P. is the result of both the addition of eroded loess (the fine silt component) and primary airborne tephra (the coarser sand-size component). The soil accumulation rate can, therefore, be adjusted to take into account the airborne tephra input of about 0.08 mm/yr (that is, 64% of 0.13 mm/yr). Such adjustments are likely to be essential in other parts of Iceland where soil accumulation rates have been used as proxies for land degradation and may therefore, have over-estimated soil erosion. The organic features and biogenic silica observed in thin section also suggest that deposition of mineral material took place on a biologically active soil environment with a vegetation cover indicating that, at least in some parts of the landscape, vegetative cover and related organic matter accumulation predominated immediately after the H_3 tephra deposition event, before silt and sand additions subsequently became more prevalent.

h Tephra (2,500 yr B.P.) – V~950 (*Landnám* tephra, AD 871±2)

Between the h tephra and V~950 (*Landnám* tephra, AD 871±2), soils are typically 7.5 YR3/4 (dark brown) colour and sandy silt loam in texture with weakly developed, fine-granular field structures. Soil accumulation rates are between 0.01 mm/yr and 0.2 mm/yr, with a mean of 0.04 mm/yr. Thus, they are lower compared to the previous accumulation period. This mean value is almost identical to the regional value of ca. 0.05 mm/yr (table 7.8). There is no statistical correlation between soil accumulation and gradient, and observations suggest that broadly similar regional processes were operating across the whole landscape, although there was varied accumulation across the Hofstaðir estate.

In thin section (tables 7.9, 7.10, 7.11) the accumulated soils have very similar attributes compared to the earlier phase of accumulation, with the exception that coarse mineral materials (pale brown and black tephras) are considerably less frequent (ca. 12%) and smaller in size (mean of ca. 120 µm). This finding suggests that much of the soil accumulation is the result of soil movement processes (e.g., solifluction) rather than direct tephra input. As in the earlier phase, accumulation during this period took place on a biologically active soil with vegetation cover. Evidence from soil thin-section micromorphology also suggests that these soil accumulation characteristics continued during the short period between the b/c tephra and V~950 (*Landnám* tephra, AD 871±2). Specifically, coarse and fine mineral materials of similar type and frequencies to those below have accumulated. Also of importance are the organic material accumulations, suggesting significant vegetation cover during this short period contributing to the relative stability of the landscape.

V~940 (*Landnám* tephra, AD 871±2)- 'a' Tephra (AD 1477)

Post-settlement soils between V-950 (*Landnám* tephra, AD 871±2) and 'a' tephra are typically colour 10YR 6/6 (brownish yellow) with silty loam textures and weakly developed granular field structures. The mean annual accumulation rate at Hofstaðir increases to 0.17 mm/yr. and is greater than the regional value of 0.15 mm/yr for soils below an elevation of 300 m. (table 7.8). Hence, human impact may account for as much as 15% of the accumulation rate. This observation confirms that human activity has a distinctive and recognisable role in historical patterns of land degradation within a regional context. Transect data suggests, however, at least in the case of Hofstaðir estate, soil accu-

Hofstaðir Transect 3, Profile 4

Sample	Depth (cm)	Coarse mineral material: Tephra: Pale brown; Inclusions	Pale brown; Vesicles	Pale brown	Black; Inclusions	Black; Vesicles	Grey; Vesicles	Grey	Diatoms	Phytoliths	Gravel; Black	Fine mineral material	Coarse organic material: Fungal spores	Lignified tissue	Parenchymatic tissue	Fine organic material: Amorphous (black)	Amorphous (brown)	Cell residues	Pedofeatures: Textural(silt)	Textural(clay coatings)	Amorphous & crypto crystalline nodule	Excremental (mammillate)	Excremental (spheroidal)	Microstructure	Coarse material arrangement	Degree of sorting	Groundmass B fabric	Related distribution
3/4/1	9 - 17	•	•	•	•	•		•		•		••• Dark brown organo-mineral	•	•	•	•	•••	•					*	Granular	Random Linear	Moderate Well	Isotropic Stipple	Porphyric Enaulic
1477AD																												
3/4/2	39 - 47	•	•	•	•			•		•		•••• Brown organo-mineral	•			•	•						*	Granular Laminar	Random Linear Clustered	Moderate Well	Isotropic Stipple	Porphyric Enaulic
3/4/3	68 - 76	•	•	•	••			•				•••• Brown +red brown organo-mineral	•			•	•		*		*		*	Laminar Granular	Random Linear	Moderate	Isotropic Stipple	Porphyric
871AD/950AD																												
3/4/4	94 - 102	•	•	•	•					•		••• Brown organo-mineral	•			•	••						*	Granular	Random	Moderate	Isotropic Stipple	Porphyric
3/4/5a	107 - 110	•	•	•	•					•		••• Brown organo-mineral	•			•	••						*	Granular	Random	Moderate	Isotropic Stipple	Porphyric
2500 yrs BP																												
3/4/5b	111 - 115			•	••					••		••• Brown organo-mineral	•	•		•	••						*	Granular	Random	Well	Isotropic Stipple	Porphyric
2800 yrs BP																												

Frequency class refers to the appropriate area of section (Bullock *et al., 1985)* • Very few •• few ••• Frequent/common •••• Dominant/very dominant.
Frequency class for textural pedofeatures (Bullock *et al., 1985)* * Rare ** occasional *** Many

Light sources: Plane Polarised (ppl)
Oblique Incident (oil)

Table 7.9 Summary thin section micromorphology descriptions of soil accumulation, Hofstaðir Transect 3, Profile 4

Hofstaðir Transect 3, Profile 6

		Coarse mineral material											Coarse organic material			Fine organic material			Pedofeatures								
		Tephra																									
Sample	Depth (cm)	Pale brown; Inclusions	Pale brown; Vesicles	Pale brown	Black; Inclusions	Black; Vesicles	Grey; Vesicles	Grey	Diatoms	Phytoliths	Gravel; Black	Fine mineral material	Fungal spores	Lignified tissue	Parenchymatic tissue	Amorphous (black)	Amorphous (brown)	Cell residues	Textural(silt)	Amorphous & crypto crystalline nodule	Excremental (mammillate)	Excremental (spheroidal)	Microstructure	Coarse material arrangement	Degree of sorting	Groundmass B fabric	Related
3/6/1	24 - 32			•	••			•		•		••• Brown organo-mineral	•	•		•	••					*	Granular	Random Clustered Linear	Well	Isotropic Stipple	Porphyric Enaulic
1477AD																											
3/6/2	49 - 57	•		•	•					•		•••• Brown organo-mineral	•			•	•					*	Granular	Random Clustered	Well	Isotropic Stipple	Porphyric Enaulic
3/6/3a	66 - 69		•	•	•					•		•••• Brown organo-mineral			•	•	•						Granular	Random	Well	Isotropic Stipple	Porphyric
871AD/950AD																											
3/6/3b	70 - 71		•	•	•							••• Brown organo-mineral	•			•	••						Granular	Random	Moderate	Isotropic Stipple	Porphyric
600/700AD																											
3/6/3c	72 - 74	•	•	•	•					•		••• Brown organo-mineral	•			•	••					*	Granular	Random	Moderate	Isotropic Stipple	Porphyric
3/6/4a	72 - 75	•	•	•						•		••• Brown organo-mineral	•			•	••					*	Granular	Random	Moderate	Isotropic Stipple	Porphyric
3/6/4b	77 - 80	•	•	•	•					•		••• Dark brown organo-mineral	•			•	•						Granular	Random	Moderate	Isotropic Stipple	Porphyric
2500 yrs BP																											
3/6/5a	86 - 89	•	•	•	••					•		••• Brown organo-mineral	•			•	•					*	Granular	Random	Moderate	Isotropic Stipple	Porphyric
3/6/5b	89 - 94				•					•		•••• Dark brown organo-mineral	•			•	••					**	Granular	Random	Well	Isotropic Stipple	Porphyric
2800 yrs BP																											

Frequency class refers to the appropriate area of section (Bullock *et al., 1985)* • Very few •• few ••• Frequent/common •••• Dominant/very dominant.
Frequency class for textural pedofeatures (Bullock *et al., 1985)* * Rare ** occasional *** Many

Light sources: Plane Polarised (ppl)
Oblique Incident (oil)

Table 7.10 Summary thin section micromorphology descriptions of soil accumulation, Hofstaðir Transect 3, Profile 6.

Hofstaðir Transect 3, Profile 9

Sample	Depth (cm)	Coarse mineral material – Tephra: Pale brown; Inclusions	Tephra: Pale brown; Vesicles	Tephra: Pale brown	Tephra: Black; Inclusions	Tephra: Black; Vesicles	Tephra: Grey; Vesicles	Tephra: Grey	Diatoms	Phytoliths	Gravel; Black	Fine mineral material	Coarse organic material: Fungal spores	Coarse organic material: Lignified tissue	Coarse organic material: Parenchymatic tissue	Fine organic material: Amorphous (black)	Fine organic material: Amorphous (brown)	Fine organic material: Cell residues	Pedofeatures: Textural(silt)	Pedofeatures: Amorphous & crypto crystalline nodule	Pedofeatures: Excremental (mammillate)	Pedofeatures: Excremental (spheroidal)	Microstructure	Coarse material arrangement	Degree of sorting	Groundmass B fabric	Related
3/9/1	2 - 10		•	••						•		••• Dark brown organo-mineral	•	•	••	•	•	•				*	Granular	Random	Moderate	Isotropic Stipple	Porphyric
1477AD																											
3/9/2	12 - 20		•	••						•		•••• Brown organo-mineral	•	•	•	•	•					*	Granular	Random	Moderate	Isotropic Stipple	Porphyric
871AD/950AD																											
3/9/3	21 - 29	•	•	••	•					•		••• Brown organo-mineral	•			•	••					*	Granular	Random	Moderate	Isotropic Stipple	Porphyric
2500 yrs BP																											
3/9/4	31 - 39	•	•	••	••	•	•			•		••• Brown organo-mineral	•	•		•	••	•				*	Granular Laminar	Random	Moderate	Isotropic Stipple	Porphyric
2800 yrs BP																											

Frequency class refers to the appropriate area of section (Bullock *et al., 1985)* • Very few •• few ••• Frequent/common •••• Dominant/very dominant.
Frequency class for textural pedofeatures (Bullock *et al., 1985)* * Rare ** occasional *** Many

Light sources: Plane Polarised (ppl)
Oblique Incident (oil)

Table 7.11Summary thin section micromorphology descriptions of soil accumulation, Hofstaðir Transect 3, Profile 9.

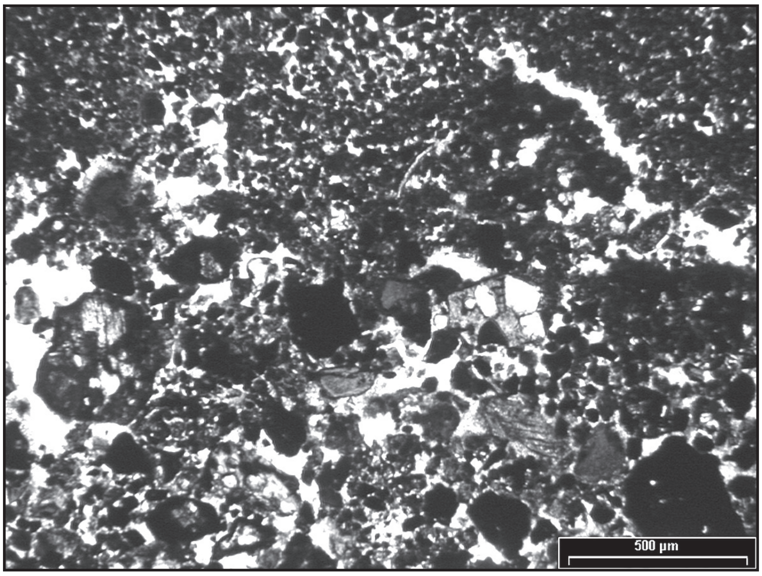

Figure 7.19 Linear accumulation of coarse mineral material; *Landnám* to 'a' tephra. Hofstaðir transect 3, profile 4, sample 2.

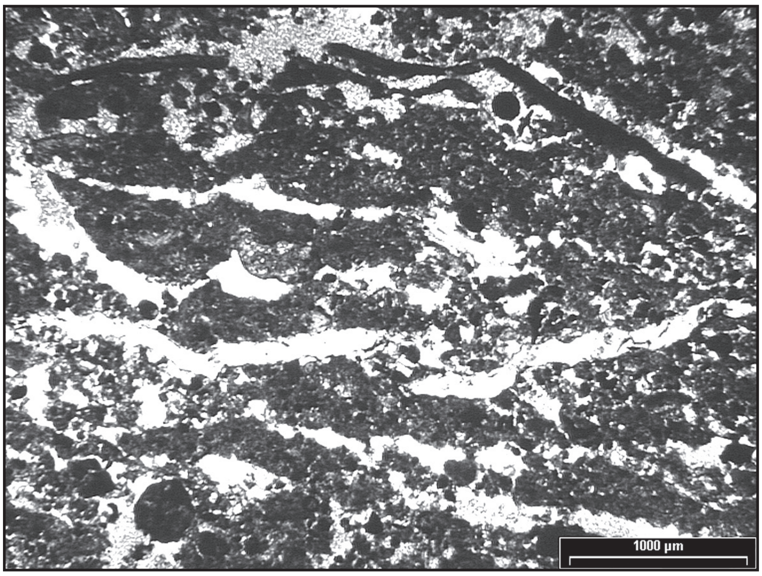

Figure 7.20 Laminar microstructures and associated silt textural pedofeatures; *Landnám* to 'a' tephra. Hofstaðir transect 3, profile 4, sample 3.

mulation is localised. Large accumulations of soil are associated with areas of bare ground on breaks of slope above the farm.

In thin section (tables 7.9, 7.10, 7.11) the frequency of coarse mineral material, although of more diverse tephra origins, declines relative to the prehistoric period. Distinct increases in soil accumulation are evident in Transect 3. The coarse material (*c*. mean of 340 µm) in profiles 4 and 6 are better sorted and are arranged into clustered and linear patterns. There is a decline in the amount of fine organic material, although coarse organic material remains at similar frequencies, and a corresponding increase in the frequency class of fine organo-mineral material. Microstructures retain a predominantly granular structure with laminar structures also evident.

These observations clearly suggest a marked change in accumulation characteristics between pre-*landnám* and post-*landnám* periods, with an accelerated increase in fine-grained aeolian deposition, and with input of organic material from surface vegetation more limited, contributing to soil instability. The clustered and linear patterns of coarse mineral fractions of different origins indicate a more localised, water-sorted, contribution to soil accumulation on the western side of the estate (fig.7.19). Laminar microstructures with associated silt textural pedofeatures indicate cooler climatic conditions with cryoturbation processes operating on what are likely to have been relatively unstable soils (fig.7.20). In general, the soils-based evidence from thin-section micromorphology points to a less stable landscape with accelerated erosion dominated by wind erosion and a significant amount of water erosion.

'a' Tephra (AD 1477) to Present Day (AD 2000)

Over the past *c*. 500 years, soil accumulation is characterised by soils that typically have Munsell colours of 10YR3/4 (dark yellowish brown) and are silty loam in texture with weakly developed granular field structures. Accumulation rates decline to a mean of 0.14 mm/yr and are substantially lower than the regional rate of 0.35 mm/yr (table 7.8). Transect evidence does, however, again indicate increased soil accumulation in the western part of the area, above the Hofstaðir farm buildings and home-field. In light of these observations, it would appear that soil erosion and accumulation dynamics within the estate were moving back to an equilibrium level with more localised erosion and accumulation that may be similar to that evident before settlement of the landscape. These results suggest that human activity did not always contribute to accelerated land degradation. Indeed, these results raise the possibility that adaptive management within this area may have minimised the impact of grazing pressure and slowed regional land degradation trends, although an alternative explanation is an increase in unpalatable plant species resulted in less grazing pressure with consequently less erosion. This latter explanation does, however, seem unlikely given the continuous occupation and utilisation of the area.

In thin section (tables 7.9, 7.10, 7.11), coarse and fine organic material increases in frequency in each of the three soil profiles, with an associated reduction in the frequency of fine mineral material introduced by aeolian deposition. This in part reflects proximity of these samples to the present-day land surface, but it is also evident that organic content closely resembles that evident in the prehistoric phases of soil accumulation. The frequency of coarse mineral material (mean diameter ca. 210 μm) is similar to the previous historical phase of deposition, and there is again evidence of well-sorted clustered and linear coarse material arrangements of different tephra. The evidence from thin-section micromorphology strongly suggests that reduced soil accumulation rates may have been the result of increased vegetation cover, contributing to a greater degree of landscape stability, although evidence of aeolian and water-related soil erosion was still apparent.

Discussion

Prior to *Landnám* the Hofstaðir area broadly conforms to the regional pattern, with thin-section micromorphology suggesting a degree of landscape stability provided by vegetative cover. These results suggest that landscape position, in addition to climate, is an important variable in determining soil erosion in pristine landscapes; this may include slope gradient, exposure and proximity to lava fields. Such landscape attributes remain to be fully tested.

After deposition of the *Landnám* tephra, a variable picture of soil erosion emerges. With settlement there is the expected initial increase in the soil accumulation rate at Hofstaðir relative to both the pre-*Landnám* and regional accumulation rates. This defines a distinct, if localised, signal associated specifically with human activity. Thin-section micromorphology suggests that this phase of land degradation took place against a background of cooler climate, and that there was erosion by both wind and water. During the later phase of the historic period, the soil accumulation rate at Hofstaðir unexpectedly declines to below the regional rate, but was still well above the pre-*Landnám* rate. We suggest that these observations imply an early phase of mismanagement with overgrazing and possibly woodland removal. The subsequent decline in the soil accumulation rate, set against a context of accelerating regional land degradation, suggests that people began to understand how to manage this area, with successful management assisted by its favourable landscape position and continuing soil organic matter input.

In an archaeological context, these results suggest that management of farm estates and landscape position were key factors contributing to the success or failure, defined by sustained human occupancy, of early settlement sites in Iceland. At Hofstaðir, a favourable landscape location meant that the initial impact of settlement did not result in irreversible soil erosion. Later, adaptive management further ensured the survival of the site, minimising the impact of grazing livestock and reducing the level of erosion to below that of regional, climatically-driven soil erosion.

Conclusions

A recurring theme to emerge from the investigation of agricultural activities at Norse Hofstaðir is a long-term commitment to management within the capabilities of the land and in the enhancement of productivity levels. There was sufficient biomass within the estate to support the numbers of livestock suggested from the zoo-archaeological data and with careful timing of grazing activity around the start and end of the growing season there was ample room for expansion. Modelling analyses of the home-field indicates fluctuating hay production potential for the over-wintering of domestic livestock from settlement through to *c*. AD 1100. However, with manuring practices that utilised animal manures and domestic waste, hay productivities were increased, provided buffering against downturns in climate and longer term consistencies in yield. Management of fuel resources is also evident with a range of resources partitioned for different combustion activities. Furthermore, increases in the proportion of wood utilization for fuel suggests that woodland management may have promoted different age structures and densities thus raising productivities.

There is clear evidence of an initial degrading impact of the landscape with settlement at Hofstaðir, seen in both home-field and rangeland areas as movement of soil material, and it is also evident that soil movement through wind and water erosion continued at a greater rate than in pre-*landnám* landscapes. However, the decline in soil movement in relation to continuing acceleration in the Mývatnssveit region suggests successful adaptive management in grazing regimes, home-field management and fuel resource extraction by the early Hofstaðir occupants. Incremental management improvements to land served to create a resilient farm based community in which a generation was sustained by and benefited from the activities of previous generations. Such observations have a wider resonance beyond Hofstaðir and Iceland, and carry major implications for the sustainability of communities in sensitive environments today.

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