Palaeoenvironmental evidence for woodland conservation in northern Iceland from settlement to the 20thCentury.

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Abstract

Narratives of Norse arrival in Iceland highlight the onset of land degradation and loss of woodland cover as major and long-term environmental consequences of settlement. However, deliberate and sustained land resource management in Iceland is increasingly being recognised, and in this paper we assess whether woodland areas were deliberately managed as fuel resources. Our study location is the high status farm site at Hofstaðir in northern Iceland. A palynological record was obtained from a small basin located just inside the farm boundary wall and the geoarchaeological record of fuel use obtained from waste midden deposits associated with the farm. Both environmental records are temporally constrained by tephrochronology and archaeological records. When viewed within the broader landscape setting, our findings suggest that there was near continuous use of birch wood from early settlement to the present day, that it was actively conserved throughout the occupation of the site and that there were clear distinctions in fuel resource utilisation for domestic and more industrial purposes. Our analyses open discussion on the role of local woodlands and their management in the Norse farm economy.

Introduction

The Norse settlers of the 9th and 10th centuries brought with them farming practices from Norway and the Northern Isles which were adapted for the use in the newly settled regions of the North Atlantic. The farm structure of communal rangeland, seasonal shielings, out fields for winter grazing, enclosed home fields for cereal production (where possible), hay production and aftermath grazing, indicate exploitation of a range of resources at farm and landscape scale (Edwards *et al.* 2005; Simpson *et al.* 2002; Vésteinsson *et al.* 2002). Archaeological, geoarchaeological and documentary evidence suggest that Norse farmers in the North Atlantic employed a range of management approaches including irrigation (Adderley and Simpson 2006), manuring recipes and practices (Buckland *et al.* 2009; Golding *et al.* 2014) and restricted seasonal usage of grazing (Simpson *et al.* 2004; Brown *et al.* 2012). Such approaches point to the knowledge of how to both manage resources effectively and maximise productivity during periods of environmental change (Simpson *et al.* 2004). Woodland and timber products would have been an important resource in the Norse farm economy with the need to balance demand and availability in regions where woodland resources would have been marginal. Iceland offers the opportunity to examine the role of woodland in the Norse farm economy, in particular the role of woodland resources for fuel and to further explore ideas of resource management within farms.

Norse settlers arriving in Iceland at *c.* AD 870 cleared woodland for farmland and grazing as well as fuel use for a range of domestic and industrial activities (Trbojevic 2016). Traditional narratives outline the rapid decline of Icelandic woodland cover associated with settlement (Hallsdóttir 1987). Extensive soil erosion and land degradation has been associated with this rapid change in vegetation cover (Dugmore *et al*. 2000, 2009; Vickers *et al*. 2011; Eddudóttir *et al*. 2016). Vegetation records show that within Iceland the picture is more complex in terms of the nature and rate of change in woodland during the Holocene (Erlendsson and Edwards 2009; Eddudóttir *et al*. 2015, 2016) and post settlement (Lawson *et al*. 2007; Erlendsson *et al*. 2009; Streeter *et al.* 2015). Palaeoenvironmental evidence indicates that woodland clearance may have been phased (Church *et al*. 2007) and that it was a managed resource (Simpson *et al*. 2003). When examined at farm scale the impact of soil erosion and land degradation also varies (Simpson *et al*. 2004; McGovern *et al*. 2007; Gísladóttir *et al*. 2010). This complexity in the records of environmental change in Iceland post settlement requires that palaeoenvironmental data sets reconstruct local farm scale variations as well as develop the regional, wider spatial scale evidence.

Mývatnssveit is an inland region of northern Iceland around Lake Mývatn (Figure 1), the farm at Hofstaðir sits on a lava flow terrace above the River Laxá which flows out of Lake Mývatn (Fig. 1). The archaeology at Hofstaðir has been investigated since 1908 and extensive archaeological and palaeoenvironmental investigations in the surrounding area (McGovern *et al*. 2007) have been on-going since 1991. Some of key archaeological features and structures are shown in Fig. 2. The archaeological data suggest a specialised use for the aisled hall (Fig. 2) at Hofstaðir, summer feasting, with the hall in use between AD 940- and AD 1030-1070 (Lucas and McGovern 2008; Lucas 2009). The archaeological record, supported by written evidence from AD 1477 onwards, suggests continued use and occupation of Hofstaðir from *c.* AD 940 up to the present day (Batt *et al*. 2015; Lucas 2009), with the modern farm moving to its current location in AD 1950 (Fig. 2). Simpson *et al*. (2003) suggest that the record of fuel residues identified from within the pit house midden (*c.* AD 945-1030; Fig. 2) show a mixture of domestic and industrial use of fuels. The persistence and increased use of wood as a fuel during the period of time associated with the use of the hall led Simpson *et al*. (2003) and Vésteinsson and Simpson (2004) to propose that woodland was being managed in the local area.

A vegetation record from Lake Helluvaðstjörn (Fig. 1; Lawson *et al.* 2007) suggests that woodland cover in the Mývatnssveit area was extensive and persisted during early settlement supporting the idea of wood fuel readily available during the early phase of settlement. However, this record indicates that woodland cover was reduced to the present day sparse coverage by *c.* AD 1300. The archaeological record points to continued occupation and farming activity at Hofstaðir but it's not clear if wood fuel continued to be used at the farm. The palaeoenvironmental data presented here aims to provide evidence of what fuel types were used and using a local vegetation record provide a basis to explore the continued management of local woodland resources at Hofstaðir.

Methods

Present day vegetation across the farm is rough grazing grassland in the home field areas with dwarf shrub vegetation (*Betula nana*, *Vaccinium uliginosum* and *Empetrum nigrum*) on slopes above the farm. Below the farm and along the steep slopes to the river the vegetation is dominated by willows (*Salix lanata* and *S. phylicifolia*), with a few tree birches (*Betula pubescens*) (Fig. 2), and associated tall herbs (*Geum rivale, Angelica archangelica, Alchemilla mollis, Ranunculus* spp.*, Geranium sylvaticum*). A series of small, well-defined mires lie just below the steep slope above the river (Fig. 2). The mires are dominated by herbs (*Coeloglossum viride*, *Bistorta vivipara*, *Hieracium* sp., *Eriophorum angustifolium*, *Cardamine pratensis*, *Bartsia alpina*, *Potentilla erecta*, *Equisetum palustre*) grasses and sedges. The pollen site is located on one of these mire sites (N 65° 36.781; W 017° 09.862, 233 m asl) just inside the Medieval farm boundary wall (Fig. 2), the basin is small, 26 m x 24 m, in diameter. The small, well-defined basin means that the pollen source area is likely to be dominated by local inputs with much of the pollen sourced from the mire surface itself and the steep rocky slopes above the site. The pollen core was taken using a 50 cm x 5 cm Russian corer to a depth of 120 cm, cores taken were 10-60 cm, 50-100 cm, 70-120 cm. The uppermost part (0-30 cm) was sampled by digging a shallow section. The cores were wrapped in the field, transported to the University of Stirling and stored at a constant 4°C.

Core sediment stratigraphy was described using a modified Troels-Smith description (Aaby and Berglund 1986). Sediments were described both in the field and in the laboratory prior to pollen sub sampling. Core correlation, to ensure a continuous sediment record for pollen analysis, was established using sediment depths and the stratigraphic units (in particular the tephra units) within each core. Organic content was determined by loss-on-ignition at 550°C for 4 hours (LOI_{550}) and carried out at a contiguous 0.5 cm sampling interval.

Sub-samples of 1 cc were taken from organic-rich stratigraphical horizons from the pollen core, avoiding tephra rich material. The pollen analysis does not include the top 5 cm of the turf mat and starts at 86 cm depth, above a tephra layer noted at 88 cm. The sub-samples were prepared at the University of Stirling using standard pollen preparation procedures (Moore *et al*. 1991). To enable the assessment of the total concentrations of pollen in each sample, one tablet containing *Lycopodium clavatum* spores of known concentration (Batch number 3862) was added to each sample and the spores counted alongside the fossil pollen (Stockmarr 1971). Pollen was identified using an Olympus BX41 light microscope at ×400 magnification with critical identifications made at ×800 and assisted by a pollen reference collection and photomicrographs (Moore *et al*. 1991), nomenclature for pollen and spores follows Bennet (2009). Flora nomenclature follows Kristinsson (2010). Each sample was found to be polleniferous and the pollen identified to a total land pollen (TLP) sum of ≥ 300. Cyperaceae pollen grains were excluded from the TLP sum to reduce the local mire signal and allow for the interpretation of landscape vegetation change. The pollen data are presented using Tiliagraph (Grimm 1992) and local pollen assemblage zones (LPAZ) established through CONISS (Grimm 1987). Tree birch (*B. pubescens*) and dwarf birch (*B. nana*) pollen grains were differentiated based on the diameter of well-preserved *Betula* pollen grains (Caseldine 2001; Lawson *et al*. 2007). The *Betula* pollen grain size frequency showed a bimodal distribution with peaks in grain size at 15 μm and 18.75 μm. The difference between the modal values are small when compared to other published Icelandic *Betula* pollen grain diameters (Barclay 2016) and so this information cannot be used to confidently differentiate between species of *Betula*.

To provide information about the depositional environment of the pollen each grain was assessed for its state of preservation using five categories; normal, broken, crumpled, corroded and degraded (Berglund and Ralska-Jasiewiczowa 1986; Tipping 1987). Grains that are broken and/or crumpled are likely to indicate damage due to mechanical processes such as through abrasion during transport. Pollen is best preserved in waterlogged (anaerobic) and acidic conditions and so corrosion and degradation suggest chemical processes whereby pollen is 'digested' by microbial activity under drier aerobic conditions.

Soil micromorphology

Excavations in 2010 at the cemetery and church site within the farm mound (Fig. 2) revealed a large pit over 3 m deep containing a stratified sequence of midden deposits (Fig. 3). Initial field interpretations identified fuel ash residues from mineral based turf, peat, wood charcoal and coal/clinker deposits. Thirteen undisturbed samples were taken from the midden stratigraphy (HST10) in 7.5 x 5.5 cm Kubiena tins (Fig. 3). The samples were prepared at the University of Stirling. Simpson *et al's*. (2003) micromorphological investigations into immediate post settlement fuel use at Hofstaðir developed a set of fuel residue reference slides. These slides were used here to define the following fuel residues; peat (800°C and 400°C), turf (800°C and 400°C), dung (800°C and 400°C), seaweed (800°C and 400°C) and wood (800°C and 400°C) including *Betula pubescens* and *Salix* sp. In addition, clinker residues were identified from type slides shown in McKenzie (2006, p 281-282). Criteria for fuel type residue categorisations were based on rubification, mineral content, presence and abundance of diatoms and phytoliths, size and shape of feature (Stoops and Vepraskas 2003). The recording of fuel type residue data followed methods outlined by Stoops and Vepraskas (2003). Care was taken to identify the fuel residues as they were mixed with other non-fuel midden materials.

A methodological approach was developed during this analysis to record and quantify fuel residues within the thin section slides. A 5 mm^2 square grid was drawn onto the reverse of the glass slides. The proportion of fuel residue within each cell was recorded as a percentage, if more than one fuel type was present the proportion of each was recorded. The proportions were estimated using a feature abundance scale as detailed in Stoops and

Vepraskas (2003). Each slide contained 187 cells, data are presented as the percentage proportion of each fuel type in the slide.

A relative chronology was established for the sequence of midden deposits sampled. White ware pottery and clay pipes were recovered from the base of the profile and were dated to the mid-18th century (Fig. 3). At the top of the profile a number of modern artefacts were recovered including plastics (Fig. 3) providing a 20th century date for the top of the profile.

Results and analysis

Pollen core stratigraphy and chronological framework

The pollen core sediments consist of silty peats and peat and are described in Table 1. Within the silty peats are four well defined minerogenic units that are identified in sediment description (Table 1) as well as in the LOI_{550} data (Fig. 4). These units are airfall deposits of tephra. Fluvial inputs from the river (3-4 m below the site) have not been identified.

Simpson (2009) and Lawson (2009) present a tephrochronological framework based on the tephras recorded and described within the soils at Hofstaðir both within the homefield and archaeological contexts. This framework was based on the sequence of tephras developed for the region by Sigurgeirsson (1995, 2001) and is used to constrain the vegetation record presented here. The pollen core was sampled in AD 2011 (=0 cm). An age depth model for the pollen core was generated in Clam Version 2.2 (Blaauw 2010), Fig. 4.

The pre settlement soil accumulation rate (SAR), between 345 BC and AD 940 is low around 0.03 mm/yr^{-1} but is comparable to rates published for the Hofstaðir farm area (Simpson 2009). Post settlement SAR rises to around 0.18 mm/yr^{-1} (AD 940- AD 1104) and around 0.16 mm/yr^{-1} (AD 1104-1477) again values are comparable to those published for the area. It is post AD 1477 to the present day that the SAR value is high at around 1.14 mm/yr^{-1} however, the SAR may be distorted by the accumulation of fibrous peat from around 30 cm (Table 1; Fig. 4) which is thought to have accumulated rapidly.

Vegetation History

Local pollen assemblage zones (LPAZ's) within the main pollen diagram (Fig. 5) were defined using CONISS. Pollen concentration values for selected taxa are shown in Fig. 6. Pollen preservation was overall very good with low proportions of broken, crumpled, corroded and degraded pollen (Fig. 7). There were slight increases in pollen grain damage above some of the tephra layers but the changes were minimal. The limited nature of variation in pollen preservation indicates that there have been no change in conditions that would affect preservation such as a drying out of the mire surface and there is no indication of pollen reworking or input from reworked sources. This supports the interpretation that the pollen sources for this pollen profile are dominated by local pollen sources.

The pollen evidence reflects a local vegetation record with relatively stable vegetation cover dominated by Poaceae, herbs and Cyperaceae with low amounts of *Betula* and *Salix* in the immediate area. The main vegetation changes post settlement reflect the amount of woodland taxa and grazing around the site rather than a clear response to climate.

LPAZ HF-1a (*c.* 345 BC to AD 940).

The pollen assemblage in this sub-zone represents the pre-settlement vegetation. *Betula* (18%) and *Salix* (10%) percentages indicate the presence of woodland taxa growing on the drier upper slopes. Poaceae (35-38%) and grassland herb taxa such as *Thalictrum alpinum* (8-10%), Ranunculaceae (8-10%) and Asteraceae sub fam. Lactucoideae (5%), with Apiaceae and *Filipendula ulmaria* indicating open areas of herb rich grassland. *Selaginella selaginoides*, *Botrychium* and Cyperaceae (40%) suggest that the open grassland is a wet grassland. Heathland taxa, *Empetrum nigrum* and *Vaccinium* type are present in this zone (<5%). Percentage values for these heathland taxa rarely go above 5% throughout the diagram suggesting that within the pollen source area this vegetation type is present but not dominant. At the end of the sub-zone *Betula* percentage values decline (10%) this decline is seen in both the pollen percentage and pollen concentration values (Fig. 6).

LPAZ HF-1b (AD 940 to AD 1104).

The vegetation in this sub-zone is associated with the early period of settlement at the farm. The percentage values for *Betula* and *Salix* decline further, this is also recorded in the pollen concentration values (Fig. 6). Herbs associated with disturbed ground such as Brassicaceae and *Polygonum aviculare* appear in this zone and open grassland apophytic taxa such as Ranunculaceae (17%), *Galium* (5%), Asteraceae sub fam. Lactucoideae (8%) and *Thalictrum alpinum* (15%) increase. Taxa that are intolerant to grazing such as Apiaceae are reduced (Vickers *et al*. 2011; Zori *et al*. 2013) and *Filipendula ulmaria* disappears from the record and does not return. Poaceae percentage values remain at 35% and Cyperaceae values show a slight increase in pollen percentages and a large increase in pollen concentrations. *Selaginella selaginoides* and *Botrychium* spores also increase, indicating an open, sedge rich grassland that allows for greater spore dispersal.

LPAZ HF-2 (AD 1104 to *c.* AD 1590).

Vegetation in this zone is associated with later settlement at the farm, and prior to the Veiðivötn AD 1477 tephra layer, is very similar to that recorded in the previous zone. At the beginning of the zone tree and shrub taxa values are low (<5%), grasses (40-50%) and apophytic herb taxa *Thalictrum alpinum* (15%) and Ranunculaceae (10%) dominate. Other taxa such as Asteraceae sub fam. Lactucoideae, *Galium* and Brassicaceae are present. Cyperaceae increases in both pollen percentage (60%) and concentration values. However, just before the tephra fall at AD 1477 and then after the tephra layer percentage values for both *Betula* and *Salix* begin to rise (to 15% and 8% respectively), similar to pre settlement values. This rise in *Betula* is also recorded in the pollen concentration values perhaps reflecting the ability of these tree species to survive tephra airfalls (Arnalds, 2013). The percentage values for Poaceae remain at between (40-50%), while many of the dominant herb taxa decline with species such as *Polygonium aviculare* disappearing from the record. Percentage values for Cyperaceae also increase (65%) in this zone and reach their highest both in terms of percentage and concentration values. *Selaginella selaginoides* and other spores decline towards the top of the zone suggesting that the landscape around the pollen site was less open.

LPAZ HF-3 (*c.* AD 1590- *c.* AD 1790).

Betula percentage values are maintained between 10-15% along with higher concentration values throughout the zone. *Salix* percentage values gradually decline during the zone with only trace amounts recorded by the end of the zone. Percentage values for Poaceae (35-

58%) and Cyperaceae (45-70%) are variable throughout the zone and this is also reflected in the pollen concentration values (Fig. 6). *Thalictrum alpinum* (10-20%) is the most dominant grassland herb taxa showing a notable increase in both percentage and pollen concentration values (Fig. 6). Other apophytic herb taxa are present and persistent throughout the zone, such as Ranunculaceae (5-10%), Brassicaceae (5%), *Galium* (<5%) and Asteraceae sub fam. Lactucoideae (5%). *Selaginella selaginoides* spores increase (15-20%) the increase is also recorded in the concentration values. Other spores such as *Diphasiastrum* and *Botrychium* are present throughout the zone. The dominance of grazing tolerant taxa, such as *Thalictrum alpinum*, *Galium* and *Selaginella selaginoides,* alongside the decline of grazing sensitive taxa, such as *Salix,* suggest that grazing perhaps intensive helped to maintain the open damp grassland (Erlendsson *et al*. 2009; Vickers et al. 2011; Riddell 2014).

LPAZ HF-4 (*c.*AD 1790-Present).

This pollen zone records the vegetation associated with the most recent occupation at the farm. This zone is marked by a decline in tree and shrub taxa. Poaceae pollen values increase to the highest values noted in the diagram to 60-80%, this increase is also recorded in the pollen concentration values. *Thalictrum alpinum* percentage values fall in this zone to <5%, this decline is also recorded in the concentration values. Other herb taxa such as Brassicaceae, Asteraceae sub fam. Lactucoideae and *Galium* remain present with a small increase in Ranunculaceae to 10-12%. Cyperaceae rises to around 50% at the top of the zone but this rise is not seen in the pollen concentration values. *Selaginella selaginoides* values fall with the species only recorded as present, this decline is also recorded in the pollen concentration values. The decline in *Selaginella selaginoides,* which is intolerant of tall vegetation (Kristinsson 2010), as well as *Thalictrum alpinum* suggests the grassland was a dense tall sedge rich sward rather than a short-cropped open grassland.

Fuel resource record

Table 2 indicates the range of fuel types used at Hofstaðir from the mid-18th to the mid-20th century. The fuel types are also noted to have been combusted at two different temperature ranges indicating fuels are used for domestic and industrial purposes. From the fuel data (Table 2) is it noted that dung is very rarely used as a fuel type and seaweed is not used at all. Peat is used occasionally and most notably recorded as 58.7% in slide 7, where its use appears to replace all the other fuel types in particular wood and is noted to be a product of high temperature combustion. Turf and wood are the most common fuel type with variable amounts but they remain in use up to the mid-20th century. Turf and wood are used for both low and high temperature combustion with no one fuel type favoured for a specific activity that is domestic or industrial use. There is an indication toward the top of the profile in slides 10, 11 and 12 that wood is used for high temperature combustion, which is industrial use and is used in place of turf and peat. Shrub and heather are present throughout but at levels of between ~ 3 and 10%. Coal is only present in two samples at low percentages (slide 8, 5.28% and slide 10 3.37%) and is not common.

Discussion

The vegetation record presented here suggests open low density woodland cover within the Hofstaðir farm boundary at pre settlement. The steep slopes that are either side of the River Laxá below the Hofstaðir farm would probably have consisted of low density tree cover and areas of wet grassland. This may have made this an attractive area for settlement. Although within the farm these steep slopes represent a narrow strip of land it is laterally continuous and would have represented valuable grazing and perhaps fodder sources (McGovern *et al*. 2007). Regional pollen records close to Hofstaðir at Helluvaðstjörn (Lawson *et al*. 2007) and Gautlönd (Barclay, 2016) (Fig. 1) indicate that pre-settlement and early settlement woodland cover was regionally more extensive and of higher density than the local scale woodland recorded at Hofstaðir. Tisdall and Verril (2010) record large amounts of *Betula* pollen from a floor fill at Sveigakot farm (Fig. 1) again indicating that at settlement *Betula* was regionally widespread and perhaps as at Sveigakot, used for both fodder and fuel use. At Hofstaðir it is suggested that at settlement, the woodland cover may have been extensive on the higher ground above the farm and to the south around Helluvaðstjörn (Fig. 1) and that woodland resources would have been widely available. Evidence for wood used as fuel both in terms of domestic and industrial use during early settlement is recorded in the fuel record for Hofstaðir, by Simpson *et al*. (2003). The archaeological record suggests that a smithy at Hofstaðir was in use between AD 940 and AD 1030 with evidence of expansion and specialist metalworking around AD 980 (Lucas 2009). Charcoal pits recorded close to Hofstaðir at Hrísheimar (Fig. 1) date to the 12th

century (Church *et al*. 2006). Therefore, from early post settlement until the 12th century wood, as a resource, was widely available and was used at Hofstaðir for both domestic and industrial use including specialist metalworking.

Lawson *et al*. (2007) have described the post settlement regional woodland decline as gradual and episodic with some recovery in *Betula* woodland noted in the pollen record, with the very low woodland cover seen today apparent from around AD 1300. The local pollen record presented here suggests a similar post settlement decline but from AD 1477, there is a recovery of local woodland with *Betula* pollen levels close to pre-settlement levels. As highlighted above, this recovery in woodland at Hofstaðir may be in part an advantageous response to the tephra airfall. At this time grassland herb taxa suggest an open, close-cropped sward. We interpret from the Hofstaðir pollen record that the woodland cover was being maintained or managed at low density from around AD 1477 to *c.* AD 1790, with the management of the local woodland cover taking place during a period associated with evidence for intensive grazing. Simpson *et al*. (2003) proposed woodland management during early settlement at Hofstaðir (*c.* AD 940 – AD 1070). Here it is suggested that the management of local woodland resources at Hofstaðir persists until *c.* AD 1790, against a background of widespread, regional woodland decline.

During the subsequent phase of low-density woodland (*c.* AD 1790-present) the mire surface was dominated by a dense, tall sward of grasses and sedges, enough to shade out taxa associated with open habitats. The change in vegetation suggests that grazing intensity has been reduced allowing the wet grassland species to dominate. This grassland, grown for fodder, may have been cut after the grasses have flowered (Broström *et al*. 2008) rather than the intensively grazed grassland as noted previously. Alternatively, the grazing regime on the mire surface may reflect a reduction in grazing (the removal of grazing animals) allowing for an increase in the sward density of the grasses and sedges (Edwards *et al*. 2004).

Within the documentary records the 18th century in Iceland is a period of general economic decline with major setbacks including a small pox epidemic in 1707 and nationwide famines in the 1750s and 1780s (Hanson 1928). The local and long-term impacts of such shocks are difficult to detect (Streeter *et al*. 2012) but the Hofstaðir pollen record is consistent with a picture of long term decline in farm productivity reflected in a reduction in grazing intensity. This period of decline from *c.* AD 1790 is coincident in the stratigraphy with the accumulation of a highly organic, fibrous peat. The accumulation of peat may be a response to the reduced intensity of grazing, an increase in the accumulation of organic matter and increased stability in the landscape leading to reduced aeolian mineral input. The lack of crumpled, corroded and degraded pollen indicates limited input to the site from reworked material (soil) in the catchment. Regionally there is a severe land degradation event in the 16th century associated with a cooler phase of the Little Ice Age (ʹOlasfdóttir and Guðmundsson 2002), however at Hofstaðir this event is not recorded in the stratigraphy suggesting the local variability in the extent of soil erosion. Dugmore *et al.* (2007) suggest that AD 1740 marks a shift in the unpredictability of climate with increased storminess and cooler temperatures. At Hofstaðir the accumulation of peat on this mire site may reflect a combination of cooler climates, reduced rates of decomposition and reduced grazing intensity.

The record of mid-18th century to present day fuel use, as determined through soil micromorphology, reveals that wood and turf continued to be the main fuel sources for both domestic and industrial activity at the Hofstaðir farm. There is a gap in the fuel use record but the continued emphasis of wood as fuel up until the mid-20th century suggests that wood has always been an important fuel at Hofstaðir.

Simpson *et al*. (2003) review the fuel use implications of the Land Register of Árni Magnússon and Páll Vídalín carried out for Mývatnssveit in 1712. The Land Register record suggests that 83% of farms in the area had access to wood and shrub as fuel resources. It was noted that dung was used where woodland was scarce. The Hofstaðir fuel record generated for the mid-18th century to the mid 20thcentury indicates that wood remains an important fuel resource for the farm, this would suggest that wood is available as a fuel resource. The local pollen record indicates that although there is decline in *Betula* pollen from around AD 1790, it persists. The persistence of *Betula* suggests continued management of birch and could have perhaps served as a very local source of wood for fuel at the farm. The fuel resource evidence points to a farm that is still very active in terms of both domestic and industrial use of wood fuel up until the mid-20th century.

Peat was only burnt once in the Hofstaðir fuel record and seems to have been used for perhaps a single industrial use and this is supported by the land register records which indicate that peat was rarely used as a fuel. The fuel use data at Hofstaðir indicates that dung was also rarely used for fuel, suggesting that woodland fuel resources were not restricted. The continued use of wood and turf as fuel is against a backdrop of the availability of imported coal from early 17th century (available in significant quantities from AD 1900) however, coal would have been expensive and here at Hofstaðir it is only recorded as being used very occasionally.

In other regions of Iceland there is additional documentary evidence that suggests that woodland cover was actively maintained into the 16th century (Sigurmundsson *et al*. 2014; Vésteinsson and Simpson 2004) but that the rapid decline of these areas of woodland was due to a lack of management and increase in the intensity of use. For the areas around Hofstaðir the pollen data sets show a regional woodland decline by *c.* AD 1300 which would suggest that there was not enough woodland to be sustainable as a fuel resource. However, the fuel use record from Hofstaðir points to the continued use of wood as a fuel for industrial and domestic uses. The pollen evidence from Hofstaðir indicates that the woodland areas that persisted were small, low density and local but that they were maintained often during phases of what is thought to have been intensive grazing. This continuous use of a resource such as wood and the absence of use of fuel such as dung indicate that Hofstaðir benefited from a reliable, sustainably managed woodland fuel source.

Conclusions

The use of two palaeoenvironmental data sets, fuel use and a local pollen evidence provide insights into farm resources at Hofstaðir, a farm that was continuously occupied from around AD 940 to the present day. The fuel resource evidence suggests that wood was an important source of fuel at Hofstaðir during early settlement, and as presented here during the mid- 18th-20th century, implying the continuous availability of wood as a fuel resource. The pollen record presented here suggests that local woodland resources existed at Hofstaðir, although at a low density and implies the successful management of local and small scale woodland as the likely fuel resource up until the mid-20th century. The widespread regional decline of woodland from around AD 1300 may have focused management of small local resources, the remaining fragments of woodland. These small areas of birch may have been sufficient for domestic farm scale uses but there are questions on the amount of woodland needed to maintain industrial activity, such as noted here at Hofstaðir, these local resources may not have been enough. This suggests that there may have been links to other sources in the region. The data presented here suggests local scale, effective management of woodland resources by Norse farmers, at Hofstaðir such management ensured the continued success of the farm. These findings highlight the need to look at these farm landscapes both at the regional and local scale and that the integration of palaeoenvironmental and archaeological data sets can provide greater insights into how resources are managed at farm scale.

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Figure and Table captions

Figure captions

Figure 1 Location of the study site within northern Iceland, other sites discussed in the text are shown. The green shaded areas on the map are areas of present day scrub/woodland.

Figure 2 Aerial view of archaeological features at Hofstaðir showing the aisled hall structure. The pit house next to the aisled hall (marked with a circle) where Simpson *et al*. (2003) sampled for fuel residue research is shown. The location of the 18th- mid 20th century midden site, next to the 11th century farm mound and the early Norse cemetery used for the fuel use research presented here is shown (marked with a star). The pollen site is located above the River Laxá and within the medieval farm boundary wall. The modern farm buildings are the red roofed structures.

Figure 3 Farm mound midden (HST10). The section drawing shows layers of midden material and location of Kubiena tins (numbered 1-13) used to generate the soil micromorphology thin sections. Archaeological finds used to determine a relative chronology for the soil micromorphology data set are also recorded in the section drawing. The distinctive stratigraphic layering of the midden material is noted in the photograph of the section.

Figure 4 Loss on ignition values, stratigraphy of the pollen core and stratigraphic location of named tephras. The Local Pollen zones are also shown (see Figure 5). Definition of the tephras is based on sediment description and published tephra chronologies for the area (see Table 1). Age depth model constructed using Clam (version 2.2) (Blaauw 2010).

Figure 5 Percentage pollen diagram for Hofstaðir showing selected taxa. The core stratigraphy and local pollen zones are also shown. The tephrochronology is based on the tephra descriptions given in Table 1 and age depth model in Figure 4.

Figure 6 Pollen concentration diagram for selected taxa at Hofstaðir. The core stratigraphy and local pollen zones are also shown. The tephrochronology is based on the tephra descriptions given in Table 1 and age depth model in Figure 4.

Figure 7 Pollen Preservation data for selected taxa at Hofstaðir following Berglund and Ralska-Jasiewiczowa (1986) and Tipping (1987). The core stratigraphy and local pollen zones are also shown. The tephrochronology is based on the tephra descriptions given in Table 1 and age depth model in Figure 4.

Table captions

Table 1 Sediment stratigraphy of the pollen core, including field description of the tephra deposits. The tephrochronology is based on the framework outlined in Simpson (2009) and the tephra descriptions given in ʹOlafsdóttir and Guðmundsson (2002).

Table 2 Proportional fuel residues from the farm mound midden. The values represent each fuel type as a percentage of the total amount of fuel residues recorded within the thin section slide.

Table 1

Depth cm	Sediment description	Tephra Chronology
0-19	Dark brown, fibrous, very poorly humified peat with abundant rootlets and large plant fragments; Th2Dh2.	
19-32	Brown, fibrous, poorly humified peat; Dh4 Sh+.	
32-61	Brown, fine fibrous, silty peat; Dh2Sh1Ag1.	
61-69.5	Very dark brown-black, fine to medium sand; Gmin4 (tephra).	Veiðivötn AD 1477
69.5-75.5	Brown, silty peat with abundant plant fragments; Dh2Ag2.	
75.5-77	Flecks of creamy white silt in brown, silty peat; Ag3Dh2 (tephra).	Hekla AD 1104
77-80	Dark brown, fine fibrous, silty peat; Dh2Sh1Ag1.	
80-81	Grey brown, fine sandy silt; Gmin1Ag3 (tephra).	Veiðivötn AD 940
81-88	Dark brown, fibrous, silty peat; Dh2Sh1Ag1.	
88-94	Pale grey cream, silt; Ag4 (tephra).	Hekla 3 (*c.* 345 BC)
94-100	Dark brown, fibrous, silty peat; Dh2Sh1Ag1.	

Table 2

Slide	Peat (High Temp)	Peat (Low Temp)	Turf (High Temp)	Turf (low temp)	Shrub/ Heather	Wood (High temp)	Wood (Charcoal)	Dung	Seaweed	Coal/Clinker
13	0.00	0.00	6.88	78.35	4.72	6.88	3.17	0.00	0.00	0.00
12	6.17	0.29	27.38	5.01	8.26	45.59	7.29	0.00	0.00	0.00
11	0.22	0.00	27.84	9.22	2.98	53.49	6.26	0.00	0.00	0.00
10	0.00	0.00	21.51	13.65	2.81	51.23	7.42	0.00	0.00	3.37
9	0.85	0.00	57.78	8.07	3.52	25.76	4.03	0.00	0.00	0.00
8	2.52	0.00	12.24	41.33	3.92	14.96	19.74	0.00	0.00	5.28
7	58.7	0.00	21.55	12.08	3.94	0.92	2.81	0.00	0.00	0.00
6	0.18	0.00	28.22	28.33	10.74	12.91	19.61	0.00	0.00	0.00
5	0.19	0.00	28.87	34.44	4.59	1.75	30.15	0.00	0.00	0.00
4	9.08	0.32	65.15	2.15	4.45	18.01	0.84	0.00	0.00	0.00
3	0.00	0.00	25.18	37.49	8.90	4.73	23.70	0.00	0.00	0.00
2	0.00	0.00	23.51	41.23	4.08	14.04	4.85	0.30	0.00	0.00
1	0.00	0.00	28.18	58.90	4.77	1.90	6.25	0.00	0.00	0.00

Colour figure (print: author charge applies - please contact the Editor for cost details)

Click here to download Colour figure (print: author charge applies - please contact the Editor for cost details) Hofstadir map

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Figure 3

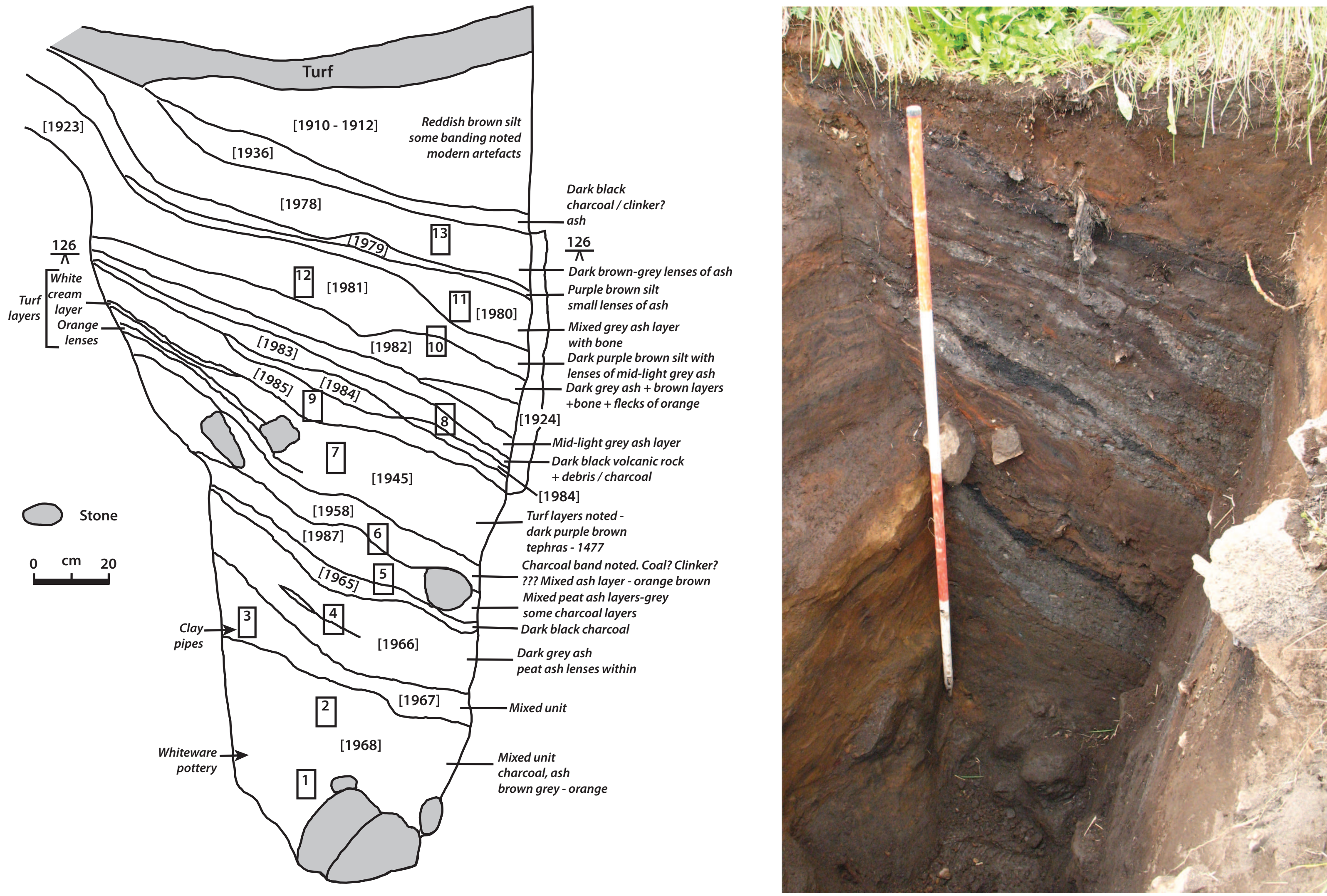

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Figure 4

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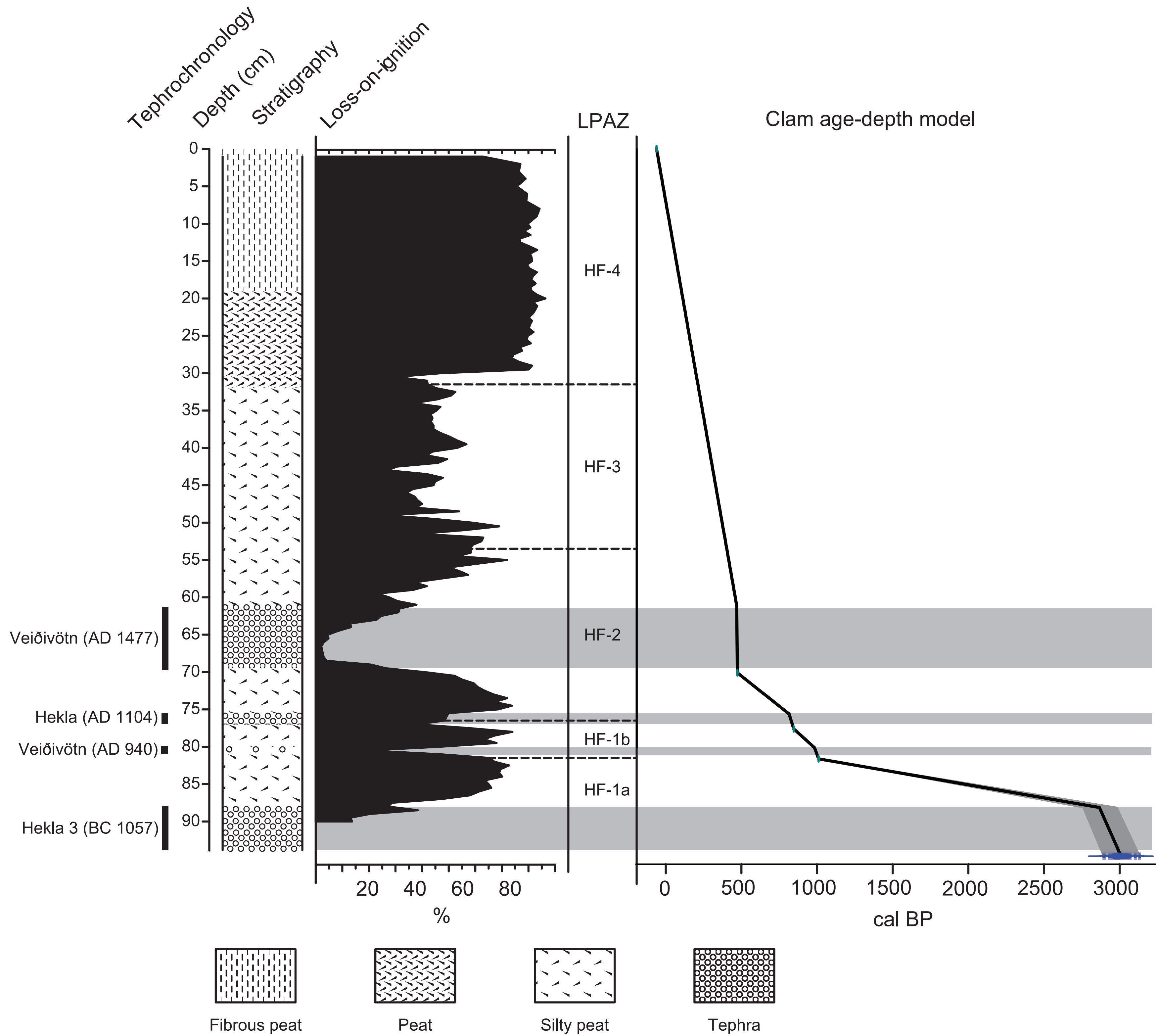

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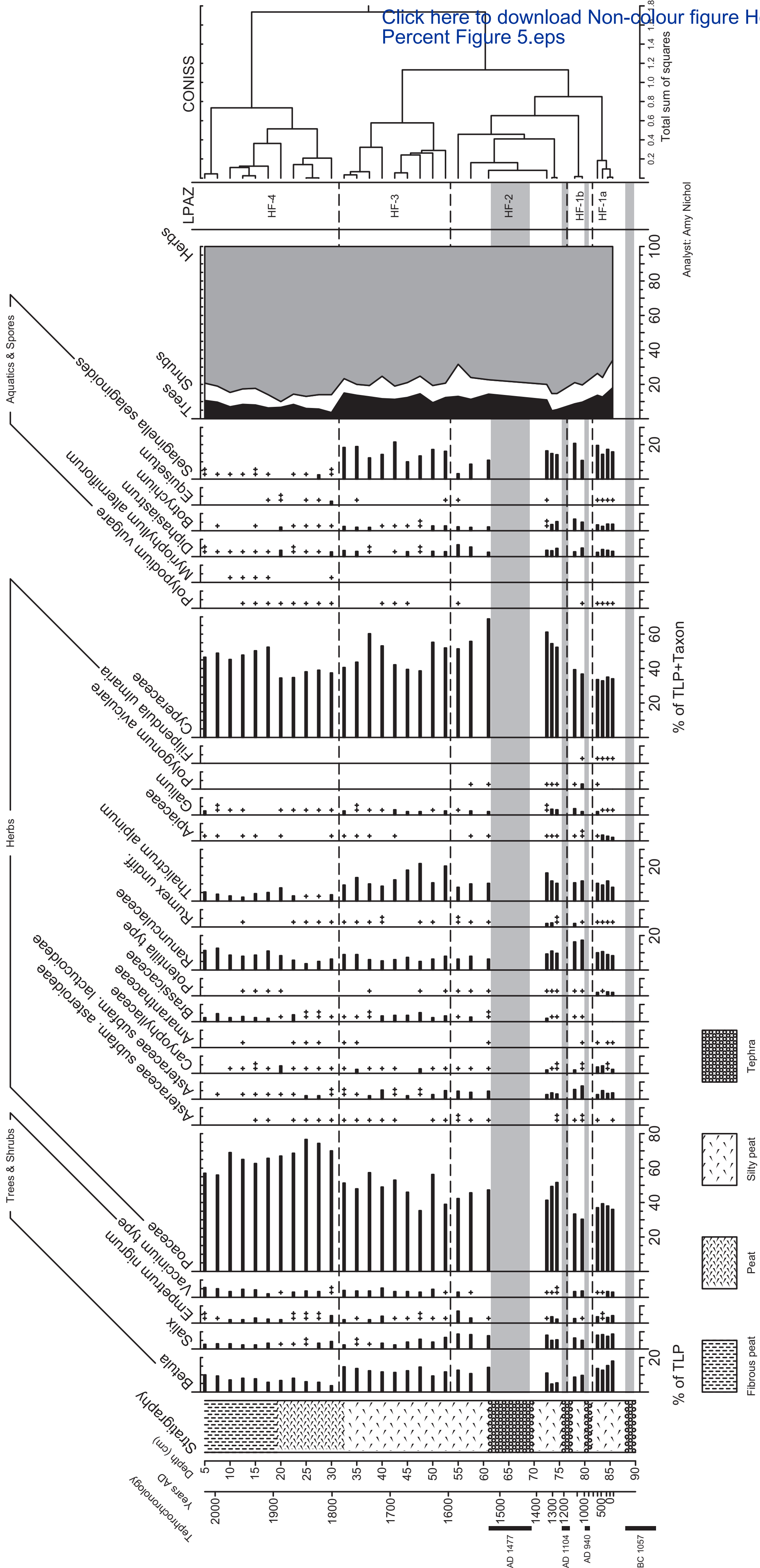
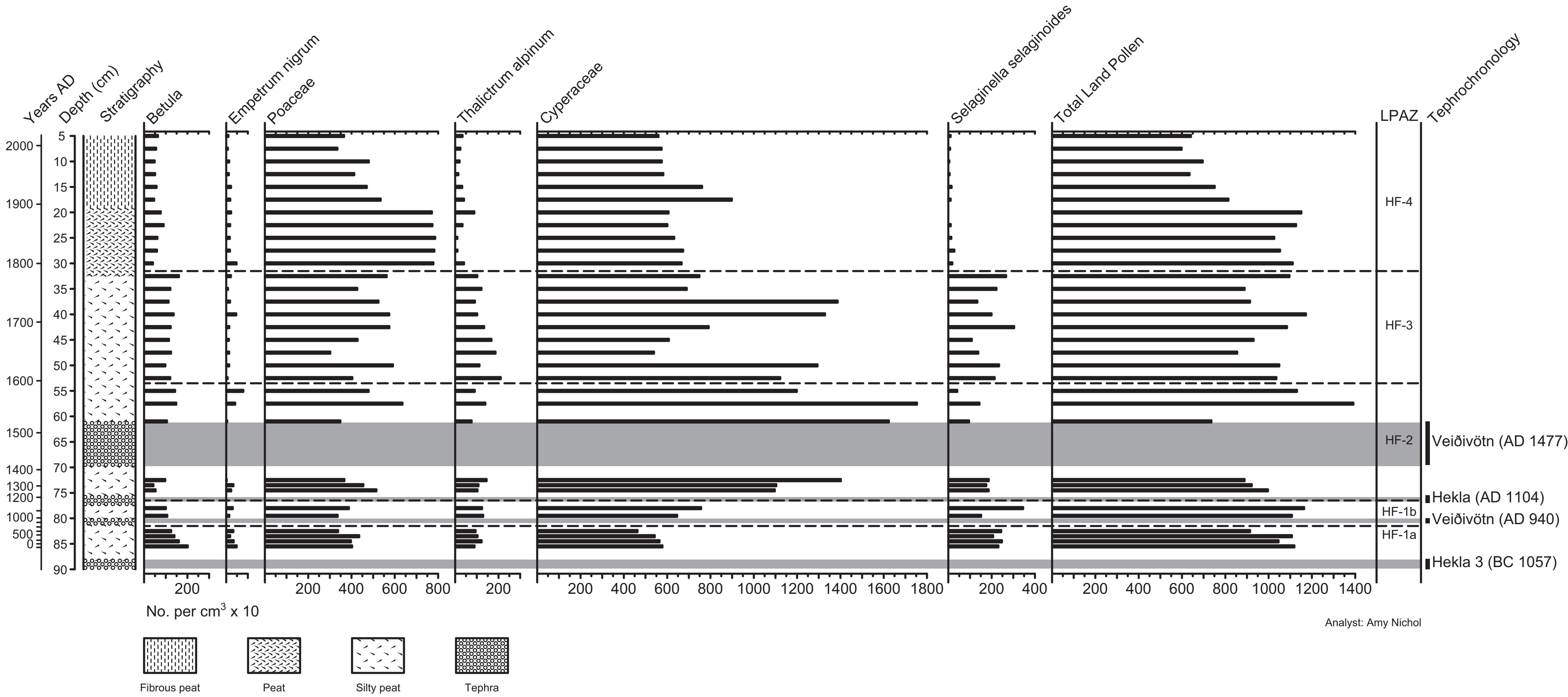


Figure 6

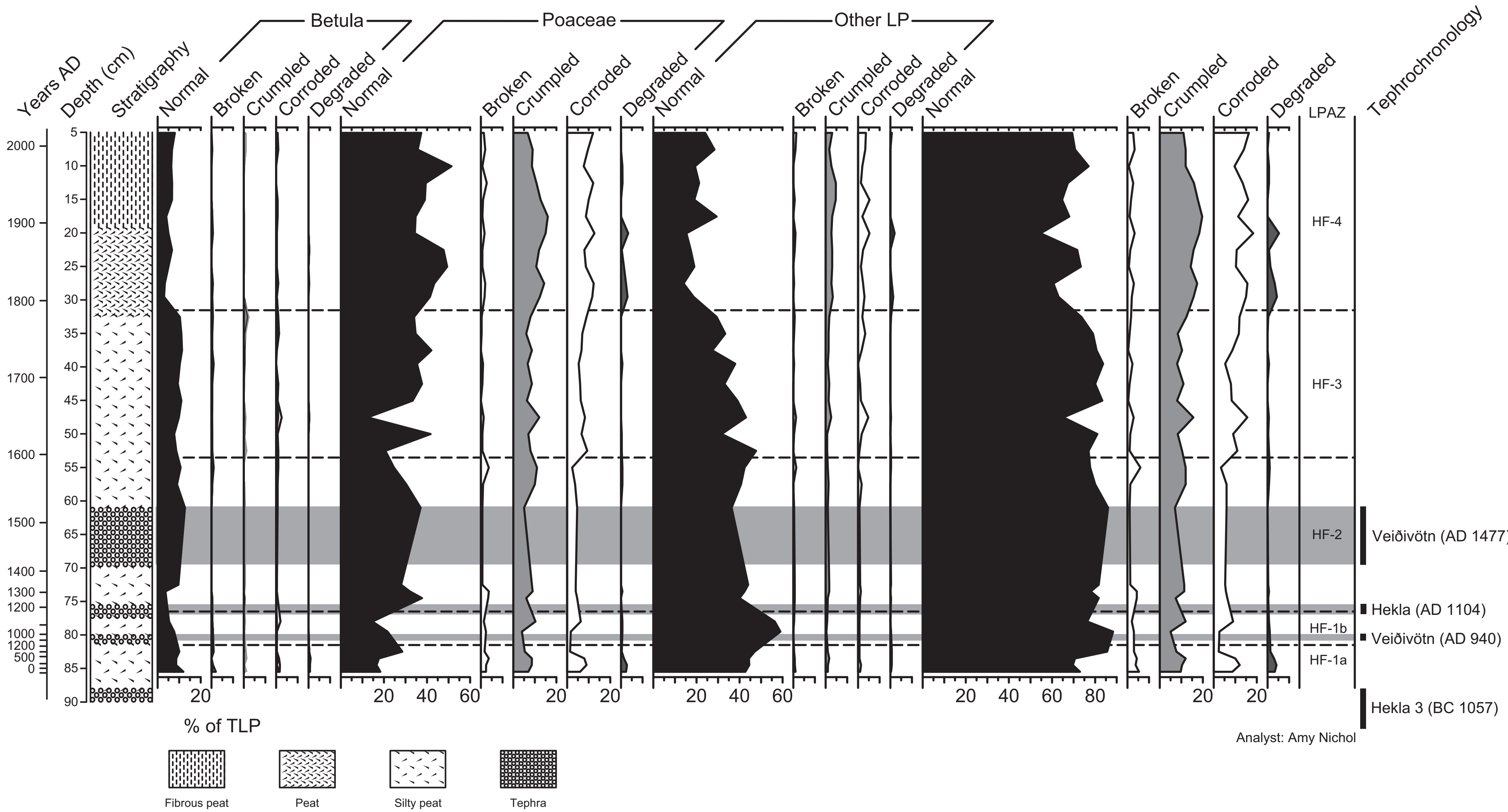


Years AD
Depth (cm)
Stratigraphy
Betula
Empetrum nigrum
Poaceae
Thalictrum alpinum
Cyperaceae
Selaginella selaginoides
Total Land Pollen
LPAZ
Tephrochronology
HF-4
HF-3
HF-2
HF-1b
HF-1a
Veiðivötn (AD 1477)
Hekla (AD 1104)
Veiðivötn (AD 940)
Hekla 3 (BC 1057)
No. per cm3 x 10
Analyst: Amy Nichol
Fibrous peat
Peat
Silty peat
Tephra

Non-colour figure

Click here to download Non-colour figure Hofstadir pres Figure 7.eps

Figure 7



Ref.: ENV265
Palaeoenvironmental evidence for woodland conservation in northern Iceland from settlement to the 20th Century.
Environmental Archaeology: The Journal of Human Palaeoecology

Dear Editor

Please find listed below the comments from the reviewer. The grammar and spelling errors have been corrected and these are shown in the track changes to the document below. The corrections have also been made to the diagrams.

The manuscript has also been reviewed for consistency in the spacing after numbers as well as with the use of capitals.

P3 l 2 comma after economy
P3 l 29 comma after record
P3 l 30 comma after onwards
P4 l 23 sp should not be italisized (and spp if more than one species)
P4 l 25 one Hierachium species or more? (see above)
P4 l 26 comma after closing bracket (the bracket should not be italisised)
P4 l 32 to P5 l1 suggest alter to ...70-120 cm. The uppermost part (0-30 cm) was sampled by...

P4-p5 still no mention of how the cores were spliced together to ensure a continuous sequence, e.g. simply on the basis of depths or if identical stratigraphic units in the different cores could be used to connect the different core segments to ensure continuity. You should say how this was done and preferably provide data in support.

Additional clarification has been provided in this section.

P 5 l 10 space between 1 and cc
P 5 l 12 space between 88 and cm. There are numerous incidents like this throughout the text. Need to go through the whole document to ensure consistency.
P 5 l 16 It is customary to provide the batch number and number of tablets added.
P 5 l 23 "full interpretation of landscape vegetation change" is perhaps too bold statement. Downscale?
P 7 l 18 Tephrochronology (like in Figure) - need to ensure consistency in the use of this word throughout tables, figures and text P 7 l 23 Based on linear interpolation?
P 7 l 26 For the area, rather than site?
P 8 l 10 supports rather than confirms
P 8 l 23 Ranunculaceae
P 8 l 24 Apiaceae (see e.g. Bennett) rather than the (I think) outdated Umbelliferae P 8 l 29-30 No, they don't really go much below 15%. Should rather say that decline in birch over this period is seen in both the percentage and concentration data.
P 9 l 4 aviculare (this applies elsewhere) P 9 l 5 Ranunculaceae (this needs amending elsewhere in the text) P 9 l 6 Apiaceae (but see above) P 9 l 13 Brackets, no fullstop. In general need to decide how to present the subheadings.
P 9 l 15 Veiðivötn
P 9 l 22-23 Better than what? And this change of course began before the tephra fall!
P 10 l 8 …throughout the zone, such as Ran….

P 10 l 9-11 Amend the sentence with comma(s) and/or fullstop(s) P 12 l 29 intensively P 13 l 25-26 Árni Magnússon

There is an overall need to improve consistency in the use of capital letters There is an overall need to improve whether to have space between numbers and symbols/units (e.g. 24 m / 24m, 15% / 15 % etc...). Perhaps best to consult with the editorial office about what the journal prefers.

In the results there is a tendency to spend much attention to what is happening within the pollen zones (which is often quite minor). This muddies the water. The zones are defined on the basis of sample homogeneity (comparable samples grouped together in a zone) and the emphasis really should be about what changes between zones, not within them. This should help prevent over-interpretation of data.

It was felt by the authors that this would entail a major rewrite of the results section and was perhaps not appropriate at this stage of the submission process.

Figure 4: The symbol used for tephra should be consistent with that used in Figs 5 and 6. Wouldn't it be nicer to have an age-axis alongside the graph like is done for figs 5 and 6?
Figure 5: Myriophyllum alterniflorum. Ideally rules/conventions in how Latin names are written (re. italics) should be used in figures as well as text. Some of the values (especially on the Y-axes) have very small letter size (applies elsewhere too).
Figure 6: Selaginella selaginoides

I would like to thank the reviewer for taking the time to review our manuscript and I hope that we have been able to reply to their comments satisfactorily.

Yours sincerely
Eileen Tisdall

Formatted: Left

Palaeoenvironmental evidence for woodland conservation in northern Iceland from settlement to the 20th Century.

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Key words; Iceland, woodland, fuel, pollen, soil micromorphology

Abstract

Narratives of Norse arrival in Iceland highlight the onset of land degradation and loss of woodland cover as major and long-term environmental consequences of settlement. However, deliberate and sustained land resource management in Iceland is increasingly being recognised and in this paper, we assess whether woodland areas were deliberately managed as fuel resources. Our study location is the high status farm site at Hofstaðir in northern Iceland. A palynological record was obtained from a small basin located just inside the farm boundary wall and the geoarchaeological record of fuel use obtained from waste midden deposits associated with the farm. Both environmental records are temporally constrained by tephrochronology and archaeological records. When viewed within the broader landscape setting, our findings suggest that there was near continuous use of birch wood from early settlement to the present day, that it was actively conserved throughout the occupation of the site and that there were clear distinctions in fuel resource utilisation for domestic and more industrial purposes.~~ that increased over time~~. Our analyses open discussion on the role of local woodlands and their management in the Norse farm economy.

Introduction

The Norse settlers of the 9th and 10th centuries brought with them farming practices from Norway and the Northern Isles which were adapted for the use in the newly settled regions of the North Atlantic. The farm structure of communal rangeland, seasonal shielings, out fields for winter grazing, ~~and~~ enclosed home fields for cereal production (where possible), ~~and~~ hay production and aftermath grazing, indicate exploitation of a range of resources at farm and landscape scale (Edwards *et al.* 2005; Simpson *et al.* 2002; Vésteinsson *et al.* 2002). Archaeological, geoarchaeological and documentary evidence suggest that Norse farmers in the North Atlantic employed a range of management approaches including irrigation (Adderley and Simpson 2006), manuring recipes and practices (Buckland *et al.* 2009, Golding *et al.* 2014) and restricted seasonal usage of grazing (Simpson *et al.* 2004; Brown *et al.* 2012). Such approaches point to the knowledge of how to both manage resources effectively and maximise productivity during periods of environmental change (Simpson *et al.* 2004). Woodland and timber products would have been an important resource in the Norse farm economy with the need to balance demand and availability in regions where woodland resources would have been marginal. Iceland offers the opportunity to examine the role of woodland in the Norse farm economy, in particular the role of woodland resources for fuel and to further explore ideas of resource management within farms.

Norse settlers arriving in Iceland at *c.* AD 870 cleared woodland for farmland and grazing as well as fuel use for a range of domestic and industrial activities (Trbojevic 2016). Traditional narratives outline the rapid decline of Icelandic woodland cover associated with settlement (Hallsdóttir 1986). Extensive soil erosion and land degradation has been associated with this rapid change in vegetation cover (Dugmore *et al*. 2000, 2009; Vickers *et al*. 2011; Eddudóttir *et al*. 2016). Vegetation records show that within Iceland the picture is more complex in terms of the nature and rate of change in woodland during the Holocene (Erlendsson and Edwards 2009; Eddudóttir *et al*. 2015, 2016) and post settlement (Lawson *et al*. 2007; Erlendsson *et al*. 2009; Streeter *et al.* 2015). Palaeoenvironmental evidence indicates that woodland clearance may have been phased (Church *et al*. 2007) and that it was a managed resource (Simpson *et al*. 2003). When examined at farm scale the impact of soil erosion and land degradation also varies (Simpson *et al*. 2004; McGovern *et al*. 2007; Gísladóttir *et al*. 2010). This complexity in the records of environmental change in Iceland post settlement requires that palaeoenvironmental data sets reconstruct local farm scale variations as well as develop the regional, wider spatial scale evidence.

Mývatnssveit is an inland region of northern Iceland around Lake Mývatn (Figure 1), the farm at Hofstaðir sits on a lava flow terrace above the River Laxá which flows out of Lake Mývatn (Figure 1). The archaeology at Hofstaðir has been investigated since 1908 and extensive archaeological and palaeoenvironmental investigations in the surrounding area (McGovern *et al*. 2007) have been on-going since 1991. Some of key archaeological features and structures are shown in Figure 2. The archaeological data suggest a specialised use for the aisled hall (Figure 2) at Hofstaðir, summer feasting, with the hall in use between AD 940-AD and 1030-1070 (Lucas and McGovern 2008; Lucas 2009). The archaeological record, supported by written evidence from AD 1477 onwards, suggests continued use and occupation of Hofstaðir from AD 940 up to the present day (Batt *et al*. 2015; Lucas 2009), with the modern farm moving to its location in AD 1950 (Figure 2). Simpson *et al*. (2003)

suggest that the record of fuel residues identified from within the pit house midden (AD 945 – AD 1030; Figure 2) show a mixture of domestic and industrial use of fuels. The persistence and increased use of wood as a fuel during the period of time associated with the use of the hall led Simpson *et al*. (2003) and Vésteinsson and Simpson (2004) to propose that woodland was being managed in the local area.

A vegetation record from Lake Helluvaðstjörn (Figure 1; Lawson *et al.* 2007) suggests that woodland cover in the Mývatnssveit area was extensive and persisted during early settlement supporting the idea of wood fuel readily available during the early phase of settlement. However, this record indicates that woodland cover was reduced to the present day sparse coverage by *c.* AD 1300. The archaeological record points to continued occupation and farming activity at Hofstaðir but it's not clear if wood fuel continued to be used at the farm. The palaeoenvironmental data presented here aims to provide evidence of what fuel types were used and using a local vegetation record provide a basis to explore the continued management of local woodland resources at Hofstaðir.

Methods

Present day vegetation across the farm is rough grazing grassland in the home field areas with dwarf shrub vegetation (*Betula nana*, *Vaccinium uliginosum* and *Empetrum nigrum*) on slopes above the farm. Below the farm and along the steep slopes to the river the vegetation is dominated by willows (*Salix lanata* and *S. phylicifolia*), with a few tree birches (*Betula pubescens*) (Figure 2), and associated tall herbs (*Geum rivale, Angelica archangelica, Alchemilla mollis, Ranunculus* spp., *Geranium sylvaticum*). A series of small, well-defined mires lie just below the steep slope above the river (Figure 2). The mires are dominated by herbs (*Coeloglossum viride*, *Bistorta vivipara*, *Hieracium* sp., *Eriophorum angustifolium*, *Cardamine pratensis*, *Bartsia alpina*, *Potentilla erecta*, *Equisetum palustre*) grasses and sedges. The pollen site is located on one of these mire sites (N 65° 36.781; W 017° 09.862, 233 m asl) just inside the Medieval farm boundary wall (Figure 2), the basin is small, 26 m x 24 m, in diameter. The small, well-defined basin means that the pollen source area is likely to be dominated by local inputs with much of the pollen sourced from the mire surface itself and the steep rocky slopes above the site. The pollen core was taken using a 50 cm x 5 cm Russian corer to a depth of 120 cm, cores taken were 10-60 cm, 50-100 cm, 70-120 cm. The

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uppermost part (0-30 cm)~~, 0-30 cm~~ was sampled by digging a shallow section. The cores were wrapped in the field, transported to the University of Stirling and stored at a constant 4°C.

Core sediment stratigraphy was described using a modified Troels-Smith description (Aaby and Berglund 1986). Sediments were described both in the field and in the laboratory prior to pollen sub sampling. Core correlation, to ensure a continuous sediment record for pollen analysis, was established using sediment depths and the stratigraphic units (in particular the tephra units) within each core. Organic content was determined by loss-on-ignition at 550°C for 4 hours (LOI_{550}) and carried out at a contiguous 0.5 cm sampling interval. ~~Core correlation was made using sediment stratigraphy and LOI_{550} values.~~

Sub-samples of 1 cc were taken from organic-rich stratigraphical horizons from the pollen core, avoiding tephra rich material. The pollen analysis does not include the top 5 cm of the turf mat and starts at 86 cm depth, above a tephra layer noted at 88 cm. The sub-samples were prepared ~~in the Palaeoecology Laboratory~~ at the University of Stirling using standard pollen preparation procedures (Moore *et al*. 1991). To enable the assessment of the total concentrations of pollen in each sample, one tablet~~s~~ containing *Lycopodium clavatum* spores of known concentration (Batch number 3862) was~~ere~~ added to each sample and the spores counted alongside the fossil pollen (Stockmarr 1971). Pollen was identified using an Olympus BX41 light microscope at ×400 magnification with critical identifications made at ×800 and assisted by a pollen reference collection and photomicrographs (Moore *et al*. 1991), nomenclature for pollen and spores follows Bennet (2009). Flora nomenclature follows Kristinsson (2010). Each sample was found to be polleniferous and the pollen identified to a total land pollen (TLP) sum of ≥ 300. Cyperaceae pollen grains were excluded from the TLP sum to reduce the local mire signal and allow for the ~~full~~ interpretation of landscape vegetation change. The pollen data are presented using Tiliagraph (Grimm 1992) and local pollen assemblage zones (LPAZ) established through CONISS (Grimm 1987). Tree birch (*B. pubescens*) and dwarf birch (*B. nana*) pollen grains were differentiated based on the diameter of well-preserved *Betula* pollen grains (Caseldine 2001; Lawson *et al*. 2007). The *Betula* pollen grain size frequency showed a bimodal distribution with peaks in grain size at 15 µm and 18.75 µm. The difference between the modal values are small when compared to other published Icelandic *Betula* pollen grain diameters (Barclay 2016) and so this information cannot be used to confidently differentiate between species of *Betula*.

To provide information about the depositional environment of the pollen each grain was assessed for its state of preservation using five categories; normal, broken, crumpled, corroded and degraded (Berglund and Ralska-Jasiewiczowa 1986; Tipping 1987). Grains that are broken and/or crumpled are likely to indicate damage due to mechanical processes such as through abrasion during transport. Pollen is best preserved in waterlogged (anaerobic) and acidic conditions and so corrosion and degradation suggest chemical processes whereby pollen is 'digested' by microbial activity under drier aerobic conditions.

Soil micromorphology

Excavations in 2010 at the cemetery and church site within the farm mound (Figure 2) revealed a large pit over 3 m deep containing a stratified sequence of midden deposits (Figure 3). Initial field interpretations identified fuel ash residues from mineral based turf, peat, wood charcoal and coal/clinker deposits. Thirteen undisturbed samples were taken from the midden stratigraphy (HST10) in 7.5 x 5.5 cm Kubiena tins (Figure 3). The samples were prepared at the University of Stirling. Simpson *et al's*. (2003) ~~conducted~~ micromorphological investigations into immediate post settlement fuel use at Hofstaðir ~~and~~ developed a set of fuel residue reference slides.~~,~~ T~~t~~hese slides were used to define the following fuel residues peat (800°C and 400°C), turf (800°C and 400°C), dung (800°C and 400°C), seaweed (800°C and 400°C) and wood (800°C and 400°C) including *Betula pubescens* and *Salix* sp. In addition, clinker residues were identified from type slides shown in McKenzie (2006, p 281-282). Criteria for fuel type residue categorisations were based on rubification, mineral content, presence and abundance of diatoms and phytoliths, size and shape of feature (Stoops and Vepraskas~~,~~ 2003). The recording of fuel type residue data followed methods outlined by Stoops and Vepraskas (2003). Care was taken to identify the fuel residues as they were mixed with other non-fuel midden materials.

A methodological approach was developed during this analysis to record and quantify fuel residues within the thin section slides. A 5 mm^2 square grid was drawn onto the reverse of the glass slides. The proportion of fuel residue within each cell was recorded as a percentage, if more than one fuel type was present the proportion of each was recorded. The proportions were estimated using a feature abundance scale as detailed in Stoops and Vepraskas (2003). Each slide contained 187 cells, data are presented as the percentage proportion of each fuel type in the slide.

A relative chronology was established for the sequence of midden deposits sampled. White ware pottery and clay pipes were recovered from the base of the profile and were dated to the mid-18th century (Figure 3). At the top of the profile a number of modern artefacts were recovered including plastics (Figure 3) providing a 20th century date for the top of the profile.

Results and analysis

Pollen core stratigraphy and chronological framework

The pollen core sediments consist of silty peats and peat and are described in Table 1. Within the silty peats are four well defined minerogenic units that are identified in sediment description (Table 1) as well as in the LOI_{550} data (Figure 4). These units are airfall deposits of tephra. Fluvial inputs from the river (3-4 m below the site) have not been identified.

Simpson (2009) and Lawson (2009) present a tephro~~a~~chronological framework based on the tephras recorded and described within the soils at Hofstaðir both within the homefield and archaeological contexts. This framework was based on the sequence of tephras developed for the region by Sigurgeirsson (1995, 2001) and is used to constrain the vegetation record presented here. The pollen core was sampled in AD 2011 (=0 cm). An age depth model for the pollen core was generated in Clam Version 2.2 (Blaauw 2010), Figure 4.

The pre settlement soil accumulation rate (SAR), between 345 BC and AD 940 is low around 0.03 mm/yr^{-1} but is comparable to rates published for the Hofstaðir farm area ~~site~~ (Simpson 2009). Post settlement SAR rises to around 0.18 mm/yr^{-1} (AD 940- AD 1104) and around 0.16 mm/yr^{-1} (AD 1104-1477) again values are comparable to those published for the area ~~site~~. It is post AD 1477 to the present day that the SAR value is high at around 1.14 mm/yr^{-1}

however, the SAR may be distorted by the accumulation of fibrous peat from around 30 cm (Table 1; Figure 4) which is thought to have accumulated rapidly.

Vegetation History

Local pollen assemblage zones (LPAZ's) within the main pollen diagram (Figure 5) were defined using CONISS. Pollen concentration values for selected taxa are shown in Figure 6. Pollen preservation was overall very good with low proportions of broken, crumpled, corroded and degraded pollen (Figure 7). There were slight increases in pollen grain damage above some of the tephra layers but the changes were minimal. The limited nature of variation in pollen preservation indicates that there have been no change in conditions that would affect preservation such as a drying out of the mire surface and there is no indication of pollen reworking or input from reworked sources. This supports~~confirms~~ the interpretation that the pollen sources for this pollen profile are dominated by local pollen sources.

The pollen evidence reflects a local vegetation record with relatively stable vegetation cover dominated by Poaceae, herbs and Cyperaceae with low amounts of *Betula* and *Salix* in the immediate area. The main vegetation changes post settlement reflect the amount of woodland taxa and grazing around the site rather than a clear response to climate.

LPAZ HF-1a (*c.* 345~~54~~ BC to AD 940).

The pollen assemblage in this sub-zone represents the pre-settlement vegetation. *Betula* (18%) and *Salix* (10%) percentages indicate the presence of woodland taxa growing on the drier upper slopes. Poaceae (35-38%) and grassland herb taxa such as *Thalictrum alpinum* (8-10%), Ranunculaceae (8-10%) and Asteraceae sub fam. Lactucoideae (5%), with Apiaceae~~Umbelliferae~~ and *Filipendula ulmaria* indicating~~e~~ open areas of herb rich grassland. *Selaginella selaginoides*, *Botrychium* and Cyperaceae (40%) suggest that the open grassland is a wet grassland. Heathland taxa, *Empetrum nigrum* and *Vaccinium* type are present in this zone (<5%). Percentage values for these heathland taxa rarely go above 5% throughout the diagram suggesting that within the pollen source area this vegetation type is present but not dominant. At the end of the sub-zone *Betula* percentage values decline (10%) this decline is seen in both the pollen percentage and ~~and this is also reflected in the~~ pollen concentration values (Figure 6).

LPAZ HF-1b (AD 940 to AD 1104).

The vegetation in this sub-zone is associated with the early period of settlement at the farm. The percentage values for *Betula* and *Salix* decline further, this is also recorded in the pollen concentration values (Figure 6). Herbs associated with disturbed ground such as Brassicaceae and *Polygonum aviculare~~ia~~* appear in this zone and open grassland apophytic taxa such as ~~Ranuculaceae~~Ranunculaceae (17%), *Galium* (5%), Asteraceae sub fam. Lactucoideae (8%) and *Thalictrum alpinum* (15%) increase. Taxa that are intolerant to grazing such as Apiaceae~~Umbelliferae~~ are reduced (Vickers *et al*. 2011; Zori *et al*. 2013) and *Filipendula ulmaria* disappears from the record and does not return. Poaceae percentage values remain at 35% and Cyperaceae values show a slight increase in pollen percentages and a large increase in pollen concentrations. *Selaginella selaginoides* and *Botrychium* spores also increase, indicating an open, sedge rich grassland that allows for greater spore dispersal.

LPAZ HF-2 (AD 1104 to *c.* AD 159~~5~~0).

Vegetation in this zone is associated with later settlement at the farm, and prior to the Veiðivöt~~e~~n AD 1477 tephra layer, is very similar to that recorded in the previous zone. At the beginning of the zone tree and shrub taxa values are low (<5%), grasses (40-50%) and apophytic herb taxa *Thalictrum alpinum* (15%) and ~~Ranuculaceae~~Ranunculaceae (10%) dominate. Other taxa such as Asteraceae sub fam. Lactucoideae, *Galium* and Brassicaceae are present. Cyperaceae increases in both pollen percentage (60%) and concentration values. However, just before the tephra fall at AD 1477 and then after the tephra layer percentage values for both *Betula* and *Salix* begin to rise (to 15% and 8% respectively), similar to pre settlement values. This rise in *Betula* is also recorded in the pollen concentration values perhaps reflecting the ~~better~~ ability of these tree species to survive tephra airfalls (Arnalds, 2013). The percentage values for Poaceae remain at between (40-50%), while many of the dominant herb taxa decline with species such as *Polygonium* *~~avicularia~~aviculare* disappearing from the record. Percentage values for Cyperaceae also increase (65%) in this zone and reach their highest both in terms of percentage and concentration values. *Selaginella selaginoides* and other spores decline towards the top of the zone suggesting that the landscape around the pollen site was less open.

LPAZ HF-3 (*c.* AD 15950- *c.* AD 17940).

Betula percentage values are maintained between 10-15% along with higher concentration values throughout the zone. *Salix* percentage values gradually decline during the zone with only trace amounts recorded by the end of the zone. Percentage values for Poaceae (35-58%) and Cyperaceae (45-70%) are variable throughout the zone and this is also reflected in the pollen concentration values (Figure 6). *Thalictrum alpinum* (10-20%) is the most dominant grassland herb taxa showing a notable increase in both percentage and pollen concentration values (Figure 6). Other apophytic herb taxa are present and persistent throughout the zone, such as, RanuculaceaeRanunculaceae (5-10%), Brassicaceae (5%), *Galium* (<5%) and Asteraceae sub fam. Lactucoideae (5%). *Selaginella selaginoides* spores increase (15-20%) the increase is also recorded in the concentration values., Oother spores such as *Diphasiastrum* and *Botrychium* are present throughout the zone. The dominance of grazing tolerant taxa, such as *Thalictrum alpinum*, *Galium* and *Selaginella selaginoides*, alongsideand the decline of grazing sensitive taxa, such as *Salix*, during this zone suggest that grazing, perhaps intensive, helped to maintain the open damp grassland (Erlendsson *et al*. 2009; Vickers et al. 2011; Riddell 2014).

LPAZ HF-4 (*c.*AD 17040- Presentc. AD 1970).

This pollen zone records the vegetation associated with the most recent occupation at the farm. This zone is marked by a decline in tree and shrub taxa. Poaceae pollen values increase to the highest values noted in the diagram to 60-80%, this increase is also recorded in the pollen concentration values. *Thalictrum alpinum* percentage values fall in this zone to <5%, this decline is also recorded in the concentration values. Other herb taxa such as Brassicaceae, Asteraceae sub fam. Lactucoideae and *Galium* remain present with a small increase in Ranunculaceae to 10-12%. Cyperaceae rises to around 50% at the top of the zone but this rise is not seen in the pollen concentration values. *Selaginella selaginoides* values fall with the species only recorded as present, this decline is also recorded in the pollen concentration values. The decline in *Selaginella selaginoides,* which is intolerant of tall vegetation (Kristinsson 2010), as well as *Thalictrum alpinum* suggests the grassland was a dense tall sedge rich sward rather than a short-cropped open grassland.

Fuel resource record

Table 2 indicates the range of fuel types used at Hofstaðir from the mid-18th to the mid-20th c~~C~~entury. The fuel types are also noted to have been combusted at two different temperature ranges indicating fuels are used for domestic and industrial purposes. From the fuel data (Table 2) is it noted that dung is very rarely used as a fuel type and seaweed is not used at all. Peat is used occasionally and most notably ~~it is~~ recorded as 58.7% in s~~S~~lide 7, where its use appears to replace all the other fuel types in particular wood and is noted to be a product of high temperature combustion. Turf and wood are the most common fuel type with variable amounts but they remain in use up to the mid-20th century. Turf and wood are used for both low and high temperature combustion with no one fuel type favoured for a specific activity that is domestic or industrial use. There is an indication toward the top of the profile in s~~S~~lides 10, 11 and 12 that wood is used for high temperature combustion, which is industrial use and is used in place of turf and peat. Shrub and heather are present throughout but at levels of between ~ 3 and 10%. Coal is only present in two samples at low percentages (s~~S~~lide 8, 5.28% and s~~S~~lide 10 3.37%) and is not common.

Discussion

The vegetation record presented here suggests open low density woodland cover within the Hofstaðir farm boundary at pre settlement. The steep slopes that are either side of the River Laxá below the Hofstaðir farm would probably have consisted of low density tree cover and areas of wet grassland. This may have made this an attractive area for settlement. Although within the farm these steep slopes represent a narrow strip of land it is laterally continuous and would have represented valuable grazing and perhaps fodder sources (McGovern *et al*. 2007). Regional pollen records close to Hofstaðir at Helluvaðstjörn (Lawson *et al*. 2007) and Gautlönd (Barclay, 2016) (Figure 1) indicate that pre-settlement and ~~during~~ early settlement woodland cover was regionally more extensive and of higher density than the local scale woodland recorded at Hofstaðir. Tisdall and Verril (2010) record large amounts of *Betula* pollen from a floor fill at Sveigakot farm (Figure 1) again indicating that at settlement *Betula* was regionally widespread and perhaps as at Sveigakot, used for both fodder and fuel use. At Hofstaðir it is suggested that at settlement, the woodland cover may have been extensive on the higher ground above the farm and to the south around Helluvaðstjörn (Figure 1) and that woodland resources would have been widely available. Evidence for wood~~land~~ used as fuel both in terms of domestic and industrial use during early settlement is recorded in the fuel record for Hofstaðir, by ~~(~~Simpson *et al*. (2003). The archaeological record suggests that a smithy at Hofstaðir was in use between AD 940 and AD 1030 with evidence of expansion and specialist metalworking around AD 980 (Lucas 2009). Charcoal pits recorded close to Hofstaðir at Hrísheimar (Figure 1) date to the 12th century (Church *et al*. 2006). Therefore, from early post settlement until the 12th century wood, as a resource, was widely available and was used at Hofstaðir for both domestic and industrial use including specialist metalworking.

Lawson *et al*. (2007) have described the post settlement regional woodland decline as gradual and episodic with some recovery in *Betula* woodland noted in the pollen record, with the very low woodland cover seen today apparent from around AD 1300. The local pollen record presented here suggests a similar post settlement decline but from AD 1477, there is a recovery of local woodland with *Betula* pollen levels close to pre-settlement levels. As highlighted above, this recovery in woodland at Hofstaðir may be in part an advantageous response to the tephra airfall. At this time grassland herb taxa suggest an open, close-cropped sward. We interpret from the Hofstaðir pollen record that the woodland cover was being maintained or managed at low density from around AD 1477 to *c.* AD 1740, with the management of the local woodland cover taking place during a period associated with evidence for intensive grazing. Simpson *et al*. (2003) proposed woodland management during early settlement at Hofstaðir (*c.* AD 940 – AD 1070). Here it is suggested that the management of local woodland resources at Hofstaðir persists until *c.* AD 1740, ~~at Hofstaðir~~ against a background of widespread, regional woodland decline.

During the subsequent phase of low-density woodland (*c.* AD 1740-1970) the mire surface was dominated by a dense, tall sward of grasses and sedges, enough to shade out taxa associated with open habitats. The change in vegetation suggests that grazing intensity has been reduced allowing the wet grassland species to dominate. This grassland, grown for fodder, may have been cut after the grasses have flowered (Broström *et al*. 2008) rather than the intensively grazed grassland as noted previously. Alternatively, the grazing regime on the mire surface may reflect a reduction in grazing (the removal of grazing animals) allowing for an increase in the sward density of the grasses and sedges (Edwards *et al*. 2004).

Within the documentary records~~,~~ the 18th century in Iceland is a period of general economic decline~~,~~ with major setbacks including a s~~S~~mall p~~P~~ox epidemic in 1707 and nationwide famines in the 1750s and 1780s (Hanson 1928). The local and long-term impacts of such shocks are difficult to detect (Streeter *et al*. 2012) but the Hofstaðir pollen record is consistent with a picture of long term decline in farm productivity reflected in a reduction in grazing intensity. This period of decline from *c.* AD 1740 is coincident in the stratigraphy with the accumulation of a highly organic, fibrous peat. The accumulation of peat may be a response to the reduced intensity of grazing, an increase in the accumulation of organic matter and increased stability in the landscape leading to reduced aeolian mineral input. The lack of crumpled, corroded and degraded pollen indicates limited input to the site from reworked material (soil) in the catchment. Regionally there is a severe land degradation event in the 16th century associated with a cooler phase of the Little Ice Age (Ólasfdóttir and Guðmundsson 2002), however at Hofstaðir this event is not recorded in the stratigraphy suggesting the local variability in the extent of soil erosion. Dugmore *et al.* (2007) suggest that AD 1740 marks a shift in the unpredictability of climate with increased storminess and cooler temperatures. At Hofstaðir the accumulation of peat on this mire site may reflect a combination of cooler climates, reduced rates of decomposition and reduced grazing intensity.

The record of mid-18th century to present day fuel use, as determined through soil micromorphology, reveals that wood and turf continued to be the main fuel sources for both domestic and industrial activity at the Hofstaðir farm. There is a gap in the fuel use record but the continued emphasis of wood as fuel up until the mid-20~~18~~th century suggests that wood has always been an important fuel at Hofstaðir.

Simpson *et al*. (2003) review the fuel use implications of the Land Register of Á~~A~~rni Ma~~á~~gnússon and Páll Vídalín carried out for Mývatnssveit in 1712. The Land Register record suggests that 83% of farms in the area had access to wood and shrub as fuel resources. It was noted that dung was used where woodland was scarce. The Hofstaðir fuel record generated for the mid-18th century to the mid 20th century ~~present day~~ indicates that wood remains an important fuel resource for the farm, this would suggest that wood is available as a fuel resource. The local pollen record indicates that although there is decline in *Betula* pollen from around AD 179~~4~~0 it persists. The persistence of *Betula* suggests continued management of birch and could have perhaps served as a very local source of wood for fuel at the farm. The fuel resource evidence points to a farm that is still very active in terms of both domestic and industrial use of wood fuel up until the mid-20th century.

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Peat was only burnt once in the Hofstaðir fuel record and seems to have been used for perhaps a single industrial use and this is supported by the l~~L~~and r~~R~~egister records which indicate that peat was rarely used as a fuel. The fuel use data at Hofstaðir indicates that dung was also rarely used for fuel, suggesting that woodland fuel resources were not restricted. The continued use of wood and turf as fuel is against a backdrop of the availability of imported coal from early 17th c~~C~~entury (available in significant quantities from AD 1900) however, coal would have been expensive and here at Hofstaðir it is only recorded as being used very occasionally.

In other regions of Iceland there is additional documentary evidence that suggests that woodland cover was actively maintained into the 16th century (Sigurmundsson *et al*. 2014; Vésteinsson and Simpson 2004) but that the rapid decline of these areas of woodland was due to a lack of management and increase in the intensity of use. For the areas around Hofstaðir the ~~regional~~ pollen data sets show a regional woodland decline by *c.* AD 1300 which would suggest that there was not enough woodland to be sustainable as a fuel resource. However, the fuel use record from Hofstaðir points to the continued use of wood as a fuel for industrial and domestic uses. The pollen evidence from Hofstaðir indicates that the woodland areas that persisted were small, low density and local but that they were maintained often during phases of what is thought to have been intensive grazing. This continuous use of a resource such as wood and the absence of use of fuel such as dung indicate that Hofstaðir benefited from a reliable, sustainably managed woodland fuel source.

Conclusions

The use of two palaeoenvironmental data sets, fuel use and a local pollen evidence provide insights into farm resources at Hofstaðir, a farm that was continuously occupied from around AD 940 to the present day. The fuel resource evidence suggests that wood was an important source of fuel at Hofstaðir during early settlement, and as presented here during the mid- 18th-20~~19~~th century~~,~~ implying the continuous availability of wood as a fuel resource. The pollen record presented here suggests that local woodland resources existed at Hofstaðir, although at a low density and implies the successful management of local and small scale woodland as the likely fuel resource up until the mid-19th century. The widespread regional decline of woodland from around AD 1300 may have focused management of small local resources, the remaining fragments of woodland. These small areas of birch may have been sufficient for domestic farm scale uses but there are questions on the amount of woodland needed to maintain industrial activity, such as noted here at Hofstaðir, these local resources may not have been enough. This suggests that there may have been links to other sources in the region. The data presented here suggests local scale, effective management of woodland resources by Norse farmers, at Hofstaðir such management ensured the continued success of the farm. These findings highlight the need to look at these farm landscapes both at the regional and local scale and that the integration of palaeoenvironmental and archaeological data sets can provide greater insights into how resources are managed at farm scale.

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Figure and Table captions

Figure captions

Figure 1 Location of the study site within northern Iceland, other sites discussed in the text are shown. The green shaded areas on the map are areas of present day scrub/woodland.

Figure 2 Aerial view of archaeological features at Hofstaðir showing the aisled hall structure. The pit house next to the aisled hall (marked with a star) where Simpson *et al*. (2003) sampled for fuel residue research is shown. The location of the 18th- mid 20th century midden site, next to the 11th century farm mound and the early Norse cemetery used for the fuel use research presented here is shown (marked with a star). The pollen site is located above the River Laxá and within the medieval farm boundary wall. The modern farm buildings are the red roofed structures.

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Figure 3 Farm mound midden (HST10). The section drawing shows layers of midden material and location of Kubiena tins (numbered 1-13) used to generate the soil micromorphology thin sections. Archaeological finds used to determine a relative chronology for the soil micromorphology data set are also recorded in the section drawing. The distinctive stratigraphic layering of the midden material is noted in the photograph of the section.

Figure 4 Loss on ignition values, stratigraphy of the pollen core and stratigraphic location of named tephras. The Local Pollen zones are also shown (see Figure 5). Definition of the tephras is based on sediment description and published tephra chronologies for the area (see Table 1). Age depth model constructed using Clam (version 2.2) (Blaauw 2010).

Figure 5 Percentage pollen diagram for Hofstaðir showing selected taxa. The core stratigraphy and local pollen zones are also shown. The tephro~~a~~chronology is based on the tephra descriptions given in Table 1 and age depth model in Figure 4.

Figure 6 Pollen concentration diagram for selected taxa at Hofstaðir. The core stratigraphy and local pollen zones are also shown. The tephro~~a~~chronology is based on the tephra descriptions given in Table 1 and age depth model in Figure 4.

Figure 7 Pollen Preservation data for selected taxa at Hofstaðir following Berglund and Ralska-Jasiewiczowa (1986) and Tipping (1987). The core stratigraphy and local pollen zones are also shown. The tephro~~a~~chronology is based on the tephra descriptions given in Table 1 and age depth model in Figure 4.

Table captions

Table 1 Sediment stratigraphy of the pollen core, including field description of the tephra deposits. The tephro~~a~~chronology is based on the framework outlined in Simpson (2009) and the tephra descriptions given in Ólafsdóttir and Guðmundsson (2002).

Table 2 Proportional fuel residues from the farm mound midden. The values represent each fuel type as a percentage of the total amount of fuel residues recorded within the thin section slide.

Table 1

Depth cm	Sediment description	Tephra Chronology
0-19	Dark brown, fibrous, very poorly humified peat with abundant rootlets and large plant fragments; Th2Dh2.	
19-32	Brown, fibrous, poorly humified peat; Dh4 Sh+.	
32-61	Brown, fine fibrous, silty peat; Dh2Sh1Ag1.	
61-69.5	Very dark brown-black, fine to medium sand; Gmin4 (tephra).	Veiðivötn AD 1477
69.5-75.5	Brown, silty peat with abundant plant fragments; Dh2Ag2.	
75.5-77	Flecks of creamy white silt in brown, silty peat; Ag3Dh2 (tephra).	Hekla AD 1104
77-80	Dark brown, fine fibrous, silty peat; Dh2Sh1Ag1.	
80-81	Grey brown, fine sandy silt; Gmin1Ag3 (tephra).	Veiðivötn AD 940
81-88	Dark brown, fibrous, silty peat; Dh2Sh1Ag1.	
88-94	Pale grey cream, silt; Ag4 (tephra).	Hekla 3 (*c.* 345 BC)
94-100	Dark brown, fibrous, silty peat; Dh2Sh1Ag1.	

Table 2

Slide	Peat (High Temp)	Peat (Low Temp)	Turf (High Temp)	Turf (low temp)	Shrub/ Heather	Wood (High temp)	Wood (Charcoal)	Dung	Seaweed	Coal/Clinker
13	0.00	0.00	6.88	78.35	4.72	6.88	3.17	0.00	0.00	0.00
12	6.17	0.29	27.38	5.01	8.26	45.59	7.29	0.00	0.00	0.00
11	0.22	0.00	27.84	9.22	2.98	53.49	6.26	0.00	0.00	0.00
10	0.00	0.00	21.51	13.65	2.81	51.23	7.42	0.00	0.00	3.37
9	0.85	0.00	57.78	8.07	3.52	25.76	4.03	0.00	0.00	0.00
8	2.52	0.00	12.24	41.33	3.92	14.96	19.74	0.00	0.00	5.28
7	58.7	0.00	21.55	12.08	3.94	0.92	2.81	0.00	0.00	0.00
6	0.18	0.00	28.22	28.33	10.74	12.91	19.61	0.00	0.00	0.00
5	0.19	0.00	28.87	34.44	4.59	1.75	30.15	0.00	0.00	0.00
4	9.08	0.32	65.15	2.15	4.45	18.01	0.84	0.00	0.00	0.00
3	0.00	0.00	25.18	37.49	8.90	4.73	23.70	0.00	0.00	0.00
2	0.00	0.00	23.51	41.23	4.08	14.04	4.85	0.30	0.00	0.00
1	0.00	0.00	28.18	58.90	4.77	1.90	6.25	0.00	0.00	0.00