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Palynological and Geoarchaeological Evidence for Homefield Formation and Management at a High-Status Norse Farmstead, Vatnsfjörður, NW Iceland

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ABSTRACT

Organic-rich soils, developed in-situ over extended time periods, provide an important record of the relationship between societal and environmental change. Here, a palaeoenvironmental record from Vatnsfjörður farm, NW Iceland, one of Iceland's richest by the late Middle Ages, offers new perspectives on land management adaptations as Norse settlers colonised the pristine Icelandic landscape. Integration of field data, soil micromorphology, and pollen analyses, chronologically constrained using tephrochronology and AMS radiocarbon dating, supported by documentary records, provides insights into the management of wet meadows in Iceland. Such meadows were an essential source of sustained fodder production for over-wintering livestock in an environment with a short growing season and limited soil fertility. The wetland at Vatnsfjörður is unusual in that it formed only after settlement and required significant efforts to maintain productivity capable of withstanding climatic and socio-economic downturns that may have supported the settlement's wealth and high status. These findings have wider implications for understanding the emergence of resilient and sustainable communities in agriculturally marginal environments.

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Introduction

Medieval North European agricultural practices were introduced to the pristine sub-Arctic environments of the Faroes, Iceland, and Greenland by Norse settlers. These marginal environments likely necessitated land management adaptations to achieve at least subsistence levels of food production (see, for example, Brown et al. 2012; Golding et al. 2011; Schofield et al. 2022; Simpson et al. 2001; Thomson, Simpson, and Brown 2005; Tisdall et al. 2018).

The traditional North European 'agricultural package' is evidenced in zoo-archaeology and landscape organisation. It included sheep, cattle, goats, pigs, and horses supplemented by marine resources, and communal rangelands for grazing. Also, residential longhouses with an attached byre (cowshed) and several outhouses, shielings (seasonal pasture and associated shelter for people) for milking dairy cattle, outfields for winter grazing and enclosed homefields (Edwards et al. 2005; McGovern et al. 2007; Vésteinsson, McGovern, and Keller 2002). The homefield, the areas of land directly adjacent to the early Norse dwellings, is evident at most early and historical farms in Iceland and was the location for a range of activities, including cereal production in favourable locations (Riddell et al. 2018, 2024; Zori et al. 2013), hay production for winter fodder, and aftermath grazing (Adderley, Simpson, and Vésteinsson 2008; Simpson et al. 2002). With challenging winter conditions in Iceland, the homefield and its management were critical to the sustainability of food resources through its provision of high-quality winter fodder, particularly for dairy livestock (Vésteinsson, McGovern, and Keller 2002).

Studies of sub-Arctic homefields have identified a range of land management practices that developed over time and included manuring 'recipes' using livestock and domestic wastes together with turf to sustain soil nutrient status. Water management through irrigation to offset summer soil moisture deficits at a critical stage in the growing season is also evident. These management practices helped maintain and enhance yields, even under deteriorating climatic conditions (Adderley, Simpson, and Vésteinsson 2008; Adderley and Simpson 2005; 2006; Golding et al. 2015; Simpson et al. 2002). Land management activities have previously only been considered and identified in drier areas of the enclosed homefields and on freely to imperfectly drained mineral-based podsols (Simpson et al. 2001, 2004).

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Here, we present a detailed palaeoenvironmental analysis from an area of wetland within the homefield of the Vatnsfjörður farmstead, in north-west Iceland (Figure 1). At Vatnsfjörður, the homefield soils are generally shallow and considered poorly suited to agriculture (Bolender 2008; Milek 2007). Investigations across the homefield soils at Vatnsfjörður offer some limited evidence of cultural additions to improve the fertility of the otherwise free-draining, nutrient-poor, drought-prone soils typical of the homefield at this farm (Milek 2009, 2011). Despite this, historical documentary sources indicate that the farm was a major power centre for the region, becoming one of the richest Icelandic farms in the Late Middle Ages (Edvardsson and McGovern 2005; Tulinius 2005). The present-day archaeological site at Vatnsfjörður contains the remains of a longhouse dated to the 10th century (Edvardsson and McGovern 2005; Milek 2007), with a series of structures and farm mounds that suggest continuous occupation through to the present day (Isaksen 2012) (Figure 2). The archaeological evidence for substantial and early settlement challenges views that the North-west peninsula was the last area of Iceland to be settled (Edvardsson and McGovern 2005; Tulinius 2005).

Within the enclosed homefield at Vatnsfjörður lies an area of wetland that is presently used as a wet meadow (Milek 2007). Access to an area of wetland is an intriguing element of initial settlement choice in Iceland (Vésteinsson 1998). Wetland areas are vital contributors to farm economies, in particular when there were seasonal fodder shortages (Aldred et al. 2025; Sigurðardóttir et al. 2019), but the role of a wetland situated in a homefield area is under researched. The organic-rich sediments within the Vatnsfjörður homefield present an opportunity to reconstruct the history of the wetland using palaeoenvironmental techniques. Here we present a palaeoenvironmental record based on a synthesis of a pollen record, thin section soil micromorphology, and a robust age-depth model (AMS radiocarbon dating and tephrochronology). With the aim of determining the formation, vegetation changes, and use of the wetland area in order to better understand the evolving



Figure 1. Location of Vatnsfjörður, north-west Peninsula, Iceland.

cultural landscape in response to climate and social change. Our palaeoenvironmental record aims to provide insights into potential adaptive and nuanced agricultural land management practices in response to climate change and highlight the contributions that this may have made to the long-term sustainability and resilience of Icelandic farm sites.

Site Description

Vatnsfjörður (65°56'24"N, 22°29'44"W, and ~23 m a.s.l.) is situated in the centre of the North-west Peninsula towards the head of the fjord, Ísafjarðarjúp (Figure 1). The main thrust of the North Atlantic Current (NAC), originating from the Gulf of Mexico, brings warmer waters to Southern Iceland. West of the Reykjanes ridge, the Irminger Current, a branch of the NAC, delivers a mix of Atlantic and Arctic waters, leading to relatively cooler climate in the North-west Peninsula (McGovern et al. 2007; Olafsdottir, Schlyter, and Haraldsson 2001). The site is currently occupied, with a modern house and church (Figure 2), and current farming activities include silage and livestock. Archaeological research at the site and the surrounding landscape has been ongoing since 2003 (Friðriksson, Tulinius, and Guðmundsson 2005; Milek 2007). Work has focused on two main areas of the site; the Viking Age farm (10th Century) and associated domestic dwellings, workshops, storage buildings and animal buildings; and the more modern 17th-nineteenth century area of the site, characterised by a large domestic dwelling, industrial areas, and middens (Forbes et al. 2010; Milek 2008, 2011). A small wet meadow is located in the homefield towards the east of settlement and has a well-defined edge to the west with the poorer soils in the remainder of the homefield area (Figure 2).

Methods

Pollen Analysis

The site WM1 (Figure 2) was selected because it had been previously excavated for AMS radiocarbon sampling to determine the timing of the wetland formation in this area of the homefield (Milek 2007); its location also avoids disturbance of the sediment record from the modern drainage ditches. A cleaned vertical section was sampled for palaeoecological analysis using a monolith tin for pollen analysis (6–45 cm) and with smaller kubiena tins for soil micromorphological analysis (Figure 3). Samples were stored at 4°C at the University of Stirling.

One cm^3 sub-samples were prepared for fossil pollen analysis following standard preparation techniques (Moore, Webb, and Collinson 1991). A known quantity of *Lycopodium clavatum* spores (batch number 938934, X = 10,679) were added to enable the estimation of pollen and charcoal concentration (Stockmarr 1971). Pollen and spores were identified using an Olympus BX41 transmitted light microscope at x400 magnifications and counting a minimum of 300 identifiable total land pollen (TLP) grains and expressed as % of TLP. Cyperaceae, aquatic taxa, and spores are expressed as % of TLP + taxon. The wet meadow is within a basin ~100 m wide, and the pollen source area is likely dominated by local sources with

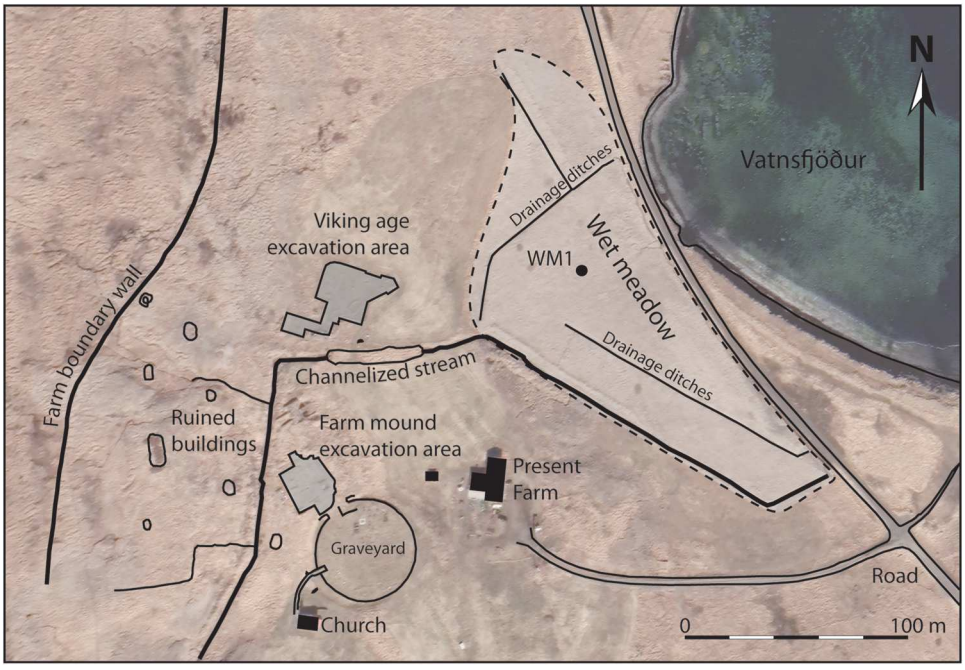
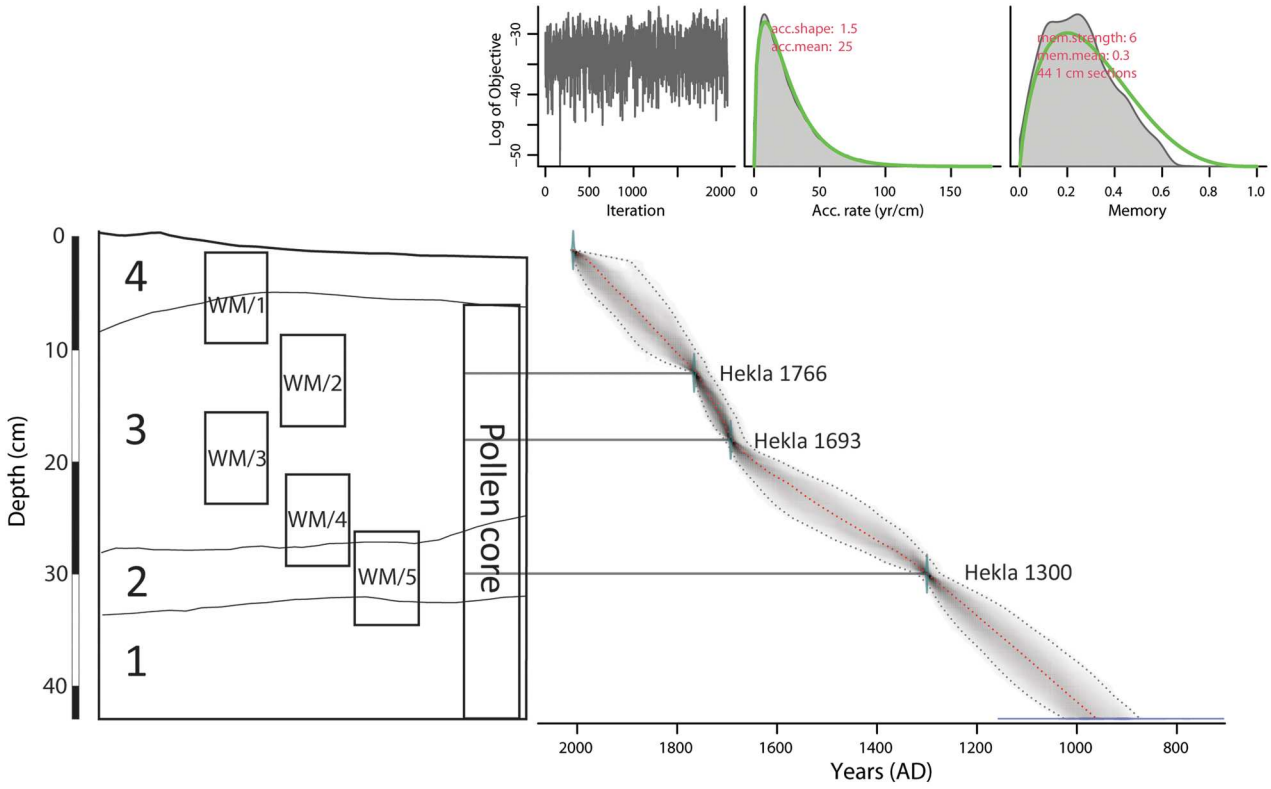


Figure 2. Vatnsfjörður homefield and location of the wet-meadow sample site (WM1) (Base image from Google Earth, location map after Gísladóttir (2008)).



1. Ag2 As1 Sh1, dark brown, well-humified organic matter and silts, combined with gravels (1-2cm) (Gmaj4), with charcoal fragments.
2. Sh3 Ag1, very dark brown, clay-silts and moderately well-humified peats.
3. Sh2 Tb1 Ag1, dark yellowish organic rich silts with moderately humified, fibrous organic material.
4. Sh1 Tb1 Th2, very dark brown, well-humified organic rich silt/peat with abundant roots.

Figure 3. (left) Scaled profile drawing of the wet meadow test pit (WM1), position of kubiena tins WM/1 to WM/5, sediments described using a modified Troels-Smith (1955) system (Units 1, 2 and 3 are presented in the stratigraphy in all subsequent pollen diagrams); (right) 'Bacon' age-depth model. Solid lines indicate depths of tephra layers.

some wind-blown extra local sources (*sensu* Jacobson and Bradshaw 1981).

Pollen was identified with reference to the pollen and spore key and glossary produced by Moore, Webb, and Collinson (1991) and the pollen type slide collection at the University of Stirling. Pollen nomenclature follows Bennett (1994; 2007), supplemented by Erlendsson (2007) and Hallsdóttir (1987), for more applicability to Icelandic flora, with plant taxonomy following Kristinsson (2010) and Löve (1983). Pollen diagrams were plotted using TILIA ver. 3.0.3 (Grimm 2011). To aid the description of vegetation communities and changes through time, the pollen record is divided into local pollen assemblage zones (LPAZ) using CONISS (Grimm 1987) based on percentage land pollen >2% of TLP (Figure 4). Pollen concentrations are presented for major taxa in Figure 5.

Assessment of the state of preservation of land pollen grains provides insight into the changing wetness at a mire surface (MSW) (Cushing 1967; Tipping 2000; Tweddle and Edwards 2010). and provides an indicator of the reliability of a pollen record (Bunting and Tipping 2000). The addition of preservation analysis to palynological studies is most useful in determining whether vegetation shifts are genuine or an artefact of the depositional or preservation environment (Tweddle and Edwards 2010). Pollen preservation was assessed using hierarchical categories. Degraded is regarded as the most significant class, followed by corroded, crumpled, broken and normal, i.e. well-preserved pollen following Cushing (1967). Grains with two or more forms of deterioration were classified by the more dominant preservation state Figure 6).

Charcoal particles were counted alongside pollen and recorded in five size classes <25 µm, 25-50 µm, 50-75 µm, 75-100 µm, >100 µm. (Patterson, Edwards, and Maguire 1987; Tolonen 1986). The input of those fragments ≤25 µm is considered continuous in most areas, with particles in the larger size categories a proxy record of past fires in the local area;

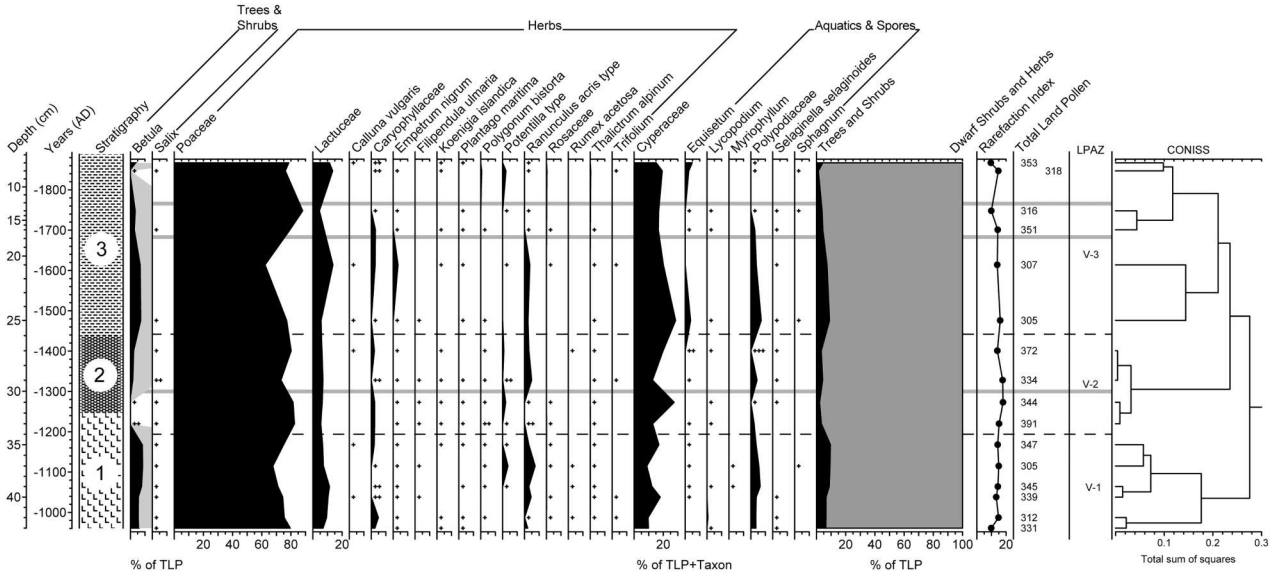


Figure 4. Percentage pollen diagram and Rarefaction index. Grey lines indicate tephra layers.

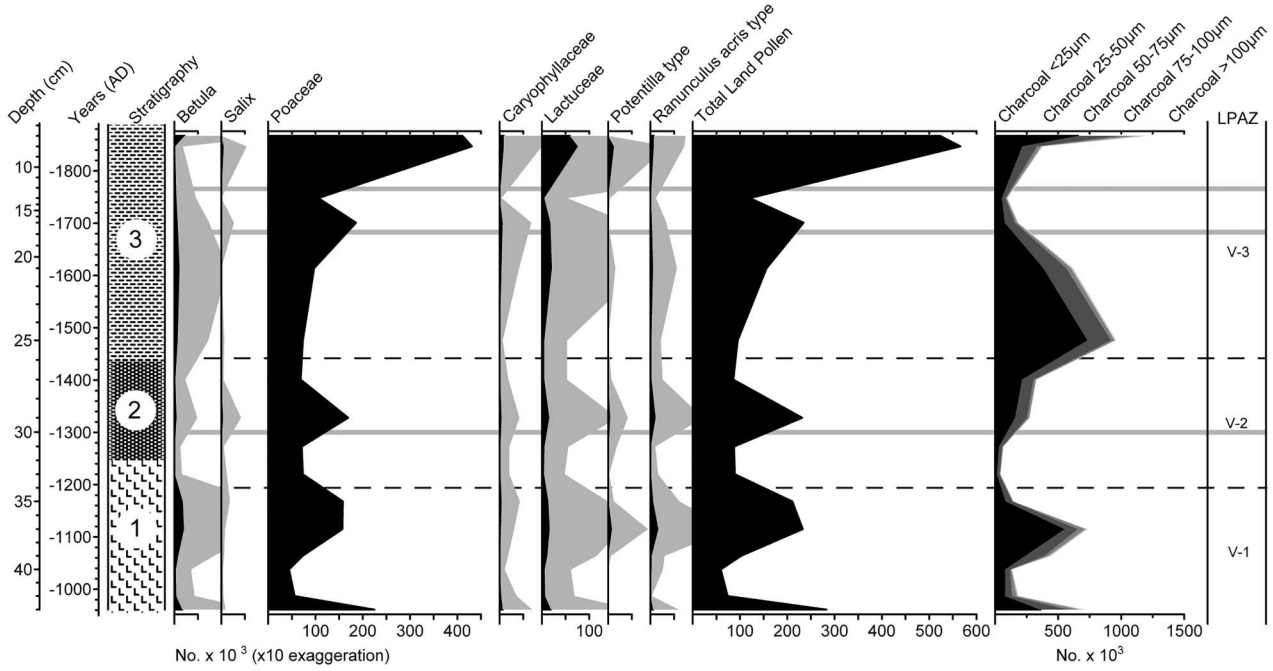


Figure 5. Pollen and charcoal particle concentration (No. cm^3) diagram. Grey shading denotes x10 exaggeration. Grey lines indicate tephra layers.

frequencies of small and large fragments do tend, however, to demonstrate strong correlations (Tolonen 1986). Charcoal data are presented alongside pollen data as concentrations (No. per cm^3) (Figure 5).

Soil Micromorphology

Five overlapping Kubiena tins were extracted from the cleaned section in WM1 (Figure 2) to provide a continuous sample covering the stratigraphical units overlying the base of the exposed stratigraphy (Figure 3). These were adjacent to the pollen profile, allowing for analysis of the section in its entirety and to enable direct comparisons with the pollen data. Due to the variable thickness of the organic-rich soils/peat, the micromorphological samples span a slightly more compressed depth of 38 cm.

Soil thin sections allowed for the semi-quantitative description of coarse and fine mineral and organic materials, pedofeatures, and soil micro-structures. Thin sections were prepared using standard procedures (Murphy 1986) and described according to Bullock et al. (1985) and Stoops (2003), supplemented by the work of Fitzpatrick (1993). Typical descriptive categories of micro horizons were further categorised by degree of organic material decomposition and

siliceous content (Gutiérrez-Castorena and Effland 2010; Stolt and Lindbo 2010) using an Olympus BX-50 petrological microscope (x10–x400); plane polarised light (PPL), cross polarised light (XPL), and oblique incident illumination (OIL).

Chronology

Charcoal fragments from the base of the section (WM1) were identified, and single entities were submitted to the Scottish Universities Environmental Research Centres (SUERC) facility for AMS dating and the ages were calibrated using CALIB 8.20 (Stuiver and Reimer 1986), implementing IntCal20 (Reimer et al. 2020).

Iceland's active volcanic nature also allows tephrochronology to be applied and enables precise dating of palaeoenvironmental studies during the post-Landnám (settlement) period. The North-west peninsula has only sporadic and limited deposition of tephra because of prevailing wind conditions (Dugmore et al. 2005), and post-settlement tephra layers are exceptionally limited. Through the geochemical characterisation of fine tephra layers, we can extend the tephrochronology of the region and provide further chronological control (Anderson 2017). The sediment profile sampled for pollen analysis (WM1) was also sampled in continuous 2 cm sections to estimate tephra concentrations. Approximately sixty shards were isolated from peak tephra layers using a syringe and mounted in resin stubs for wavelength dispersive X-ray spectroscopy (WDS) electron microprobe analysis (EMPA). EMPA major element data provided the geochemical composition of the glass shards and, where possible, enabled the correlation of tephra layers with known eruptions (Dugmore, Larsen, and Newton 1995).

A calibrated age-depth model was produced for the sediment profile using the Bayesian programme 'Bacon' (Blaauw and Christen 2011), implementing the IntCal20 calibration curve (Reimer et al. 2020) (Figure 3). The weighted mean ages from the 'Bacon' model provide the age–depth axis (cal. years AD) to constrain our palynological and geoarchaeological records (Figures 4–6).

Results

Soil and Sediment Stratigraphy

The upper, steep slopes to the west of the Vatnsfjörður homefield are characterised by shallow soils (<30 cm) underlain by basaltic bedrock (Milek 2007). Soils increase slightly in depth (40 cm) on descent into the 10th Century settlement area of the homefield and increase to ~50–60 cm to the east. Behind a raised beach deposit (the modern road edge, Figure 2) presently lies a wet meadow with organic-rich soils/peat. Gravelly substrate beneath the soil/peat would tend to permit free draining conditions, limiting organic matter accumulation. However, gleyic colour patterns of mineral material within these organic-rich soils indicate they were poorly drained and suggest waterlogged conditions. The soils in the wet meadow area are organic-rich and saturated whereas

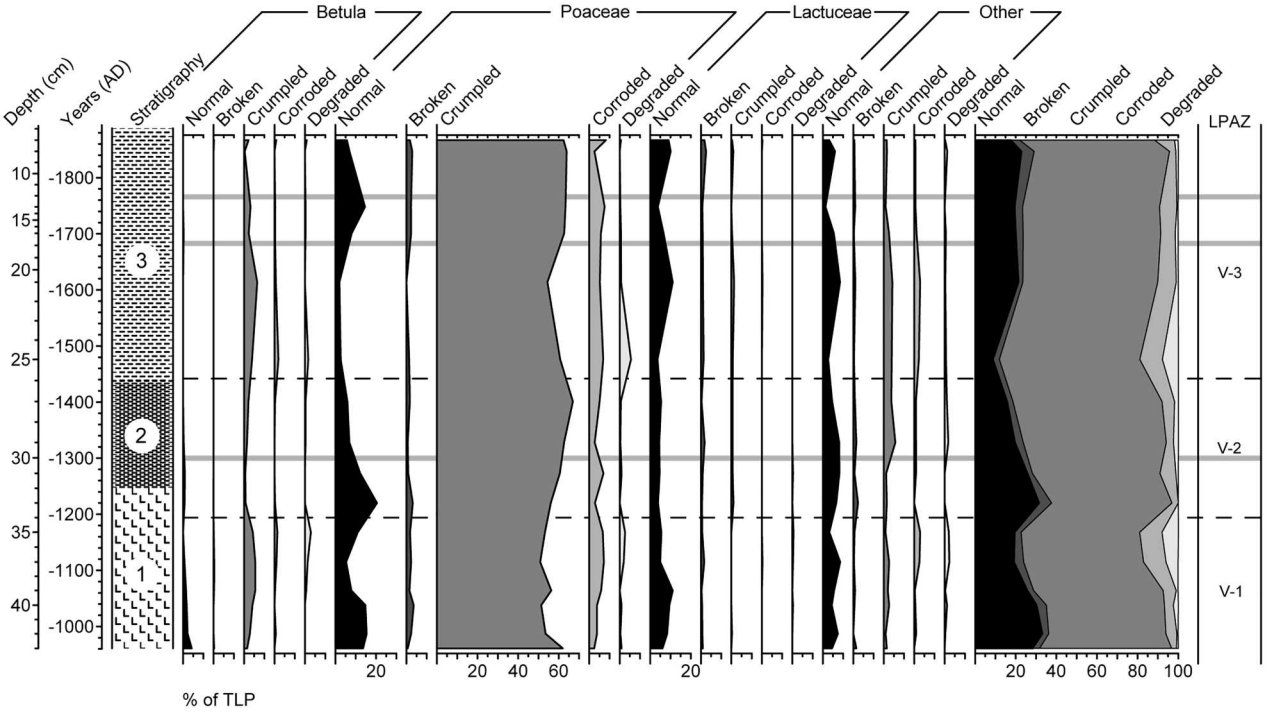


Figure 6. Percentage pollen preservation diagram of major taxa and the sum of all other land pollen. Grey lines indicate tephra layers.

the most extensive part of the homefield soils are relatively shallow silty loams, dry in nature. Our sample section in the wet meadow (WM1) comprised organic-rich soils/peat overlying beach sands and gravels (Figure 3).

Chronology

Radiocarbon dates obtained from the sample section (WM1) are presented in Table 1. The ^{14}C age of 1090 ± 35 (SUERC-8386) was selected to provide a reliable date for the start of organic accumulation onsite and for use in the age-depth model. The adjacent sample 1050 ± 35 (SUERC-8391), although close in age, is from wood of *Pinus sylvestris* and non-native to Iceland. However, the ages obtained indicate that our record post-dates the settlement of Iceland (Landnám) dated 871 ± 2 (Grönvold et al. 1995) and 877 ± 1 (Schmid 2018).

The WM1 sediment profile has a consistent small background signal of tephra ranging in colour from white/clear to dark brown. Geochemical analysis revealed that there were distinct, identifiable tephra layers (Anderson 2017). The density of tephra deposition within the sediment profile appears to be the result of multiple eruptions from Hekla volcano over a relatively short period of time. Selected higher-density tephra layers within the sampled sediment profile have been correlated with known eruptive events (Table 2, Supplementary figure S1).

The first notable peak of tephra within the section at WM1, OxT-4672 (11–13 cm), correlates to the Hekla AD 1766 eruption (proximal glass chemistry from Larsen et al., 2011). The glass chemistry of OxT-4675 (17–19 cm) correlates to the eruption of Hekla AD 1693 (proximal glass chemistry from Dugmore et al. 2007). Historical accounts of Icelandic eruptions from the sagas provide multiple sources describing the ash fall of 13th February 1693, as having reached Vestfirðir in quantities great enough to impact agriculture (Þórarinsson 1955; 1967). OxT-4679 (29–31 cm) contains tephra that correlates to the eruption of Hekla AD 1300.

The combined ^{14}C basal age and three tephra ages constrain our palaeoenvironmental record (Table 1). The Vatnsfjörður age-depth curve shows a relatively linear age-depth relationship, with the increasing accumulation rate between AD 1693 and AD 1766 represented by a short steepening in the curve (Figure 3).

Pollen Analysis

The pollen data were first evaluated for the likelihood of post-depositional taphonomic issues and suitability of data to support interpretation (Bunting and Tipping 2000). All tests were passed except for the 'Percentage resistant taxa test' with Lactuceae (dandelions) exceeding 6% in all but 3 depths (12.75, 24.5, and 33 cm). Given the prevalence of Lactuceae in Icelandic grasslands and in particular homefields, samples were not excluded from further analysis based on the failure of this test. The age-depth profile indicates that the organic-rich sediments in the wet meadow accumulated continuously over time and with limited disturbance to the profile, either through human activity or mixing of the horizons through soil forming and biological processes.

The basal age of the sediment profile indicates that all zones span the post Landnám (settlement) period for the farm site. Throughout the sediment profile Poaceae (grasses) dominates with percentages never falling below 65% of TLP and species richness appears to be low for the entire record (~20 R. I.). Taxa present throughout tend towards those indicating wet meadow pasture type habitats (Behre 1986) including Caryophyllaceae, Lactuceae, *Trifolium, Ranunculus acris* type, *Plantago maritima,* and Cyperaceae. Three local pollen assemblage zones (LPAZs), highlighting subtle changes in the pollen record, were identified

Table 1. Radiocarbon (^{14}C) and tephra ages from the Vatnsfjörður wet meadow (WM1). ^{14}C ages have been calibrated using CALIB 8.2 (Stuiver and Reimer 1986) implementing IntCal20 (Reimer et al. 2020).

Lab Code	Material	Depth (cm)	^{14}C Age	± 1σ	Age AD (median)	$\delta^{13}C$ (‰)
OxT-4672	Tephra	11-13	-	-	1766	-
OxT-4675	Tephra	17-19	-	-	1693	-
OxT-4679	Tephra	29-31	-	-	1300	-
SUERC-8386	Charcoal–Betula	43	1090	35	888 (955) 1021*	−26.7
SUERC-8391	Charcoal–Pinus sylvestris	43	1050	35	892 (998) 1038*	−24.5

* Calibrated age ranges are given to 2σ.

Table 2. Summary WDS-EPMA data (after filtering) for the samples extracted from section WM1. This table shows the average compositional percentage and standard deviation to 1σ. Where applicable, the data have been divided into compositional groups based on shard colours. The data in this table have not been normalised. The full WDS-EPMA data is available in supplementary table T1.

Sample	OxT-4672 mean	n = 15 1σ	OxT-4675 mean	n = 8 1σ	OxT-4679 mean	n = 22 1σ
SiO_2	59.91	0.68	58.79	0.97	59.83	0.42
TiO_2	1.30	0.07	1.27	0.08	1.29	0.09
Al_2O_3	15.35	0.40	15.19	0.36	15.57	0.52
FeO	9.22	0.39	9.61	0.53	9.46	0.45
MnO	0.25	0.05	0.29	0.06	0.24	0.04
MgO	1.77	0.15	1.81	0.14	1.76	0.13
CaO	5.32	0.15	5.16	0.25	5.33	0.23
Na_2O	3.51	0.40	3.68	0.31	3.65	0.50
K_2O	1.45	0.08	1.77	0.82	1.42	0.15
Correlation	Hekla 1766		Hekla 1693		Hekla 1300	

using CONISS (Grimm 1987). Fluctuations in charcoal concentrations reflect variations in the smaller sized fragments (< 50μm), concentrations of larger charcoal fragments (>50μm) are consistent over time.

LPAZ V-1 (*c.* AD 955-1195): This zone is dominated by Poaceae with lesser proportions of other herbaceous taxa, particularly those indicative of disturbance, e.g. Lactuceae, Caryophyllaceae, *Ranunculus acris* type, and trace amounts of *Rumex acetosa* and *Plantago maritima.* These taxa are also typically grazing tolerant and linked to pasture-type habitats and agricultural activity. The presence of *Filipendula ulmaria* also points to localised wetter conditions in the meadow. The trace presence of *Filipendula ulmaria* and *Myriophyllum spicatum*, generally regarded as temperature indicators in Iceland (Hallsdóttir 1996; Kristinsson 2010), probably indicates a warmer climate at this time.

The presence of trees and shrubs in the zone is marked by a small, but continuous presence of both *Betula* and traces of *Salix*, with the former present at levels >5% of TLP, which although low is a relatively significant value in comparison with other zones. These percentages are likely linked to the longer distance transport of pollen, possibly from the sloping sides of the farm and within the valley, particularly given the prolific pollen production of *Betula,* and its frequent over-representation in pollen diagrams (Rymer 1973). The open nature of the vegetation is also expressed by the presence of those species requiring open canopy conditions, or closely cropped swards, such as *Koeniga islandica, Thalictrum alpinum,* and *Selaginella selaginoides*. The most frequent species outwith the total land pollen (TLP) sum include Cyperaceae and Polypodiaceae. Other aquatic and spore taxa present include *Equisetum*, *Lycopodium*, and *Selaginella selaginoides*.

Pollen preservation throughout the zone is good, despite high percentages of crumpled grains (up to 65% of TLP). Percentages of well-preserved grains (normal) reach up to 35% of TLP, the highest value for the site. The total percentage of crumpled grains is predominantly made up of Poaceae, a pollen grain typically more susceptible to mechanical damage and repeated cycles of wetting and drying of the wetland surface (Campbell and Campbell 1994).

Charcoal concentrations fluctuated, with two sharp peaks (~700,000 cm^{-3}) before falling to ~185,000 cm^{-3} towards the upper zone boundary. The charcoal peaks broadly coincide with rising concentrations of *Betula* and Poaceae pollen. Both pollen and charcoal concentrations then decline towards the top of the zone.

LPAZ V-2 (AD 1195 - 1440): During this short zone (~245 years) the pollen assemblages are dominated by Poaceae, with Lactuceae and Caryophyllaceae present at low percentages (<5%) throughout the zone. *Potentilla* type is present (~2%) at *c.* AD 1270 and is associated with a peak in Cyperaceae values (27%), both of which are tolerant of wetter conditions. Other herb species are present but at very low levels, around 1% of the TLP sum. At the start of the zone, proportions and concentrations of *Betula* are reduced to trace proportions. This reduction in *Betula* is mirrored in the zone by a sharp decrease in charcoal, persisting for the entirety of the zone. Species diversity slightly increases during LPAZ V-2. The presence of degraded pollen decreased within this zone, with corresponding increases in normally preserved pollen.

LPAZ V-3 (AD 1440-1890): This zone is marked by a resurgence in *Betula* pollen, with total proportions of tree and shrub taxa increasing overall. Peak values for *Betula* (~7.5% of TLP) are recorded at *c.* AD 1480 - 1610 and are coincident with minor increases in grazing tolerant taxa, in particular Lactuceae, Caryophyllaceae, and *Ranunculus acris* type present at < 10% of TLP until declining to trace amounts at c. AD 1700. The herbaceous taxa are predominantly made up of grasses and weed taxa. Grazing sensitive species, such as *Salix* and *Filipendula ulmaria*, present previously, disappear from the pollen spectra at *c.* AD 1500, probably a result of increased grazing pressures, or alternatively a result of increased competition from other taxa.

After c. AD 1660 pollen diversity declines, indicating further dominance of Poaceae. *Betula* continues to decline with low percentages (<5% of TLP) throughout the remainder of the zone, with this also reflected in the concentration diagram. Cyperaceae values from an initial high of ~30% of taxon + TLP gradually decline to remain constant throughout the rest of the zone at around 20% of taxon + TLP, remaining a significant component of the vegetative assemblage for this period. *Equisetum* and Lactuceae increased towards the top of the zone, which, alongside high percentages of Poaceae, would appear to have similar vegetation composition to the present landscape at Vatnsfjörður.

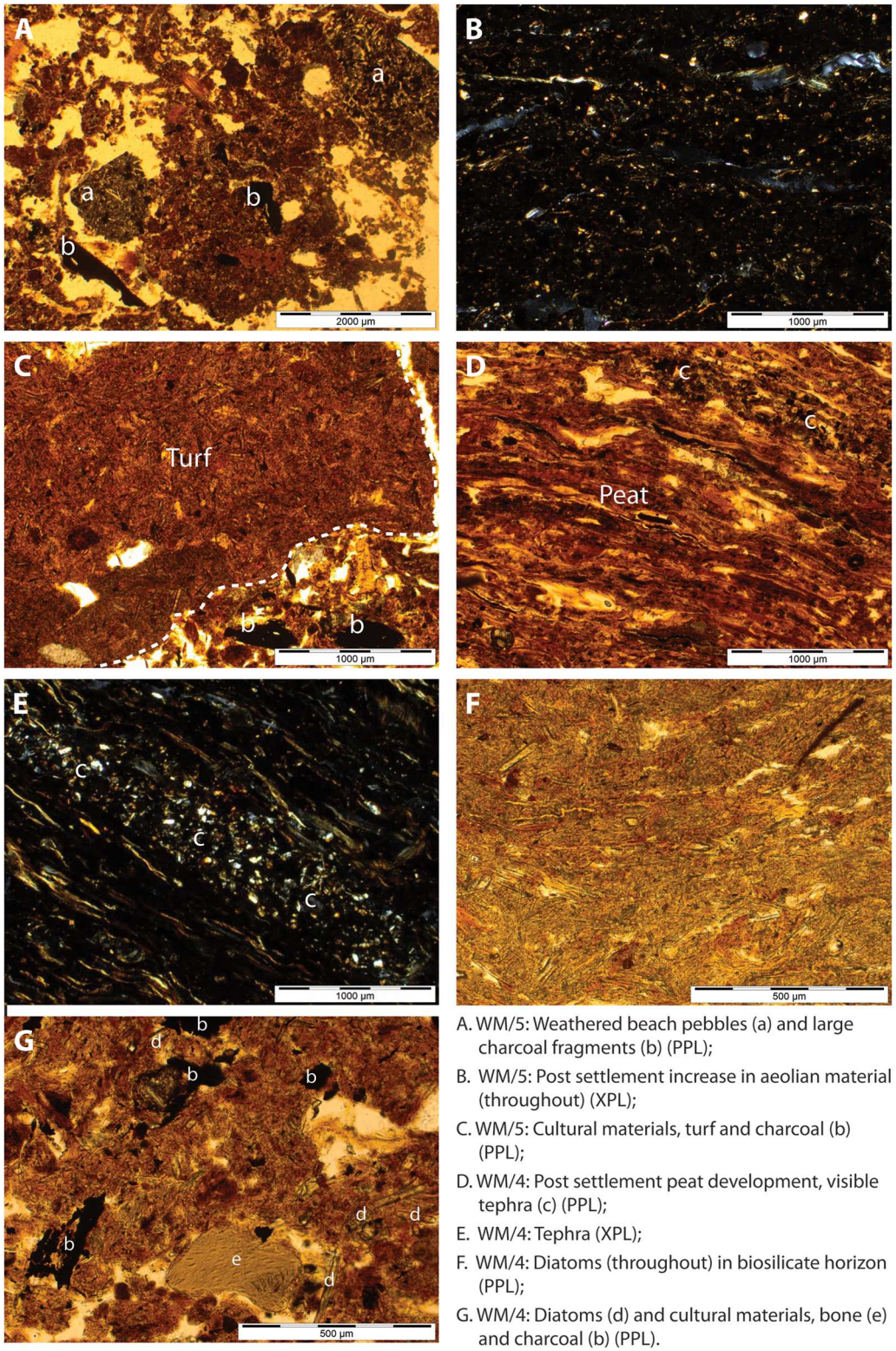
At the start of the zone there is a sharp, well-defined peak in charcoal concentration with the maximum concentration occurring at c. AD 1480. Charcoal concentration values then decline until a sharp increase towards the top of the zone, peaking at ~1,215,000 grains cm^{-3}. Pollen values for this upper zone are marked by sharp increases in pollen concentration values (~560,000 grains cm^{-3}), comprised mostly of Poaceae (~430,000 grains cm^{-3}). This may reflect changes in the sediment structure with wet meadow beginning to dry out because of modern drainage ditches. Pollen preservation appears not to have been affected by this, with percentages of corroded and degraded pollen remaining relatively low, suggesting the drawing down of the water table was not severe and or was more recent, and has not

dried the organic material for a long period (Davies, Fyfe, and Charman 2015).

Soil Micromorphology

Soil micromorphological analysis provided a better understanding of the paedogenic processes operating within the wetland area and the peat/organic-rich soils, with a focus on formation, function, and management. This includes cultural additions and periods of accumulation and decomposition. Results for the thin sections from site WM1 (see Figure 7) are summarised in Supplementary material T2.

Throughout much of the profile, coarse mineral material is virtually absent, except for traces of tephra (Figure 7D and E) and rare fragments of igneous



A. WM/5: Weathered beach pebbles (a) and large charcoal fragments (b) (PPL);

B. WM/5: Post settlement increase in aeolian material (throughout) (XPL);

C. WM/5: Cultural materials, turf and charcoal (b) (PPL);

D. WM/4: Post settlement peat development, visible tephra (c) (PPL);

E. WM/4: Tephra (XPL);

F. WM/4: Diatoms (throughout) in biosilicate horizon (PPL);

G. WM/4: Diatoms (d) and cultural materials, bone (e) and charcoal (b) (PPL).

Figure 7. Key micromorphological features in Vatnsfjörður thin sections from WM1, kubiena tins WM/4 and WM/5 covering Units 1, 2 and 3 (see Figure 3).

(basaltic) rock; the latter concentrated in the basal horizon. The base of the WM1 section demonstrates the changing soil environment between pre- and post-settlement at Vatnsfjörður. Sub-angular and rounded weathered igneous rock fragments are consistent with field observations of beach sands and gravel and reflect the original land surface above which organic-rich soils/peat developed (Figure 7A). Typical Icelandic freeze-thaw conditions are evidenced in the lowermost micro horizons with soil microstructures and silt coatings on the beach gravels, linked to the pedoturbation of fine silt material by cryoturbation (Romans, Robertson, and Dent 1980). The organic matter in the post settlement profile is more decomposed (amorphous) and blacker within the lower profile.

Discrete layers of diatoms, including *Eunotia* sp. and *Pinnularia* sp., suggest periods of pools of standing freshwater on the peat surface (Figure 7F and G). The increased incidence of excremental pedofeatures (few-common), as well as granular and crumb microstructures, indicates conditions were suitable to support micro- and macrofauna. Therefore, the surface might have been saturated periodically sufficiently to support diatoms, followed by drier periods supporting soil fauna. Wetting and drying conditions are further expressed within other iron-based soil features, namely traces of amorphous cryptocrystalline pedofeatures and stone rims. These may be the result of soil processes related to the cultural period or overprinting from more recent environmental processes.

Accumulation of organic material with phases of limited decomposition is the dominant process that builds up the profile, relative stability in the wider landscape is expressed in the limited aeolian inputs (Figure 7B) and high incidence of indicators of biological activity. Periods of increased aeolian inputs are noted close to the top of the section (19 cm and 5–8.5 cm). This is not an uncommon ecofact of Icelandic soils and has frequently been observed within other parts of Iceland, associated in these cases with large wind-blown events and tephra deposits (Romans, Robertson, and Dent 1980; Simpson, Milek, and Gudmundsson 1999; Stoops 2007; Stoops, Gérrard, and Arnalds 2008).

Cultural signals are present throughout the entire profile. Bone and turf fragments, and potential midden material have been added to the wetland (Figure 7C, Buckland et al. 2009; Golding et al. 2015; Schofield et al. 2022; Zori et al. 2013). Fungal sclerotia and calcium spherulites, animal dung indicators, also suggest farming activity, potentially linked to the introduction of grazing animals, or through the application of animal manure on the site. Large fragments of charcoal (>50 µm) indicate the deliberate addition of material, likely originating from on-going domestic and industrial activities at the farm. The smaller particles of charcoal may also have been added or blown onto the meadow from domestic fires.

Discussion

The stratigraphic evidence at Vatnsfjörður indicates the accumulation of organic-rich soils/peat in the wetland area. The origin of the wetland soon after Landnám is uncertain. The underlying gravels were deposited during the Mid- to Late Holocene marine transgression, ~1 m above present sea-level, followed by emergence towards present sea-level from *c.* 3.1 ka (Lloyd et al. 2009). The presence of the storm beach ridge and/or the use of fire to clear vegetation during settlement probably led to paludification and the accumulation of organic-rich soils/peat. The wetland is in sharp contrast to the thin soils of the surrounding homefield, lacking in organic matter and leached of nutrients. It is likely that, with the free-draining substrate, the thin homefield soils also experienced periods of drought. Therefore, the nature of these wider homefield soils presents a limitation to productivity. Vatnsfjörður itself presents additional limitations to production, as Aldred (2005) describes, the area is a long ridge extending north to south along the western edge of the farm and enclosed by a fjord. At a site of such topographic variability, problems regarding ease of production and land management techniques would have arisen. The extent of land use and farm expansion will also be restricted by the topography in this region, a limitation similar to that experienced by settlers in the Faeroe Islands (Adderley and Simpson 2005). Unfavourable climate is another factor limiting productivity on site; it may, therefore, be assumed that each of these limitations to productivity in turn would call for an increase in management techniques.

Wetland Management

The pollen evidence from Vatnsfjörður indicates that since the early development of the wetland the vegetation composition has not varied considerably. Grasses dominated the pollen assemblage, remaining at relatively stable and high percentage values until the present day. Various herb taxa grew alongside Poaceae, although in much smaller quantities and never dominating the pollen assemblages. This suggests that once the habitat type of a wet, grass rich meadow was established it persisted until the present day. Here we propose that the maintenance of the grass rich meadow would have required some form of intervention, to prevent the encroachment or dominance of other species such as Cyperaceae or would have required sufficient disturbance to prevent plant succession to climax communities. Management could have been either through removal of the

vegetation for fodder or through grazing or both at separate times. Micromorphological evidence of calcium spherulites and fungal sclerotia suggests the presence of grazing livestock and manure. Whether through direct grazing or through the application of animal manure and general barn waste, either suggest a form of management of the wet meadow. The herbaceous diversity may also indicate that there has been some form of management to maintain the modest level of diversity. Direct or indirect manuring might have maintained enhanced levels of Poaceae throughout the period of occupation and supports the potential use of this area for fodder production, a hay meadow. Appearance and disappearance of grazing sensitive tall herbs (e.g. *Filipendula ulmaria*) might also point to varying uses of the meadow through time, with this pollen deposited either directly onto the meadow from plants growing on site, or pollen transported from areas of site fenced off to grazing animals.

While there is evidence for limited soil improvements in the form of midden material close to structures within the homefield area (Milek 2011), there is more evidence for active management of the wetland. Micromorphological analyses suggest improvements were made to the wetland through the addition of charcoal, bone, and turf. The relatively level topography suggests that it is unlikely such material was transferred to the wetland surface by slope processes. The addition of midden material is indicative of improving farm resources, a widespread practice in the North Atlantic and identified in several farms in Iceland (Buckland et al. 2009; Sveinbjarnardóttir et al. 2006; Zori et al. 2013).

What is less clear from the pollen and micromorphological analysis is whether the water table at the site was managed, maintained through irrigation, or if once organic-rich material began to accumulate, drainage was impeded sufficiently to sustain the wet meadow. Wetland taxa are present in low values throughout the profile and would suggest that the site was at least periodically flooded. The continued accumulation of organic material also requires persistent anaerobic conditions. Evidence for periodically wetter conditions is supported by the clustering of diatoms in micro horizons (Fig. 7G), which provides further evidence of frequent inundation of the wetland. Such quantities would typically be associated with standing water and poorly drained environments (Bouma, Fox, and Miedema 1990; Clarke 2003; Gutiérrez-Castorena and Effland 2010). Documentary resources have mentioned the intentional flooding of meadows in early spring to insulate and prevent the freezing of meadows, with the intent to promote earlier yields (Buckland et al. 2009; Sveinbjarnardóttir, Buckland, and Gerrard 1982). This became a common land management practice in medieval Iceland (Zutter 1997). The grasses growing at the site would have benefited from the protection from frosts and thúfur development (small hummocks or earth mounds) during periods of inundation.

The intermittent nature of the flooding of the wetland at Vatnsfjörður is highlighted by the abundant presence of faecal material and microstructures indicative of soil faunal processes, which indicate that the wetland was allowed to periodically dry out (Bouma, Fox, and Miedema 1990). The concentrations of faecal material in the upper layers are probably more contemporary and associated with drainage of the wetland area in more recent years to allow for more mechanised farming practices.

The concentration values of larger charcoal fragments (>50 μm) remain constant throughout the profile. This would indicate that the overall changes in charcoal concentration values were not a result of processes such as in-situ or very localised burning, which would have generated more mixed sizes of charcoal fragments. The variations in charcoal concentrations noted in Figure 6 are in response to changes in the smaller fraction size (<50 μm), suggesting changes in inputs from windblown sources. These sources are likely to be industrial from the smithy within the farm and/or from domestic activity elsewhere in the farm settlement (Milek 2007, 2009). The micromorphology suggests charcoal is more frequent towards the base of the profile, above the beach sediments. This is a typical feature of settlement practices in Iceland, where vegetation was burned during land clearance for agriculture.

Climate and Environmental Change

The highly friable nature of Icelandic soils, due to their low organic content and poorly developed structures, makes them highly susceptible to wind and water transport when exposed as a result of vegetation removal (McGovern et al. 2007; Olafsdottir, Schlyter, and Haraldsson 2001). These aeolian materials are also evident throughout the sediment profile (WM1), although as a small proportion relative to the organic material, lessening the impacts more extensive deposition might have had on agricultural potential. Aeolian materials increase in frequency immediately post settlement; this pattern is seen across much of Iceland as previously pristine soils were disturbed during normal settlement activities. Several more intense erosion events are noted within the profile after c. AD 1700. These are likely linked to increased storminess associated with the Little Ice Age (Stewart et al. 2023).

In north-west Iceland cold phases have been identified between AD 1683–1710, AD 1765–1780 and AD 1890–1917, with relative drops in summer temperatures in the order of 1.5–2°C (Langdon et al. 2011), with temperatures in the 18th and 19th centuries the

coolest conditions in the past 2000 years, with significantly cooler climates between AD 1730–1780 (Axford et al. 2009; Geirsdóttir et al. 2009). Our pollen record suggests that during these periods of cooler climates (LPAZ V-3 AD 1660 - 1805) the vegetation assemblages remain relatively stable. However, there are reductions in the diversity of plant species present, and the vegetation is dominated by grasses, perhaps a response to cooler and/or more variable climate conditions. During this period of cooler conditions, the low proportions of corroded and virtual absence of degraded pollen suggests the persistence of wetter conditions at the surface of wetland (Cushing 1967; Tipping 2000). The small peaks in corroded and degraded pollen at c. AD 1150 and 1480 (Fig 6) are probably linked to repeated wetting and drying cycles, highlighted in the micromorphological analysis, that triggered aerobic bacterial and fungal activity and subsequent microbial attack on pollen (Campbell and Campbell 1994; Tweddle and Edwards 2010).

Settlement and Continuity

The choice of a site like Vatnsfjörður for settlement in the early phases of colonisation is unusual in that it does not fit with the general pattern of settlement in Iceland. Power centres were generally amongst the first sites settled and were, therefore, in a position to claim the best land, allowing for the retention of their status (Erlendsson et al. 2006; Vésteinsson 1998). The land at Vatnsfjörður in contrast appears to have been poorly suited to agriculture. However, Edvardsson and McGovern (2005) and Tulinius (2005) have suggested that in this case the sea may have dictated settlement, and the enclosed fjords would have provided a safe harbour for ships and provided settlers with a prime position to monitor traffic both on the fjords and over land, controlling all major routes in the region. Archaeological evidence at Vatnsfjörður suggests coastal activity, with a series of structures, some thought to be boat houses, in use from the 11th–seventeenth century AD, which corresponds to the settlement of the main site (Mikołajczyk et al. 2015; Mikołajczyk and Milek 2016; Mooney 2013; Mooney, Sveinbjarnarson, and Mikołajczyk 2012). The coastal archaeology is tied to changes in relative sea level with structures built to maintain access to the sea as the relative sea level changed (Mikołajczyk et al. 2015). This suggests that marine resources and/or marine access were important supplements to the agricultural productivity/economy during the occupation of the main Vatnsfjörður farm site.

With the advent of modern agricultural techniques and the use of heavy machinery, wetland areas such as at Vatnsfjörður became less important to farm economies. However, given the wealth of palaeoenvironmental information held in these organic-rich sediments, they are of major importance because of their potential contribution to better understanding ecological and cultural heritage.

Conclusions

The wetland area at Vatnsfjörður was a valuable resource, and the palaeoenvironmental data sets suggest that it was actively managed as a wet meadow. The presence of the storm beach ridge and then activity to clear the vegetation (burning) during settlement may have impeded the drainage sufficiently to allow for wet conditions to persist and organic-rich soils to accumulate. We can speculate whether this was by accident or design, regardless of the timing of formation of the wet meadow being coincident with settlement. The wet meadow became a resource that was the focus of homefield improvements that included manuring, addition of midden material and possibly irrigation. The relative stability of the meadow's organic-rich soils and grass-rich vegetation suggests that throughout the occupation period the wet meadow was likely used to produce subsistence-level fodder to sustain livestock through the Icelandic winter. This strategy appears to have been sufficient to maintain productivity at a level able to preserve the settlement's wealth and high status, despite the limitations of the location, and to buffer external influences of climatic and socio-economic downturns experienced across Iceland.

The techniques presented here can be readily applied to wetlands associated with homefields and farm structures in other areas of the North Atlantic region, helping to enhance understanding of the complexity of early Icelandic settlement and farming systems (Caitlin 2021; Caitlin and Bolender 2022) and improve the spatial scale of palaeoenvironmental research in Iceland (Bates et al. 2022; Hallsdóttir and Caseldine 2005).

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