UNIVERSITY
OF ICELAND

Ph.D. Thesis

in Geography

Monks and mires: the vegetation and land use histories of monasteries and their tenancies in Medieval Iceland

Scott John Riddell

June, 2023

FACULTY OF LIFE AND ENVIRONMENTAL SCIENCES

Monks and mires: the vegetation and land use histories of monasteries and their tenancies in Medieval Iceland

Scott John Riddell

Dissertation submitted in partial fulfilment of a
Philosophiae Doctor degree in Geography

Ph.D. Committee
Professor Egill Erlendsson
Professor Steinunn Kristjánsdóttir
Dr. Sigrún Dögg Eddudóttir
Professor Guðrún Gísladóttir

Opponents
Dr. Eileen Tisdall, University of Stirling, Scotland
Professor Orri Vésteinsson, University of Iceland, Iceland

Faculty of Life and Environmental Sciences
School of Engineering and Natural Sciences
University of Iceland
Reykjavik, 2 June 2023

Monks and mires: the vegetation and land use histories of monasteries and their tenancies in Medieval Iceland, Dissertation submitted in partial fulfilment of a *Ph.D.* degree in Geography

Faculty of Life and Environmental Sciences
School of Engineering and Natural Sciences
University of Iceland
Sturlugata 7
102, Reykjavik
Iceland

Telephone: 525 4000

Bibliographic information:
Scott John Riddell, 2023, *Monks and mires: the vegetation and land use histories of monasteries and their tenancies in Medieval Iceland*, PhD dissertation, Faculty of Life and Environmental Sciences, University of Iceland, 153 pp.

Author ORCID: 0000-0003-4589-3925
ISBN: 978-9935-9697-7-4

Abstract

Focussing upon the monastic sites of Þingeyraklaustur and Helgafellsklaustur, palynological data are utilised to explore the role of Icelandic monasticism with regard to vegetation change and land use in the Medieval period. Consideration is also given to two farms, Ásbjarnarnes and Helgadalur, that were tenancies of monasteries. Vegetation change at all sites is evaluated against the settlement of Iceland, European monasticism, plague, Reformation, and the prevailing climate of the time. Pollen data are supplemented with sedimentary data and set within a chronological framework constructed through a combination of known tephra layers and ^{14}C or Plutonium (Pu) dating. The relative precision of tephrochronology allows palynological data to be cross-referenced with historical sources. The foundation of both monasteries is visible in the pollen record, with subsequent land use focussed upon pastoralism. There is a hiatus at Þingeryraklaustur due to plague in the 15th century, with continuity at Helgafellsklaustur, both findings in keeping with the historical record. With regard to the tenancies, no direct monastic influence is discerned at Helgadalur, with haymaking a primary activity. At Ásbjarnarnes, there is evidence of woodland management, perhaps influenced by Þingeyraklaustur. There is no evidence of disruption associated with the Lutheran Protestant Reformation at any of the four sites. Further findings have allowed for some comparison between the four sites with regard to vegetation and climate, palaeoecological change associated with human colonisation, and the pre-monastic era. There is also pollen evidence of exotic plants with medicinal and/or culinary applications at Helgafell, introduced prior to the foundation Helgafellsklaustur.

Útdráttur

Rannsókn þessi beinir sjónum að áhrifum klausturhalds á gróðurbreytingar og landnotkun á miðöldum. Til rannsóknar voru tvær klausturjarðir, Helgafell og Þingeyrar, auk Ásbjarnarness og Helgadals sem voru jarðir í eigu klaustra. Gróðurbreytingar voru metnar í samhengi við landnám á Íslandi, evrópska klausturhefð, svarta dauða, siðaskipti og loftslag á miðöldum. Frjógreining var hornsteinn aðferðafræðinnar. Greiningar á jarðvegi voru notaðar sem mælikvarðar á jarðvegsrof. Gögnin voru lögð inn í tímaraðir sem byggja á gjóskulagatímatali og aldursgreiningum með geislakoli (^{14}C) og Plútoni (Pu). Gjóskulög bjóða upp á nákvæman samanburð upplýsinga úr frjógreiningu við söguleg gögn. Þegar við upphaf klausturhalds má greina gróðurbreytingar vegna landnotkunar og aukinnar kvikfjárræktar. Á Þingeyrum dróg úr umfangi reksturs klaustursins á tímum svarta dauða en slík áhrif birtast ekki á Helgafelli. Þetta samræmist sögulegum upplýsingum um afdrif klaustranna á tímum plágunnar. Engin ummerki um breytt gróðurfar eða landnotkun, sem rekja má til áhrifa frá klaustrum, fundust á jörðunum tveimur sem voru í klaustureign. Heyframleiðsla virðist hafa verið helsta form landnotkunar innan þeirra. Á Ásbjarnarnesi birtast þó vísbendingar um varfærna nýtingu kjarr/skóglendis á miðöldum, hugsanlega vegna áhrifa frá Þingeyraklaustri. Engar vísbendingar fundust á jörðunum fjórum um breytt eðli eða umfang landnotkunar við siðaskipti. Auk upplýsinga um landnotkun og gróðurbreytingar tengdar klausturhaldi leggur rannsóknin til gögn sem bjóða upp á samanburð á milli staðanna fjögurra m.t.t. loftslags- og umhverfisbreytinga á tímum landnáms og fyrir klausturhald. Í frjógögnum frá Helgafelli eru einnig vísbendingar um innfluttar plöntutegundir sem tengjast lækningum og matargerð. Þær birtast fyrst áður en klaustrið var sett á fót þar.

To Mum, to Glóey, to Lewis,

with love

Table of Contents

List of Figures

List of Tables

List of Publications

Paper I

Riddell, S.J., Erlendsson, E., Eddudóttir, S.D., Gísladóttir, G. & Kristjánsdóttir, S. (2022) Pollen, Plague and Protestants: The medieval monastery of Þingeyrar (Þingeyraklaustur) in Northern Iceland, *Environmental Archaeology*, 27 (2), 193-210.

Scott John Riddell (SJR) planned the study and acquired research funding. Fieldwork was by SJR and Egill Erlendsson (EE). Laboratory work (pollen processing, tephra and ^{14}C preparation) was by SJR. All pollen analysis was by SJR. Tephra identification was by EE with age-depth modelling, ordination, and *Betula* grain size charts by Sigrún Dögg Eddudóttir (SDE). The manuscript was written by SJR. Co-authors EE, SDE, Guðrún Gísladóttir and Steinunn Kristjánsdottir provided helpful feedback on the manuscript.

Paper II

Riddell, S.J., Erlendsson, E., Eddudóttir, S.D., Farnsworth, W.R., Gísladóttir, G. & Kristjánsdóttir, S. (no date) A script born of sediment: vegetation and land use at the medieval monastery of Helgafell (Helgafellsklaustur) in western Iceland, manuscript submitted to the journal of *Vegetation History and Archaeobotany.*

Scott John Riddell (SJR) planned the study and acquired research funding. Fieldwork was by SJR, Egill Erlendsson (EE), Theresa Bonatotzky, Karl Benediktsson and Einar Egilsson. Laboratory work (pollen processing) and pollen analysis was by SJR. Tephra identification and age-depth modelling was by Wesley Randall Farnsworth (WRF) with ordination and *Betula* grain size charts by Sigrún Dögg Eddudóttir (SDE). The manuscript was written by SJR. Co-authors EE, SDE, WRF, Guðrún Gísladóttir and Steinunn Kristjánsdóttir provided helpful feedback on the manuscript.

Paper III

Riddell, S.J., Erlendsson, E., Eddudóttir, S.D., Gísladóttir, G. & Kristjánsdóttir, S. (2022) The vegetation and land use histories of two farms in Iceland: settlement, monasticism and tenancy, *Vegetation History and Archaeobotany*, 31, 395-414.

Scott John Riddell (SJR) planned the study and acquired research funding. Fieldwork was conducted by SJR, Egill Erlendsson (EE), and Susanne Claudia Möckel. Laboratory work (pollen processing, tephra and ^{14}C preparation) and pollen analysis was by SJR. Tephra identification was by EE with age-depth modelling and ordination charts by Sigrún Dögg Eddudóttir (SDE). The manuscript was written by SJR. Co-authors EE, SDE, Guðrún Gísladóttir and Steinunn Kristjánsdóttir provided helpful feedback on the manuscript.

Abbreviations

AD	Anno domini
ÁSB	Ásbjarnarnes
BP	Before present
C	Carbon
^{14}C	Carbon-14 (radiocarbon)
CFS	Coprophilous fungal spores
DCA	Detrended correspondence analysis
DI	*Diplomatarium Íslandicum*
DBD	Dry bulk density
EPMA	Electron probe micro-analyser
HEL	Helgadalur
HFK	Helgafellsklaustur
HCl	Hydrochloric acid
LTL	Landnám Tephra Layer
LIA	Little Ice Age
LPAZ	Local pollen assemblage zone
LOI	Loss on ignition
MS	Magnetic susceptibility
MCO	Medieval Climatic Optimum
NaOH	Sodium hydroxide
NPP	Non-pollen palynomorph
OM	Organic matter
PAR	Pollen accumulation rate
PZ	Pollen zone
PCA	Principal component analysis
SCM	Soil moisture content
Sn-1	Snæfellsjökull tephra
spp.	Species (plural)
TLP	Total land pollen
Þing	Þingeyraklaustur

Acknowledgements

Where to begin! There are so many people who have helped and contributed to this piece of work. The obvious place to start is with my supervisory panel, Egill Erlendsson, Guðrún Gísladóttir, Sigrún Dögg Eddudóttir, and Steinunn Kristjánsdóttir. Egill has been stalwart in his supervision, a steady hand at the tiller, steering me back to shore when I have strayed (at times even lost). I've always been able to knock on his door, and his support and patience in the field (definitely not afraid to get his hands dirty), in the lab, and at the microscope, has been greatly appreciated. Guðrún is a powerhouse, for whom nothing is impossible. It is hard not to hold faith in the face of the energy she suffuses. Sigrún is a shrewd, tight hand on the reins. Her scrutiny of my work has always improved it, and I have valued our conversations on the Holocene, Icelandic politics, and the universe as we trawled through pollen at our microscopes. Digging into Iceland's past with Steinunn has been enlightening and a joy, and she is another person with an unbounding and inspiring energy for her work. Further collaborators include Wes Randall Farnsworth for his tephra work (for whom nothing is a problem) and Benjamin Hennig for his most excellent maps. I am also grateful to Ingimundur Sigfússon (1938-2018) of Þingeyrar and Hjörtur Helgasson of Helgafell for allowing access to their land for the purposes of this research.

Fellowship is important in academia, and I am especially thankful to Susanne Claudia Möckel, soil scientist extraordinaire, for regularly checking in on what condition my condition is in. Sharing knowledge and exploring ideas is a further feature of university life and for that I have been greatly indulged by my peers over the years; María Svavarsdóttir, Theresa Bonatotzky, Ölvir Styrmisson, Utra Mankasingh, Olga Vilmundardóttir, Friðþór Sófus Sigurmundsson and Hoskuldur Þórbjarnarson; Her Ryal Maijesty the Quine o Scotland bowys maist humbill afore ye aw. Outwith the university campus, thanks are due to Jóna Kolbrún Sigurjónsdóttir, Torfi Stefán Jónsson, and Einar Ásgeir Sæmundsen for having me back at Þingvellir Þjóðgarðurinn year after year.

At home, I have relied upon my sweetheart Glóey Helgudóttir Finnsdóttir for far more than I should have. She has stood by me with love through it all, the epitome of patience and kindness; even when I'm crabbit. To quote the song "Just the smile" by Irishman Rory Gallagher:

"*But like the rain that is falling all over the land,*
She cools down my mind with a touch of her hand"

And then there's my laddie, Lewis Árni Riddell, for the tunes, laughs, and Star Wars; Am a richt or am a wrang? Naw, yer a donut! Braw!

A wee nod to my Mum (Isabella "Isa" Riddell nee Thomson, 1936-2017) who unfortunately never got to see me reach the end of my studies. A great leveller, with a wee Scots twang she would often ask "*are you going to be a student all your life?*". I'd have liked to have been able to tell her that I think I'm done now (at least with regard to the job title).

This work was possible with financial support from the Icelandic Research Fund (RANNÍS: 163290; 140983; 141842, 228576), the Landsvirkjún Energy Research Fund (NÝR-05-2016; NÝR-05-2017; NÝR-05-2019; NÝR-07-2020), and the University of Iceland PhD Teaching Fund. I also received funding from the University of Iceland Travel

Fund and the University of Iceland Geography Department Travel Fund to promote my work overseas.

Informa UK Limited (Taylor & Taylor & Francis Group), have allowed me to reproduce content from S.J. Riddell, E. Erlendsson, S.D. Eddudóttir, G. Gísladóttir & S. Kristjánsdóttir (2022), Pollen, Plague & Protestants: The Medieval Monastery of Þingeyrar (Þingeyraklaustur) in Northern Iceland, *Environmental Archaeology*, 27:2, 193-210 © copyright 2023. Similarly, S.J. Riddell, E. Erlendsson, S.D. Eddudóttir, G. Gísladóttir, & S. Kristjánsdóttir (2022), The vegetation and land use histories of two farms in Iceland: settlement, monasticism, and tenancy, *Vegetation History and Archaeobotany*, 31, 395-414, is reproduced here with the kind permission of Springer Nature.

1 Introduction

Iceland is situated in the North Atlantic, remote from both the European and North American continents and as a consequence, it was one of the last large islands on the planet to be colonised by humankind (Karlsson, 2019). This settlement (henceforth also referred to as Landnám) occurred in the late 9th century, prior to which, environmental and ecological conditions in Iceland were dictated exclusively by climate and volcanism. As a consequence, Landnám has become a focal point of research concerned with the interphase between humankind and the environment, with palynological studies at the forefront e.g. Edwards et al. (2021); Einarsson (1963); Erlendsson (2007); Hallsdóttir (1987); Streeter et al. (2015); Thorarinsson (1944). Such research has shown that Landnám introduced a significant alteration to the vegetation and environment of Iceland; this thesis is concerned with what happened next. Set within the temporal and cultural context embraced by medieval Icelandic monasticism (12th century to 16th century), high resolution pollen sampling sheds light upon the land use practices associated with these religious institutions and the vegetation change that they induced. In turn, this introduces the potential to place Icelandic monasticism within a wider European context, gain insight into the monastic mission, as well as consider its impact upon the tenant farms that were subject to it. Furthermore, Icelandic monasteries were themselves exposed to external forces; plague, Protestant Reformation, volcanism and a cooling climate, all potentially capable of leaving their mark on the Icelandic pollen record.

1.1 The vegetation history of Holocene Iceland

It is important to outline something of the development of vegetation in Iceland during the Holocene (c. 11,000 BP to Landnám c. AD 877) in order to inform the interpretation of pollen assemblages for later periods with regard to habitats, volcanism, and climate.

Palynological studies concerned with the evolution of early Holocene vegetation are derived mostly from northern Iceland (Caseldine et al. 2006; Eddudóttir et al. 2015; Eddudóttir et al. 2016; Hallsdóttir, 1995; Rundgren, 1998). Within this area, there is both temporal and spatial variation with regard to the demographics and pace of vegetation change linked to climate, topography, rates of de-glaciation, and proximity of seed sources (Caseldine et al. 2006; Hallsdóttir, 1995; Rundgren, 1998; Rundgren & Ingólfsson, 1999). Broadly therefore, from c. 10,100 BP, the recently de-glaciated landscape of northern Iceland comprised of fellfield supporting a sparse vegetation dominated by Poaceae (grasses), Caryophyllaceae (campions, chickweeds, stitchworts and mouse-ears), and *Oxyria digyna* (mountain sorrel). In response to increasing warmth, these fellfield plant communities were replaced by a low arctic heath dominated by *Salix* (willow) before giving way to *Juniperus communis* (juniper) dominated communities by 9200 BP (Björck et al. 1992; Hallsdóttir, 1995; Rundgren, 1998).

Subsequent to this, the presence of *Betula pubescens* (downy birch) becomes ever stronger in the pollen record, and woodland becomes a feature across north and south Iceland (Caseldine et al. 2006; Eddudóttir, 2016; Hallsdóttir, 1995). There is some evidence from the lowlands of the south to suggest that woodland was more dense in inland areas than it was by the coast (Hallsdóttir, 1995). Woodland expanded from lowland areas, up mountainsides to c. 400 m (c. 6700-6000 BP), and encroached upon the central Highland zone (c. 7800-6500 cal. yr. BP), to reach its maximum extent sometime between c. 7200 and 6000 BP (Eddudóttir, 2016; Hallsdóttir, 1995; Wastl et al. 2001). This was probably the result of a combination of an ameliorating climate (Hallsdóttir, 1995; Hallsdóttir & Caseldine, 2005) and increasingly stable environmental conditions i.e. potentially mobile substrates from deglaciated areas and volcanic ash deposits (tephra) were immobilised due to increased vegetation cover (Eddudóttir, 2016).

From c. 6000 cal. yr. BP, there is a retrogressive succession (perhaps more so in the south) toward a *B. pubescens* woodland of a more open character which allowed both heath and mire habitat types to become more prominent in the landscape (Eddudóttir, 2016; Erlendsson et al. 2009; Hallsdóttir, 1995). This was likely linked to the cooling of the climate c. 5500 cal. yr. BP, subsequent increased instability in environmental conditions, and the onset of Neoglaciation (Eddudóttir, 2016; Larsen et al. 2012; Striberger et al. 2012). However, several episodes of *B. pubescens* expansion do arise during the latter part of the Holocene prior to Landnám (Eddudóttir, 2016; Hallsdóttir & Caseldine, 2005). These may be connected with brief phases of climate amelioration e.g. the Medieval Climatic Optimum (MCO) c. AD 800-600 (Erlendsson & Edwards, 2009; Patterson III et al. 1987). A further palynological feature that has been linked to climate amelioration is the hybridisation of *B. pubescens* with *Betula nana* (dwarf birch), arising when *B. pubescens* encroaches upon areas occupied by *B. nana* and ultimately displacing it (Karlsdóttir, 2014; Karlsdóttir et al. 2009). The fundamental point here is that prior to the arrival of humankind in Iceland in the late 9th century, climate was the primary agent of vegetation change.

Whatever the prevailing climate regime, volcanism is an ongoing feature of the Icelandic environment. The effects of such might be obvious with regard to vegetation in close proximity to eruption sites i.e. fire, lava etc. (Buckland et al. 1995; Thorarinsson, 1944). Perhaps a less immediately obvious impact is the deposition of tephra of various thicknesses across vast swathes of the Icelandic landscape. For example, in Svínadalur in northern Iceland, tephra deposits from the Hekla 4 (H4) eruption (c. 4200 cal. yr. BP) can be up to 8 cm thick despite being c. 170 km from the source volcano. Pollen data from lowland Svínadalur show that *B. pubescens* at that time was largely resilient to the H4 tephra fall, despite the impact being exacerbated by a cool climate. However, where *B. pubescens* was growing in less ecologically optimal parts of Svínadalur i.e. on the margin of the Icelandic Highland zone, it was replaced by dwarf shrub heath (Eddudóttir et al. 2017).

1.2 The vegetation and land use history of Landnám and Medieval Iceland

Despite the vagaries of Holocene volcanism and climate, most of lowland Iceland was vegetated in the period immediately prior to the to the arrival of the settlers and their domestic animals. Southern and western Iceland was comprised of a matrix of woodland (of open character), dwarf shrub heath, and wetland outwith the active volcanic zones and glacier outwash plains (Erlendsson, 2007; Hallsdóttir, 1987, 1995; Hallsdóttir & Caseldine, 2005). We also know that settlement occurred not long after a peak in *B. pubescens* (Erlendsson & Edwards, 2009; Hallsdóttir, 1987) i.e. woodland may have been open and dispersed but it remained a significant feature of the landscape (Einarsson, 1962, 1963).

Indeed, while it is perhaps an exaggeration (Edwards et al. 2011), the quasi-historical *Íslendingabók* describes Iceland at Landnám as covered in woodland "*á miðli fjalls ok fjóru*" i.e. between the mountains and the shore (Benediktsson, 1968; Friðriksson & Vésteinsson, 2003; Grønlie, 2006). In light of this statement, palynologist Þorleifur Einarsson (1962, 1963) concluded that "*the birch forest was devastated very rapidly…*", mirrored by an expansion in Poaceae and the introduction of cultural indicators e.g. *Hordeum*-type (barley), following the settlement of Iceland in the late 9th century. Einarsson's analysis was primarily based upon pollen derived from two wetland cores from Borgarmýri (Reykjavík) and Skálholt. Margarét Hallsdóttir (1987) draws similar conclusions from her study of four sites in south west Iceland (Vatnsmýri in Reykjavík, Mosfell and Svínavatn in Grímsnes, and Þrándarholt in Hreppar) with regard to the devastation of woodland, at least in the vicinity of the sampling sites, which she suggests occurred very rapidly (within 80 years). The implication here is of active woodland clearance in order to create hayfields and pasture for domestic livestock, said animals inhibiting any chance of woodland recovery through grazing. As a consequence, grassland, heathland and wetland habitats became more prominent in the pollen record (Einarsson, 1963; Hallsdóttir, 1987).

With specific regard to cultural indicators, Einarsson (1963) identified a suite of plant species he considered anthropophilous, and following Edwards et al. 2011, can be divided into two groups; 1) apophytes, a suite of plants that benefitted from the land use practices of the settlers e.g. Caryophyllaceae, *Polygonum aviculare* (common knotgrass), *Plantago maritima* (sea plantain) and *Rumex* (sorrel); 2) archaeophytes, plants that were either deliberately or accidentally introduced to Iceland by the settlers e.g. *Valeriana* (valerian), *Linum* (flax), *Artemisia* (mugwort/woodbine), *Hordeum*-type and (possibly) *Myrica gale* (bog myrtle). These groups of species have since been elaborated and refined upon by others e.g. Erlendsson (2007), Hallsdóttir (1987), and Edwards et al. (2021), along with a further suite of species considered grazing sensitive i.e. those negatively impacted by the presence of grazing animals e.g. *Filipendula ulmaria* (meadowsweet) and *Angelica* spp.

It must be borne in mind that the emphasis of the work by Einarsson (1962, 1963) and Hallsdóttir (1987) largely applies to the south west of Iceland, and in association with what are thought to have been large, high status, farms. It should therefore not be surprising that significant changes in vegetation are found on these landholdings (Edwards et al. 2021; Erlendsson, 2007). Indeed, the pollen investigations of Egill Erlendsson (2007) of three landholdings, dispersed between southern and western Iceland, have shown that the story may be more complex. At Stóra Mörk in southern Iceland, the swift demise of woodland and shrub taxa along with other grazing sensitive species (*F. ulmaria*) in hand with an increase in values for apophytes (e.g. *P. aviculare*), generally corresponds with the findings of Einarsson (1962, 1963) and Hallsdóttir (1987). In Reykholtsdalur, in the lowlands close to the farmstead, a similar process occurs with woodland swiftly replaced by a pastoral landscape dominated by Poaceae and Cyperaceae (sedges). There is also strong evidence indicative of cereal cultivation i.e. *Hordeum*-type and associated arable weeds. In upland areas of Reykholtsdalur (Breiðavatn), while pollen values for *B. pubescens* decline, the magnitude of change is less pronounced than in the lowland zone and woodland persists. In contrast to both Stóra Mörk and Reykholtsdalur, at Ketilsstaðir, where woodland was generally absent prior to Landnám, there was very limited indication of anthropogenic alteration to the vegetation. Anthropochores are largely absent, and the drying out of wetlands is linked to tephra falls from the Katla AD 920 and Eldgjá AD 935 eruptions. This work was complimented further by research from northern Iceland

(Mývatnsveit) where *B. pubescens* can again be seen to persist into later periods following Landnám, its decline gradual rather than immediate (Lawson et al. 2007). Furthermore, rather than Poaceae or Cyperaceae dominated habitats, heath (*Empetrum nigrum*; crawberry) and mire (*Sphagnum*) predominately replace *B. pubescens*. Overall, these findings highlight the need to evaluate each pollen assemblage in its own right rather than to draw broad conclusions for the entirety of Iceland (Erlendsson, 2007; Lawson et al. 2007).

Collectively, the in-depth work of Einarsson (1962, 1963), Hallsdóttir (1987), Erlendsson (2007) and Lawson et al. (2007) represent the foundation of palynological studies concerning the arrival of humankind in Iceland, recognised for their contribution to the understanding of human settlement patterns in Iceland (Vésteinsson, 1998), the human colonisation of North Atlantic islands (Edwards et al. 2021), and the Anthropocene (Streeter et al. 2015). This work has been further enhanced through a swathe of recent studies that cast ever more light upon the rate and magnitude of human colonisation across Iceland in the late 9th century. In Mosfellsdalur (southwest Iceland), it has been demonstrated that although settlement was simultaneous across the valley, its impact upon the environment and ecology in terms of magnitude varied between the five farms investigated (Riddell et al. 2018). On a broader scale, the work of Bates et al. (2022), Hiles et al. (2021), and Tisdall et al. (2018) has reinforced the perception that the evolution of a pastoral landscape in northern Iceland was initially less intensive than it was in the southwest of Iceland with *B. pubescens* persisting into later periods. Akin to the work of Erlendsson (2007) at Ketilsstaðir, the research of Roy et al. (2018) has found that northeast Iceland (Svalbarðstunga) was largely devoid of tree cover prior to Landnám. Nonetheless, the introduction of domestic animals promoted Cyperaceae and Poaceae dominated habitats with an increased apophyte signal (*P. aviculare*). Meanwhile, there is now evidence of human occupation and/or transhumance from the Highland margin (Barðalækjartjörn) in Svínadalur, an area now considered uninhabitable (Eddudóttir, 2016).

An aspect of both Holocene and Landnám pollen studies in Iceland is the high concentration of pollen sampling around a specific event e.g. climate, an eruption, and of course Landnám. Although the overall sampling sequence in these studies may extend into earlier and later periods, sampling resolution is usually lower. This is likely a consequence of research questions, but also to do with the condition of potential sampling sites in Iceland. Upper stratigraphies containing later pollen assemblages are often disturbed by human activities e.g. turf/peat cutting, modern agricultural improvement, especially where cores are acquired from close to farmsteads. Such can either introduce a hiatus to the sedimentary sequence e.g. (Erlendsson, 2007; Erlendsson et al. 2009), or obliterate stratigraphies entirely. Similar issues can also arise as a consequence of past soil erosion and the subsequent redeposition of windblown materials (Dugmore et al. 2009). Nonetheless, high pollen sampling resolution is being applied to later sediments in an effort to understand better what happened to the vegetation of Iceland following Landnám e.g. variation in land use practices (Erlendsson, 2007), soil erosion (Gísladóttir et al. 2011; Gísladóttir et al. 2010), cereal cultivation and social status (Riddell et al. 2018; Zori et al. 2013). In light of this, while continuing to incorporate Landnám into the pollen analysis, the present study will continue to build upon developing a palynological understanding of the Medieval period in Iceland with regard to Icelandic monasteries and their tenant farms.

1.3 Soils and Icelandic vegetation history

The parent materials of all Icelandic dryland soils are tephra and aeolian sediments comprised of volcanic glass, with aeolian processes, tephra deposition, and cryoturbation all actively modifying soil conditions (Arnalds, 2004). In particular, aeolian processes are responsible for redistributing materials and recharging soil surfaces from source areas i.e. glacio-fluvial floodplains (*sandur*) and volcanically active areas (Arnalds, 2008). This results in two broad soil categories defined by drainage and rates of aeolian redeposition; Andosols and Histosols (wetlands), covering an estimated 86% and 1% of Iceland respectively (Arnalds, 2004). Andosols are characterised by their high organic content, high water holding capacity, and low cohesion. Due to moisture capacity and the Icelandic climate, Andosols are vulnerable to intense cryoturbation, which can give rise to solifluction and erosion. Histosols share andic properties but contain much higher amounts of carbon (≥20% C) as a consequence of being poorly drained and are more resilient to degradation (Arnalds, 2004; Möckel et al. 2017); indeed, it is thought that Icelandic wetlands would be almost 100% organic if it were not for volcanic (andic) input (Arnalds, 2008).

In terms of the Holocene, Icelandic soils grew progressively thicker as older soils were buried beneath subsequent volcanic deposits and aeolian inputs, with most weathering occurring at the surface, and organic C accumulating during periods of mild climate (Arnalds, 2008). Within this framework, three phases of significant soil degradation are recognised (at least in northeast Iceland), two of which (c. 5000 BP and c. 2500 BP) are linked to deteriorating climate, elevation, and topography (Ólafsdóttir & Guðmundsson, 2002). The third phase was initiated at Landnám c. AD 877 with the introduction of large herbivores by the settlers which disrupted the prevailing pattern of soil development (Arnalds, 2008; Ólafsdóttir & Guðmundsson, 2002). Studies in southern Iceland have shown that the earliest impacts of grazing were felt in ecologically marginal areas i.e. uplands, where vegetation cover became fragmented, allowing soil erosion to develop (Dugmore et al. 2009). In such instances, Andosols beneath the vegetation were undermined by wind, rain, and livestock, to create escarpments (*rofaborð*) which retreat and leave barren land (glacial till, lava) behind (Arnalds, 2008). The aeolian redeposition of this material had a minimal impact as the upland soils were relatively shallow i.e. there was little material to be denuded in the first place. However, from c. AD 1500, localised overgrazing in lowland areas led to similar developments, and even though rates of denudation were slower, deeper soils resulted in a much greater movement of eroded material (Dugmore et al. 2009). The aeolian redeposition of eroded soils can abrade and bury vegetation and ultimately kill it. Such loss of vegetation cover can lead to further destabilisation of soils and their redeposition, leaving desert behind (Arnalds, 2008). Indeed, overgrazing in combination with a perfect storm of increased volcanism and a deteriorating climate can be catastrophic with a legacy lasting centuries (Gísladóttir et al. 2011). It is unsurprising therefore, that from its earliest days, analysis of sedimentary data has been a feature of palynological study as a complimentary proxy to understanding past environmental conditions in relation to past vegetation (Einarsson, 1962, 1963). In particular, ratios between minerogenic and organic material in lakes and wetland sediments can be informative with regard to the environmental impacts of climate, volcanism, and humankind (Dearing, 1994; Erlendsson, 2007; Gísladóttir et al. 2011; Gísladóttir et al. 2010; Heiri et al. 2001).

1.4 Medieval monasticism in Iceland

Drawing again upon the saga tradition, particularly Kristni Saga (Grønlie, 2006), the formal conversion of Iceland to Christianity occurred around AD 1000 with a declaration made at the Alþingi, Þingvellir, following strife between Christians and non-Christians. From this time, the material remains of pagan burial in Iceland disappear from the archaeological record (Karlsson, 1996). Private churches were founded, situated within farmsteads that belonged exclusively to individual families. The foundation of public churches that fulfilled a missionary role was a parallel development e.g. Þórarinsstaðir (Kristjánsdóttir, 2004). Episcopal seats (Fig. 1) were established first at Skálholt in the mid-11th century, followed by Hólar in the early 12th century with parochial oversight for north and south Iceland divided between them (Kristjánsdóttir, 2023). Both were ultimately subject to the Archdiocese of Níðaros (Tröndheim), Norway. The first Icelandic monastery was founded at Bær (Fig. 1; Bæjarklaustur). This monastery was very short lived and it was not until the 12th century that monasticism became firmly embedded in Icelandic society (Fig. 1; Kristjánsdóttir, 2023). At this time, seven monasteries were founded (Flateyjarklaustur and Helgafellsklaustur are essentially the same institution) followed by a handful of others in the 13th century, with Skriðuklaustur the last in the 15th century. Keldnaklaustur, Hítardalsklaustur and Saurbærjarklaustur failed to persist but the remainder continued until the Lutheran Protestant Reformation in the early 16th century.

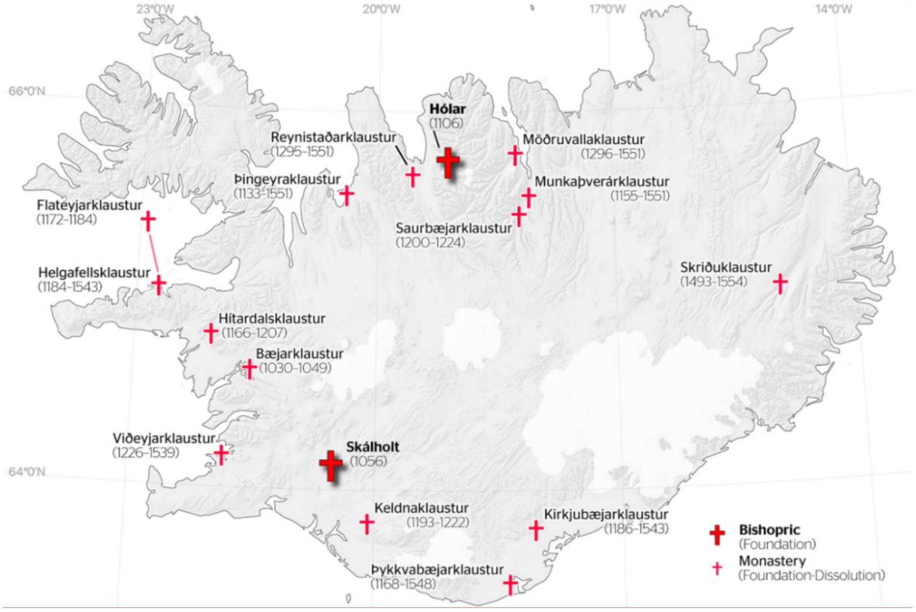


Figure 1 The Medieval bishoprics and monasteries of Iceland (adapted from Kristjansdottir 2023).

Until recently, the impact of these monasteries upon Icelandic society and environment has largely been dismissed. This has been attributed to nationalistic and sectarian historical perspectives prevailing in the Nordic sphere long after the Reformation and into the modern period (Kristjánsdóttir, 2023). On considered reflection, the establishment of these monasteries was clearly part of the wider development of the Roman Church across Scandinavia and the North Atlantic in the 12th century (Clark, 2021), and nor can it be unrelated to a broader renaissance in European monasticism at that time (Aston, 2000). Furthermore, from foundation, Icelandic monasteries immediately began to accumulate land and given their longevity (up to 420 years), this must have had some bearing upon land use. Indeed, these monasteries were to become some of the largest landowning entities in medieval Iceland, particularly from the 14th century (Júlíusson, 2014; Kristjánsdóttir, 2023). This underpinned their most enduring legacy, the production of manuscripts e.g. at Helgafellsklaustur (Drechsler, 2021) and Þingeyraklaustur (Jensson, 2021), artefacts that have since become fundamental to the national identity of Icelanders (Loftsdóttir, 2019).

Archaeological excavations at Skriðuklaustur (Fig. 1) have also gone some way to revising the conventional perception of monasticism in Iceland. The physical layout of the monastery conforms to that of continental institutions while forensic analysis of burials suggests that this monastery functioned as a hospital (Kristjánsdóttir, 2023); a mission again consistent with European monasticism (Kristjánsdóttir, 2010b). The medical role is borne out further by the remains of artefacts that might have been surgical implements while palynological analysis of bulk sediment samples from archaeological contexts has revealed the presence of introduced medicinal plants e.g. *Allium* sp., *Borago officinalis,* and *Plantago major* (garlic, borage, and greater plantain respectively), perhaps grown in the cloister garden (Kristjánsdóttir, 2010b, 2023; Kristjánsdóttir et al. 2014). The pollen of introduced plants with medical and/or culinary applications e.g. *Artemisia*-type, *M. gale, P. major, Sanguisorba officinalis* (great burnet), *Urtica* sp. (nettle) and *Valerian officinalis,* has also been detected from archaeological contexts at Viðeyjarklaustur (Hallsdóttir 1993). Furthermore, a recent survey of monastic sites in Iceland found populations of introduced plants with medicinal applications that are considered relics of the cloister garden e.g. garlic at Bæjarklaustur, nettle at Reynistaðarklaustur, and *Asperugo procumbens* (madwort) at Þingeyraklaustur (Åsen, 2021; Kristjánsdóttir et al. 2014).

The understanding of the role of Icelandic monasteries in influencing the wider landscape, both in their immediate surroundings and that of their tenant farmers, is limited. Zooarchaeological material from Gásir in Eyjafjörður has implicated both Möðruvallaklaustur and Munkaþverárklaustur in the production of beef cattle to supply meat to this seasonal trading port (Harrison et al. 2008). Möðruvallaklaustur may have been further engaged with Gásir through the export of woollen goods necessitating the evolution of a specialised sheep station on its landholding (Harrison, 2014). The supply of beef and woollens goods to Gásir would demand a considerable area of grazing land for livestock, incorporating a number of tenancies, and would presumably have some impact upon the composition and resilience of plant communities within. This has yet to be tested palynologically. With regard to the more immediate vicinity of the cloister, there is some pollen evidence of wood/scrub clearance in association with Viðeyjarklaustur, and interestingly, the introduction or intensification of cereal cultivation there (Hallsdóttir, 1993). The agricultural developments of Möðruvallaklaustur and Viðeyjarklaustur are very much in keeping with the activities of monasteries elsewhere in Europe, especially from the 12th century (Aston, 2000; Bond, 2004; Gilchrist, 2014; Hall, 2006). At its simplest, palynology identifies the active clearance of woodland and scrub (*assarting*) by monastic institutions to create agricultural land (Table 1). These types of development drove technological innovation, such as the construction of cultivation terraces, wetland drainage, and even the introduction of nitrogen-fixing plants to pasturelands. Were Icelandic monasteries importing similar ideas of land use and management, perhaps intimated by the pollen evidence from Viðeyjarklaustur?

While European monasteries clearly harboured the potential to significantly alter the landscape environmentally and ecologically, they were also subject to environmental, ecological, and societal change. Broadly, altered human demographics due to the Black Death are visible in the European pollen archive i.e. the recovery of woodland in formerly intensively farmed landscapes (van Hoof et al. 2006; Yeloff & van Geel, 2007). More specifically in relation to monasteries, pollen studies show that heathland encroached upon formerly cultivated land once the Dominican monastery of Selja relocated to the episcopal seat in Bergen (Hjelle et al. 2010). In England, after the Protestant Reformation, the dissolution of Furness Abbey and the division of its lands witnessed swathes of pasture give way to a mixed agricultural economy (Wimble et al. 2000). Can similar features be identified in the Icelandic pollen record?

There is evidence from Britain to show that the scale of land use change associated with monasteries as discussed above, could extend beyond the immediate vicinity of the cloister landholding (Tipping, 2010; Wimble et al. 2000). Contemporary with the foundation of Icelandic monasticism in the 12th century, many formerly independent landholdings were transitioning into tenancies subject to a manor-type farm (Jakobsson, 2013; Júlíusson, 2010) and a peasant society evolved (Júlíusson, 2007; Vésteinsson, 2007). As landownership became increasingly centralised in Iceland, outwith niche markets and marine commodities, subsistence shifted toward cultivating a surplus in woollen goods for export, the latter evident in altered bovine/caprine bone ratios from medieval farm middens (McGovern et al. 2017). It was under such a regime that by the 14th century, the monasteries of Iceland had amassed a large number of landholdings, tenancies submitting rental payments in the form of fish, dairy, meat, woollens, charcoal etc. (Jakobsson, 2013; Júlíusson, 2014; Kristjánsdóttir, 2023). However, from both an archaeological and historical perspective, while considerable effort has been given to investigating the household economics of individual farms in Iceland on the one hand, and the macro-economics of international trade on the other, there remains a gap in understanding as to how this may apply to tenant farms (Bolender et al. 2020; Júlíusson et al. 2020; Lucas, 2012; Pálsson, 2018). This also holds true for palaeoecology, with methodologies only recently being deployed to consider questions pertaining to socio-economic circumstances in Iceland's past, e.g. social status (Riddell et al. 2018) and the management of commons (Sigurmundsson et al. 2014). Is it possible to utilise palaeoecological methods to discern the influence of monasticism over newly acquired tenancies in the 14th century?

The majority of Iceland's monasteries were established during the 12th century, within the span of the Medieval Climatic Optimum (MCO, AD 900-1500) when mild climatological conditions prevailed in the North Atlantic (Mann, 2002a). Such conditions, in both monastic and secular contexts, likely enhanced the potential for agricultural development in the Icelandic landscape, mitigating the detrimental environmental impacts derived from woodland clearance and livestock grazing e.g. erosion. By the time of the dissolution of Icelandic monasteries during the Lutheran Reformation in the mid-16th century, Iceland was in the thrall of the Little Ice Age (LIA), AD 1500-1900 (Mann, 2002b), the cooling climate actively contributing to the degradation of vegetation cover and denudation of soils (Dugmore et al. 2009). In terms of environmental and ecological impact and how this may have affected monasticism in Iceland, this simplified interpretation of the MCO and LIA stands. Note however that the climate regime encompassed by the timeline of the MCO and LIA is far more complex for Iceland (Mann, 2002b; Ogilvie & Jónsson, 2001). Marine sedimentary proxies from the Greenland Sea infer that the MCO in Iceland occurred AD 800-1350, followed by the LIA which lasted until AD 1900 (Eiríksson et al. 2000). Data from lacustrine sediments refine the MCO to

AD 950-1150, with the LIA spanning AD 1250-1900 (Larsen et al. 2012). The latter is consistent with analysis of historical sources although these identify two distinct phases to the LIA (Ogilvie & Jónsson, 2001); a relatively mild early phase punctuated by brief periods of harsh climate c. AD 1250-1500 followed by an era where the incidence and severity of hostile conditions intensified c. AD 1500-1900.

Table 1 Palynological evidence of monastic land use and associated environmental and ecological change in Europe, Scandinavia, Britain and Ireland.

Location	Pasture	Arable	Terraces	Drains	Archaeophyte	References
Abbeyknockmoy, Galway, Ireland	✓	✓				Lomas-Clarke & Barber (2004)
Melrose, Borders, Scotland	✓				✓	Tipping (1997)
Furness, Cumbria, England	✓	✓				Wimble et al. (2000)
Lac d'Annecy, Alps, France	✓					Noël et al. (2001)
Fénay, Burgundy, France		✓		✓		Laine et al. (2010)
Rieti, Lazio, Italy (Apennines)	✓	✓		✓		Mensing et al. (2016)
Schwaz, Tyrol, Austria	✓					Breitenlechner et al. (2010)
Pfälzerwald, Palatinate, Germany	✓	✓	✓			Stolz & Grunert (2010)
Selja, Vestland, Norway	✓	✓				Hjelle et al. (2010)
Viðey, Reykjavík, Iceland	✓	✓				Hallsdóttir (1993)

1.5 Consilience and palaeoecology in Iceland

An aspect of this study will be the interpretation of palynological data with reference to historical sources. This has been identified as the 'confirmatory' approach or as 'consilience', where correlation between data sources is sought (Haldon et al. 2018; Tipping, 2004). There are inherent difficulties attached to this i.e. the imposition of general histories with vague spatial resolution upon very specific, fixed points in the landscape; pollen sampling resolution may not be concentrated enough in relation to specific time periods; data sets may be contradictory. Utilising histories that are specifically identified with the pollen site under investigation immediately overcomes the spatial concerns, and in this case, the *Diplomatarium Islandicum* (DI-I-XVI, 1857-1976) is particularly relied upon. Mitigation of temporal issues is addressed through the increased resolution of pollen sampling for the period in question (as discussed previously with regard to Landnám and the medieval period that follows). Contradiction between documentary and palynological data simply emphasises the value of interdisciplinary approaches, allowing for subtlety and nuance to be more fully appreciated (Haldon et al. 2018; Mensing et al. 2020; Tipping, 2004). Concern has also been expressed over the chronological disparity between the fixed calendar dates of historical sources and the imprecision attached to conventional radiocarbon dating (Dumayne et al. 1995; Tipping, 2004). Fortunately, in Iceland, this problem is offset through the application of tephrochronology where volcanic ash layers of known provenance and age are used to synchronise and date palaeoecological data between study sites (Larsen & Eiríksson, 2008; Lowe, 2011; Thorarinsson, 1944).

1.6 Research aim and objectives

The principal aim of this project is to reconstruct the evolution of past vegetation communities at four sites (two monasteries and two monastic tenancies) in Iceland through palynological analysis. Pollen analyses is supplemented by sedimentary data and documentary sources (where applicable). The specific objectives are to:

- Determine whether or not the introduction of monasticism to Iceland in the 12th century was accompanied by changes in the environment/ecology of the monastic landholding (**Papers I & II**).

- Track the development of environmental/ecological change on the monastic landholding over time (12th century to 16th century) as a reflection of land use practices initiated by Icelandic monasteries (**Papers I & II**).

- Discern the presence of European influences upon Icelandic monastic land use practices through the introduction of new plants and/or land use systems, and/or the intensification of established land use practices (**Papers I & II**)

- Assess the manner in which farm tenants on monastic landholdings responded to the introduction of monastic ownership i.e. societal change identifiable via altered land management practices expressed through environmental/ecological change (**Paper III**).

2 Methods

2.1 Site selection and field methodology

The first consideration of site selection was historical context i.e. farms that were known to have formerly hosted a monastery, or tenancy of a monastery, during the medieval period. The key historical source is the *Diplomatarium Islandicum* (DI-I-XVI, 1857-1976), a collection of Icelandic letters, deeds, annals and inventories from c. AD 1150-AD 1550. It is assumed that the places named in DI are consistent with their modern counterparts, qualified by the geographical descriptions as given in DI, and with reference to archaeological investigations (Kristjánsdóttir, 2023; Zori & Byock, 2014).

The second prerequisite was to determine the presence of suitable coring areas in close proximity to the identified farmsteads i.e. wetlands and small waterbodies (ponds, tarns, lakes), anaerobic depositional environments which lend themselves to the preservation of pollen (Moore et al. 1991). This was achieved with reference to aerial images with the underlying premise that coring in the near vicinity of farmsteads enhanced the potential to detect past land use practices (Erlendsson, 2007). Broadly, most pollen found within wetland sediments (**Papers I & III**) originates from the wetland itself or from its immediate vicinity i.e. inwash from the surrounding slopes (Moore et al. 1991). Waterbodies, while also capturing pollen from adjacent slopes, will also acquire pollen from their wider watershed (Moore et al. 1991). This latter point needs to be accommodated with regard to site specific analysis i.e. by ensuring that the entire watershed is within the area or landholding under investigation (**Paper II**). Both habitats are subject to long and mid-range dispersal, including pollen originating from beyond Iceland. Research has shown that overseas material has limited impact upon the interpretation of pollen assemblages in Iceland (Hättestrand et al. 2008). This variable is further reduced by woodland cover (Berglund, 1985), although this might only apply in this study with regard to pre-Landnám contexts. Mid-range factors need to be considered on a site-by-site basis with wind direction, woodland cover, erosion of terrestrial sediments, and proximity to open landscapes associated with volcanism or flooding taken into account (Möckel et al., 2021).

A third factor is the presence of an intact sedimentary sequence in the selected wetland or waterbody, preferably incorporating identifiable and dateable tephra layers. A review of academic literature and isopach maps will inform as to what tephra layers may be found in a given area e.g. Larsen & Eiríksson (2008), but field identification remains nominal.

For wetlands in Iceland, the upper strata of sedimentary sequences can often be disturbed by human activities e.g. peat and turf cutting and/or modern agricultural improvement; especially close to farmsteads. These activities can introduce a hiatus to the sedimentary sequence or destroy them entirely e.g. (Erlendsson, 2007; Erlendsson et al. 2009). Disturbance may also arise as a consequence of past soil erosion and the redeposition of windblown material (Arnalds, 2008; Dugmore et al. 2009). Therefore, integrity of wetland cores is initially determined through the random test coring of selected wetlands (**Paper III**). Once an intact stratigraphy supporting a suite of potentially identifiable tephra layers is found, a pit is cut (c. 1 m^2 and usually to a depth between 0.75

m and 1.5 m), and a monolith is extracted. An alternative approach is to extract a monolith from the bank of a ditch once the desired section has been cleaned (**Paper I**). Extracted monoliths/cores are protected by plastic guttering, wrapped in plastic film (to inhibit contamination and moisture loss), and stored at 4°C prior to laboratory analysis.

With regard to lake coring (**Paper II**), a Livingstone piston corer with a Bolivia adapter and a 75 mm diameter polycarbonate tube is used to extract a sediment core (which are stored a 4°C prior to laboratory analysis). This can require a number attempts in order to ensure an intact stratigraphy containing potentially identifiable tephra layers. The deepest part of the lake is preferred, where depositional conditions tend to be more stable; inflows are avoided due to the potential risk of disturbance to sediments (Moore et al. 1991).

2.2 Sampling sites

The four sampling sites are dispersed across northern and western Iceland (Fig. 2).

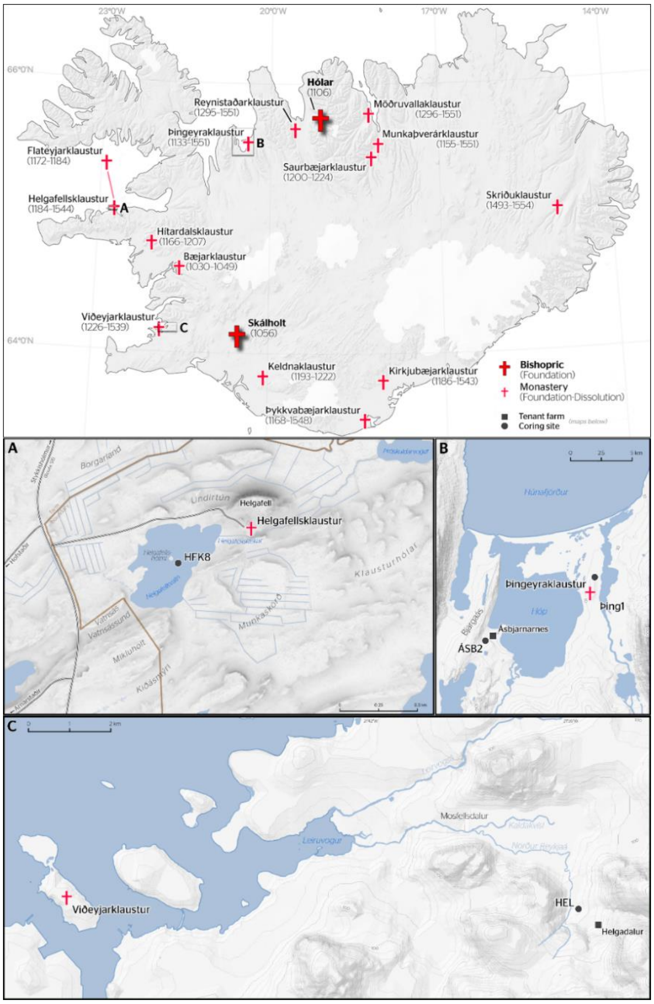


Figure 2 Monastery and tenancy sampling sites.

Climate information is given in Table 2. Icelandic Vegetation Classifications (Ottósson et al. 2016) apply unless otherwise stated. Erosion categorisation follows Arnalds (2004).

Table 2 Climate data for study sites (Icelandic Meteorological Office, 2007).

	Blönduos/ Hjaltabakki	**Stykkishólmur**	**Reykjavík**
Location	N65°42’10” W20°10’24” N65°39’42” W20°15’1”	N65°04’44” W22°44’03”	N65°36’54” W19°57’15”
Elevation (m a.s.l.)	8/23	10	52
Avg. temp °C tritherm	8.7	8.1	10
Avg. temp °C July	9.4	9.2	10.6
Avg. temp °C January	-2.5	-1.3	-0.5
Avg. pptn. mm yr^{-1}	458	704.6	799
Recording period	1961-1999^{a}	1961–1990	1961–1990

Þingeyrar (**Paper I**; Fig. 2B) is the former site of a medieval monastery (Þingeyraklaustur). It is located in Vestur-Húnavatnssýsla, northern Iceland, c. 13 km southwest of the town of Blönduós (from where climate data are derived). A sediment monolith (ÞING) c. 75 cm long was extracted from the bank of a ditch (N 65° 33’ 5.94” W 20° 23’ 8.54”) c. 500 m from the modern farmstead and historic monastery site. The ditch lies within a wetland (c. 20 m a.s.l.) that is nominally an Icelandic black sedge-brown moss fen (D4.162) but has been planted with conifers. Due to the dynamic coastal context, erosion in the surrounding area ranges from considerable, to severe, to extreme. Where vegetation prevails it is comprised of heathland, wetland and coastal plant communities. Soil conservation measures have also been implemented i.e. the introduction of the *Lupinus nootkatensis* (Alaskan lupin).

Helgafell (**Paper II**; Fig. 2A) is the former site of a medieval monastery (Helgafellsklaustur). It lies c. 4 km south of the village of Stykkishólmur (from where climate data are derived) on Snæfellsnes in western Iceland. A core (HFK8) c. 1.5 m long was extracted from Helgafellsvatn (c. 17 m a.s.l., water depth 125 cm), a lake adjacent to the modern farmstead (N 65° 2’44” W 22° 44’168”). The vegetation surrounding the lake includes improved and semi-improved pasture, fen and dwarf shrub heath. Aquatic plants typical of Helgafellsvatn include *Equisetum fluviatile* (water horsetail), *Menyanthes trifoliata* (bogbean) and *Myriophyllum alterniflorum* (alternate water milfoil).

Ásbjarnarnes (**Paper III**; Fig. 2B) is located c. 9 km west of Þingeyrar. A sediment monolith (ÁSB2) c. 75 cm long was extracted from Sund (N 65° 31’ 8.44” W 20° 35’ 32.48”), within the portion of the farm described as belonging to Þingeyraklaustur (Fig. 2B) from AD 1361 (DI-III, 1857-1976, pp. 179-181). Sund (c. 20 m a.s.l, 0.4 km^2) is a North Atlantic boreo-alpine heath (F2.255) dominated by *B. nana* (dwarf birch) c. 90 m southwest of the farm mound of Ásbjarnarnes. The surrounding landscape is comprised of a matrix of heath, fen and modified pasture with considerable erosion on higher ground. Climate data originate from Blönduós and Hjaltabakki.

Helgadalur (**Paper III**; Fig. 2C) is a tributary valley of Mosfellsdalur, in southwest Iceland, c. 25 km east of Reykjavík (from where climate data are derived). The farm was acquired by Viðeyjarklaustur c. AD 1395 (DI-III, 1857-1976, p. 598). A sediment monolith (HEL) c. 1 m long was extracted from a modified wetland (c. 95 m a.s.l., a minimum of 0.27 km^2) c. 600 m northwest of the modern farmstead of Helgadalur (N 64° 9’ 49.19” W 21° 35’ 38.65”). This wetland is now classified as agricultural land (pasture) with Poaceae dominant and Cyperaceae sub-dominant. The immediate surroundings include pasture, hayfields and mixed-broadleaved/conifer plantation. The slopes of the encompassing uplands experience considerable erosion with surviving vegetation comprised of moss, grassland and heath.

2.3 Sedimentology

Sediment stratigraphies for all sites were described according to Troels-Smith (1955) as modified by Aaby & Berglund (1986), supplemented by Munsell Soil Color Charts (2009). These descriptions are simplified for the sediment and pollen charts presented in **Papers I, II and III**.

The length of each core was measured for magnetic susceptibility (MS; SI) with a Bartington MS2 meter and MS2E probe (Dearing, 1994) prior to being processed for other sediment properties. Resolution ranged between every 0.5 cm to every 1 cm with the purposes of detecting minerogenic influxes into the strata, tephra layers in particular. Measures of dry bulk density (DBD) and organic matter (OM) were taken every 1 cm. Samples were heated at 105 ºC for 24 hours and the DBD (g cm^{-3}) calculated by dividing the dry weight of each sample by sample volume (1.2 cm^3), consistent with Brady & Weil (1996). OM (%) was determined by combusting the remaining material of each sample at 550 ºC for 4 hours, the number derived from the difference in sample weight before and after burning (Heiri et al., 2001).

2.4 Age determination

The use of tephra underpins the chronologies of all study sites (Lowe, 2011). Tephra samples were extracted from specific horizons identified within the cores (visually or via MS). In order to discern the origin of the tephra samples, each was cleaned of humic material, sieved (63 µm), mounted, polished and carbon-coated for geochemical analysis. Tephra geochemistry was analysed at the University of Iceland using a JEOL JXA-8230 electron probe micro-analyser (EPMA). The acceleration voltage was 15 kV, the beam current 10 nA, with a beam diameter of 10 µm, except for intermediate or rhyolitic tephra which were set at 5 µm (due to crystallization and thin walls). The standards A99 (for basaltic tephra), ATHO and Lipari Obsidian (both for silicic and intermediate tephra), were measured prior to, and after, the analyses in order to verify consistency in analytical conditions. Data were then inspected for, and cleaned of, anomalies and analyses with sums <96% and >101%.

In some instances, it was necessary to supplement the tephrochronology with other dating methods i.e. ^{14}C (**Papers I & III**) or Pu (**Paper II**). ^{14}C dates were acquired by sieving (<250 µm) sediment samples and selecting suitable material for analyses e.g. wood and bark. This material was analysed by ETH Zurich, Switzerland, and the results were calibrated using IntCal20 (Reimer et al., 2020). While the uppermost sedimentary layers of HFK8 are ostensibly recent (2019/2020), the interface with the water column is ambiguous (Moore et al. 1991). Therefore, in order to secure a more reliable date, the top ten centimetres (0-10 cm) of the core were sampled for plutonium ($^{239+240}$Pu) as derived from nuclear weapons testing in 1963/1964 (Ketterer et al. 2002). These samples were subjected to Inductively Coupled Plasma Mass Spectrometry (ICPMS) analysis performed using a Thermo X2 quadrupole ICPMS system at the Northern Arizona University, procedures adapted from Ketterer et al. (2004).

For (**Papers I & III**), smooth-spline age-depth models were constructed using the clam package in R (Blaauw, 2010). For (**Paper II**), the chronology was developed with the Bacon package v. 2.5.0 (Blaauw & Christen, 2011) using the IntCal20 dataset (Reimer et al. 2020). The plot was created in RStudio (R version 3.3.3; R Core Team 2021). The purpose of the latter approach was to improve upon the presentation of the age/depth model in terms of error margins. Sediment Accumulation Rates (SAR) were calculated based upon these chronological frameworks.

2.5 Palynology

Between 36 and 45 pollen samples were evaluated per core at intervals of between 0.5 and 4 cm with resolution intensified for Landnám and the medieval period. The volumes of the pollen samples were determined by displacement in 10% HCL (Bonny, 1972) with one *Lycopodium clavatum* tablet added per sample (Stockmarr, 1971) to determine pollen concentrations (grains cm^{-3}). Volumes ranged between 1-2 cm^{3}, the amounts adjusted where low pollen concentration was encountered. Samples were rinsed in 10% HCL to remove residual glue from the control tablet, 10% NaOH to break down humic material, and sieved (through a 150 µm mesh) to remove coarse material (Moore et al. 1991). Minerogenic material was removed by dense media separation using LST Fastfloat, density 1.9-1.915 g/ml (Björck et al., 1978; Nakagawa et al. 1998). Pollen grains were separated from other organic material via acetolysis before being slide-mounted with silicone oil (viscosity of 12,500 cSt.) and counted with a microscope at 400× to 1,000× magnification (Moore et al. 1991).

Pollen identification relies upon Moore et al. (1991) with pollen and spore taxonomy adapted to the Icelandic context (Erlendsson, 2007). Plant nomenclature follows Kristinsson (1986). A minimum of three hundred indigenous land pollen grains were counted per sample (total land pollen; TLP) with high chronological resolution favoured over large counts. The determination of the relative proportions of pollen and spore taxa within the sample is based upon TLP (Birks & Birks, 1980). In some instances, Cyperaceae can be overly dominant in Icelandic wetland pollen assemblages, and as TLP values are co-dependent, this can suppress values for other taxa (Caseldine & Hatton, 1994; Moore et al. 1991). In an effort to overcome this, some sample counts exceed 300 TLP to ensure a minimum of 100 non-Cyperaceae pollen types are represented for each sample (**Papers I & III**). Furthermore, the percentage values of some aquatic pollen and non-pollen palynomorphs (NPP) can exceed 100% TLP and as a consequence, pollen and spore concentration data are used to supplement interpretation (Moore et al. 1991).

Recorded NPP's comprise of (Moore et al. 1991) microscopic charcoal (Patterson III et al. 1987) and coprophilous fungal spores (CFS). Microscopic charcoal and CFS are considered environmental proxies for human activity and the presence of livestock in Iceland (Edwards et al. 2011; Edwards et al. 2021). CFS identification follows Cugny et al. (2010) and van Geel et al. (2003). All Poaceae pollen grains were evaluated as potential cereal-type pollen i.e. a mean grain diameter >37 µm and an annulus diameter >8 µm (Andersen, 1979). For **Papers I & II**, all *Betula* (birch) pollen grains were measured in order to distinguish between *Betula nana* and *Betula pubescens*. Following Karlsdóttir et al. (2007), the mean size of *B. nana* pollen grains is 20.4 µm while that of *B. pubescens* is 24.2 µm. This differentiation can be used to separate dwarf birch heathland from birch woodland (Caseldine, 2001; Erlendsson & Edwards, 2009; Mäkelä, 1996). Due to relatively high TLP, non-triporate *Betula* pollen is distinguished from *Betula* for HFK8 as an indicator of hybridisation between *B. nana* and *B. pubescens* (Karlsdóttir, 2014; Karlsdóttir et al. 2009).

Pollen, spore, and NPP count data were entered into TILIA (version 2.0.41) and subjected to a total sum of squares analysis (CONISS), producing a stratigraphically constrained dendrogram for each of the study sites (Grimm, 2011). Visual evaluation of the dendrograms allowed the data to be divided into PZ/LPAZ. In order to understand better the relationship between PZ/LPAZ at each study site, ordination analysis was utilised via the package vegan in R (Oksanen et al. 2016). Subject to Detrended Correspondence Analysis (DCA), axis lengths shorter than 2 SD on the first axis suggested a linear response in all the datasets (Hill & Gauch, 1980). Therefore, Principal Component Analysis (PCA) was applied to Hellinger transformed data. This consisted of pollen, spores, and NPP with percentages ≥1% (including microscopic charcoal for **Papers II & III**).

3 Results

3.1 Age determination (Papers I, II & III)

Tephrochronology is the fundamental component of age determination across all four sites investigated in this study (Table 3). Tephra data were supplemented with ^{14}C dates for two sites (Table 4). The ^{14}C date for ÞING (**Paper I**) was not adopted into the chronology as the date did not conform with the tephrochronological elements of the age-depth model. This could be due to a hiatus or disturbance to the sedimentary sequence of ÞING but reference to the sediment core and associated properties suggests a clear continuity in the strata between the H4 and H1 tephra layers. The age-depth model for HFK8 (**Paper II**) was supplemented with measures of Pu concentrations that suggest the upper 5.5 cm of the core represented the post peak fall out from nuclear weapons testing 1963/64 (Ketterer et al. 2004).

*Table 3 Tephra layers of known origin and date for **Papers I, II & II**.*

Tephra & Date	ÞING Paper I	ÁSB2 Paper III	HFK8 Paper II	HEL Paper III	References
Hekla AD 1766	✓				Sverrisdottir (2007)
Katla AD 1500				✓	Thorarinsson (1967) Eiríksson et al. (2000); Haflidason et al. (1992)
Reykjanes (Medieval) AD 1226				✓	Jóhannesson (1988)
Hekla (H1) AD 1104	✓	✓			Eiríksson et al. (2000)
Katla AD 920		✓			Haflidason et al. (1992)
Veidivötn/Torfajökull (LTL) AD 877$^{\pm1}$	✓	✓	✓	✓	Schmid et al. (2017)
Snæfellsjökull (Sn-1) AD 170$^{\pm45}$ (^{14}C)			✓		Larsen et al. (2002)
Hekla A c. 480$^{\pm20}$ BC (^{14}C)				✓	Larsen et al. (2020)
Hekla 3 c. 927$^{\pm34}$ BC (^{14}C)	✓				Larsen et al. (2020)
Hekla 4 c. 2248 BC (^{14}C)	✓				Dugmore et al. (1995)

Table 4 ^{14}C dates for Papers I & III.

Core	Code	Depth (cm)	^{14}C Date (BP)	Error 1σ	$\delta\,^{13}$C (‰)	Calibrated age (AD) 2σ	Weight (mg)	Source
ÞING Paper I	ETH-82940	24.5-25.5	2463	35	-30.2	762-429	1.5	Wood
ÁSB2 Paper III	ETH-107374	14-14.5	476	21	-29.9	1416-1448	1.5	Wood & bark
	ETH-97880	18-19	584	20	-29.7	1307-1411	1.5	Wood
	ETH-109395	50-51	1630	23	29.10	404-538	1.5	Wood & bark

3.2 Þingeyrar (Paper I)

Visual evaluation of the CONISS dendrogram allowed six LPAZ to be identified for ÞING. Ordination analysis reaffirmed this zonation. While distinct, there is some overlap between ÞING I and ÞING II, the distinction defined by altered *Betula* values. The main divide between the LPAZ is between ÞING II and ÞING III with Cyperaceae taking precedence. Again there is some overlap between ÞING III, ÞING IV and ÞING V, with apophytes the common denominator. There is a clear separation between these LPAZ and the ÞING VI as Poaceae becomes more prominent. Based upon pollen percentage values, detailed descriptions for each of the PZ's are given as follows:

3.2.1 ÞING I (28.5-25.5 cm. c. AD 432-877)

The pollen assemblage at Þingeyrar from c. AD 432 (ÞING I) is characterised by an abundance of *Betula* (between 55.7% and 61.9% TLP) with *Betula* pollen grain size ($19^{\pm1}$ µm) suggesting *B. nana* (Karlsdóttir et al., 2007). Cyperaceae is co-dominant (≤40% TLP) with *Salix* (≤5% TLP) and Poaceae (≤8% TLP). With regard to sediment properties, there is little variation (MS <5 SI, DBD <0.4 g cm^{-3}, OM 55.7-61.9%).

3.2.2 ÞING II (25.5-20.7 cm. c. AD 877-1104)

From c. AD 877 (ÞING II) *Betula* (pollen grain size $19^{\pm1}$ µm) and Cyperaceae values fall to ≤40% TLP and ≤30% TLP respectively with declines also apparent for *Salix*, *F. ulmaria*, *Angelica* undiff. and *Vaccinium*-type (blaeberry). Ericaceae and Empetraceae (Ericales; heaths) and *E. nigrum* rise from ≤1% TLP to ≤5% TLP and ≤6% TLP respectively while Poaceae values remain constant (≤8% TLP). Sediment data reveal a decline in OM (≥40%) with a corresponding increase in MS (≤10 SI) and DBD (≤0.6 g cm^{-3}).

3.2.3 ÞING III (20.7-15.5 cm. c. AD 1104-1332)

From c. AD 1104 (ÞING III) *Betula* drops as low as 5% TLP (pollen grain size $19^{\pm1}$ µm) with *Salix*, Ericales, *E. nigrum* and *Angelica* undiff. almost disappearing from the pollen record. In contrast, Poaceae increases to ≤20% TLP, Cyperaceae is almost completely dominant (≤90% TLP), with greater variety of herbaceous plants present e.g. Lactuceae (dandelions, hawkweeds etc.), *Lynchis viscaria*-type (e.g. *Lynchis alpine*; alpine catchfly), *Parnassia palustris* (grass of Parnassus) and *P. maritima*. Furthermore, the presence of *Selaginella selaginoides* (lesser clubmoss) and *Galium* (bedstraw) is more consistent while that of *Thalictrum alpinum* (Alpine meadow rue) increases (≤5% TLP). CFS (*Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113) appear for the first time in the Þingeyrar pollen assemblage. OM (≥20%) reaches its lowest values with corresponding increases in MS (≤60 SI) and DBD (≤1 g cm^{-3}).

3.2.4 ÞING IV (15.5-11.5 cm. c. AD 1332-1515)

From c. AD 1332 (ÞING IV) *Betula* recovers briefly (≤20% TLP; pollen grain size $19^{\pm2}$ µm) at the expense of Poaceae (≥10% TLP) and Cyperaceae (≥55% TLP). *Angelica* undiff. and *F. ulmaria* also return to the pollen record. A single pollen grain of *Hordeum*-type is present as is *Anthemis*-type (e.g. yarrow/sneezewort), with *T. alpinum* increasing (≤12% TLP) and *Rumex acetosella* (sheep's sorrel) more consistent. CFS (*Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113) are present. OM (≤55%) is returning to higher values recovering with corresponding declines in MS (≤15 SI) although DBD (≤1 g cm^{-3}) remains unaltered.

3.2.5 ÞING V (11.5-9.5 cm. c. AD 1515-1606)

From AD 1515 (ÞING V) *Betula* (≤5% TLP; pollen grain size $20^{\pm2}$ µm) is considerably reduced, Cyperaceae (≤70% TLP) and Poaceae increase (≤20% TLP) with a slight recovery for *E. nigrum* (≤2% TLP). CFS (*Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113) are present. OM (≤60%) values are high but declining. MS is also declining (≤10 SI) while DBD (≤1 g cm^{-3}) is relatively stable.

3.2.6 ÞING VI (9.5-6 cm. c. AD 1606-1766)

From AD 1606 (ÞING VI) Poaceae is now dominant (≤44% TLP; pollen grain size $19^{\pm1}$ µm) with Cyperaceae (≤40% TLP). Consistency and/or raised values apply for *T. alpinum* (≤15% TLP), *Rumex acetosa* (common sorrel), *R. acetosella*, *Oxyria*-type (e.g. *O. digyna*; mountain sorrel) and *S. selaginoides* (≤5% TLP). The CFS (*Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113) signal is more consistent than previously. DBD and OM are stable with an increase in MS associated with the Hekla AD 1766 tephra deposit.

3.3 Helgafell (Paper II)

Visual evaluation of the CONISS dendrogram allowed five PZ's to be identified for HFK8. Ordination analysis reaffirmed this zonation, a fundamental divide between pre-Landnám (HFK8 I & II) and post-Landnám (HFK8 III-V) particularly apparent. With reference to the pre-Landnám context, an expansion in *Betula* distinguishes HFK8 II from HFK I. For the post-Landnám context, HFK8 III harbours characteristics that span both the later PZ´s of HFK8 IV and HFK8 V with the expansion of Cyperaceae and Poaceae keeping apace following Landnám. The division between HFK8 IV and HFK8 V is characterised by the increasing presence of apophytic taxa, culminating with Poaceae, Cyperaceae, apophytes and CFS. Based upon pollen percentage values (supplemented by pollen concentration data where relevant), detailed descriptions for each of the PZ's are given as follows:

3.3.1 HFK8 I (104.5-93.5 cm. c. AD 212-507)

From AD 212 *Betula* values are relatively high (≤49.2% TLP), *B. nana* according to pollen grain size ($21^{\pm2}$ µm). *Salix* (≤5% TLP), *J. communis* (≤1% TLP), *Vaccinium*-type (≤2% TLP) and *E. nigrum* (≤1.7% TLP) are present, with a decreasing trend for *Salix*. Both Cyperaceae and Poaceae are present (≤21% and ≤18.5% TLP respectively) with *Caltha palustris* (marsh marigold; ≤1% TLP), *Geum rivale* (water avens; ≤3% TLP), *Hippuris vulgaris* (common mare's tail; ≤2.7% TLP), *R. acetosa* (≤1.7% TLP), *T. alpinum* (≤2% TLP), *Oxyria*-type (e.g. ≤0.7% TLP). *Angelica archangelica* (garden angelica; ≤1% TLP), *Angelica sylvestris* (wild angelica; ≤1.7% TLP), and *Ranunculus acris*-type (buttercup; ≤0.3% TLP). CFS (*Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113) are present (≤1.3% TLP; ≤124 spores per 1 cm^3). With regard to sediments, OM (≤ 35%) increases following the deposition of the Sn-1 tephra with a corresponding decline in DBD (≤0.18 g cm^{-3}). MS follows DBD but suggests that there may have been some disruption.

3.3.2 HFK8 II (93.5-76 cm. c. AD 507-920)

From AD 507 *Betula* values are consistently above 50% TLP with a peak of 57.4% TLP with grain size ($23^{\pm2}$ µm) inferring that *B. pubescens* is replacing *B. nana*. Non-triporate *Betula* are 1.1% TLP on average. *Betula* pollen concentration doubles (10118 grains cm^{-3}) with a similar increase in non-triporate *Betula* pollen (≤335 grains cm^{-3}). A slight increase can be seen for *J. communis* (1.8% TLP), more visible with regard to pollen concentration (343 grains cm^{-3}). *E. nigrum* is stable (≤1.7% TLP) while *Vaccinium*-type (≤2.3% TLP) and Ericales (≤1.6% TLP) are slightly raised. Overall, *Vaccinium*-type is dominant among these shrub taxa. Cyperaceae is constant (18.6% TLP on average) while Poaceae is lower (≤14% TLP). *Salix* (1.6% TLP on average) is also reduced. Pollen concentration is raised for all species and taxa (including aquatics, and especially *Isoëtes*). The CFS *Podospora*-type HdV-368, *Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113 are present (≤1.6% TLP, ≤365 grains cm^{-3}). Traces of microscopic charcoal are present (≤0.3% TLP, ≤56 grains cm^{-3}) prior to a substantial change in following the deposition of the LTL (≤20.6% TLP, ≤4675 grains cm^{-3}). In relation to sediments, OM (≤39.4%) increases, DBD is relatively stable (≤0.10 g cm^{-3}), and MS declines to become negligible. Macrofossil wood fragments (up to 2.5 cm long and 8 mm broad) and bark flakes (≤8 mm) are found in sediments within and just below the LTL (between 79.5-77.5 cm) raising the OM to 62.6% at 79.5 cm; the OM signal of the wood within the LTL itself (7.4%, 78.5 cm) is suppressed due to the overriding minerogenic content of the tephra deposit. Following the deposition of the LTL, OM falls to below half that of the earlier sediments (on average 14%), in association with influxes of minerogenic material which persist into HFK8 III (76-61 cm).

3.3.3 HFK8 III (76-61 cm. c. AD 920-1144)

From AD 920 *Betula* is ≤56.7% TLP (43.3% on average; *Betula* pollen grain size $21^{\pm1}$ µm) with a reduction in *J. communis* (≤0.3 % TLP), *Salix* (1.3% TLP on average), and *Vaccinium*-type (1.7% TLP on average). *E. nigrum* remains constant (1.7% TLP on average). In contrast, Cyperaceae (23.8% TLP on average) and Poaceae (18.8% TLP on average) increase. A number of taxa also appear in the pollen record for the first time e.g. *Anthemis*-type, *Artemisia*-type, *Carum carvi* (caraway), *Chelidonium majus* (greater celandine), *Plantago lanceolata* (ribwort plantain), *P. aviculare* and *R. acetosella* (75.5 cm, ≤2% TLP). Increased values and/or greater consistency regarding presence applies to Lactuceae (≤2.6% TLP), *P. maritima* (≤0.6% TLP), and *T. alpinum* (≤2.7% TLP). In the aquatic environment, following a previous collapse in concentration values, *Myriophyllum alterniflorum* (alternate water-milfoil) recovers to ≤56.4% TLP (≤12899 grains cm^{-3}). *Isoëtes* (quillwort) experiences a declining trend. CFS (*Podospora*-type HdV-368, *Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113) values rise (≤583 grains cm^{-3}) and are more consistent. Microscopic charcoal is present (≤6261 grains cm$^{-3).}$ In regard to sediments, OM increases from 71 cm (on average 22.3%) following the disruption of the LTL, sustained into HFK8 IV (27.1% on average), MS values fluctuate, and DBD (range 0.22 to 0.09 g cm^{-3}) is in decline.

3.3.4 HFK8 IV (61-44.5 cm. c. AD 1144-1407)

From the mid-12th century *Betula* is ≤55.3% TLP (*Betula* pollen grain size $22^{\pm1}$ µm) with a decreasing trend in the longer term. *Betula* pollen grain size is $22^{\pm2}$ µm. *Vaccinium*-type continues to decline (1.3% TLP on average) while *E. nigrum* increases (2.7% TLP on average). Similarly, Cyperaceae (20% TLP on average) has declined while Poaceae (19.4% TLP on average) has increased marginally. *Hordeum*-type is present for the first time while *Anthemis*-type and *Artemisia*-type recur. *R. acetosella* (≤2.9% TLP) increases while *P. maritima* (≤0.9% TLP) is more than double than previously recorded. In the aquatic environment, there is an increase in pollen concentration for both *M. alterniflorum* (≤109.1% TLP, ≤21099 grains cm^{-3}) and *Myriophyllum spicatum* (spiked water-milfoil; (≤2.7% TLP, ≤341 grains cm^{-3}). CFS (*Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113) persist and the signal for *Podospora*-type HdV-368 is stronger. Microscopic charcoal is present, on average 9.3% TLP (1487 grains cm^{-3}). The only interruption to the ongoing recovery of OM arises at 46.5 cm with a possible eruption/erosion event (only detectable via the sediment properties rather than being visible to the naked eye).

3.3.5 HFK8 V (44.5-35.5 cm. c. AD 1407-1524)

From the early 15th century *Betula* drops to below 40% TLP (33.2% on average) and *Betula* pollen grain size is $22^{\pm2}$ µm. *E. nigrum* remains relatively stable (2.6% TLP on average) with a slight increase in *Vaccinium*-type (1.7% TLP on average). Values for Poaceae (≤28.1% TLP) and Cyperaceae (≤29% TLP) increase, with the former more dominant overall (26.7% TLP on average compared with 22.2% TLP). New herbaceous taxa include *Gentianella*-type (gentian), *Montia fontana* (water blinks), *Rhinanthus*-type (e.g. yellow rattle) and *Sinapis*-type (mustard). The values for *R. acetosella* (≤2.6% TLP) and *T. alpinum* (≤3.9% TLP) decrease slightly while Caryophyllaceae (≤1.3% TLP) flourishes. Similarly, with regard to the wetland context, the signal of *G. rivale* appears more regularly (≤1.3% TLP). In the lake, *M. alterniflorum* pollen concentration is reduced to ≤39% TLP (≤10116 grains cm^{-3}). CFS (*Podospora*-type HdV-368, *Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113) are more consistently represented (≤3.3% TLP, ≤545 grains cm^{-3}). Microscopic charcoal is present, on average 7.5% TLP (1259 grains cm^{-3}). Sediments are stable with regard to MS and DBD with OM 40.4% on average and peaking at 44.6% at 36.5 cm (greater than for HFK8 I and II). HFK8 V (44.5-35.5 cm) terminates upon the deposition of minerogenic material at 35.5 cm derived either from an eruption or erosion.

3.4 Helgadalur (Paper III)

Visual evaluation of the CONISS dendrogram allowed four LPAZ to be identified for HEL. Ordination analysis reaffirmed this zonation with PCA clearly distinguishing HEL I from the later LPAZ in association with *Betula*, Ericales, *Angelica* indet. and *F. ulmaria*. HEL II is characterised by Cyperaceae with HEL III and HEL IV defined by Poaceae in association with *T. alpinum*, *P. maritima*, *R. acetosella* and *S. selaginoides*. Based upon pollen percentage values, detailed descriptions for each of the LPAZ are given as follows:

3.4.1 HEL I (43.5-37.75 cm. c. AD 711-885)

From AD 711 Cyperaceae is dominant (≤61.7% TLP) with *Betula* ultimately sub-dominant (≤38% TLP). Ericales (≤5% TLP), *E. nigrum* (≤3.9% TLP), *Angelica* indet. (≤1.7% TLP), *F. ulmaria* (≤8.3% TLP) and *Sphagnum* are in decline. Woody peat defines the sediment context with OM ≤84.5% TLP until truncated by the LTL c. AD 877. DBD and MS are correspondingly low (≤0.5 g cm^{-3} and ≤10 SI respectively). Traces of microscopic charcoal are present.

3.4.2 HEL II (37.75-28 cm. c. AD 885-1235)

From AD 885 Cyperaceae remains dominant (≤84.4% TLP) with Poaceae fluctuating between 6.1% TLP and 19.5% TLP. The pollen assemblage is also populated by e.g. *P. maritima*, *Potentilla*-type (cinquefoils), *Rumex/Oxyria* undiff. and *S. selaginoides* while *T. alpinum* increases (≤11.6% TLP). In contrast, values for *Sphagnum* and *Angelica* spp. collapse (≤1% TLP) with *E. nigrum* and *Betula* values considerably reduced (to ≤1.4% TLP and ≤1% TLP and respectively). Microscopic charcoal is present, accompanied by CFS (*Podospora*-type HdV-368, *Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113). A silty peat defines the sedimentary context with OM ≤60.2%, with lowered OM values associated with tephra deposits.

3.4.3 HEL III (28-14.25 cm. c. AD 1235-1614)

From AD 1235 Cyperaceae remains dominant (≤80.3% TLP) but Poaceae is rising (≤23% TLP) in association with persistent and/or increased values for *P. maritima*, *T. alpinum* and *S. selaginoides*. Microscopic charcoal is sustaining higher values than previously (≤56.1% TLP). CFS (*Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113) are present. *Betula* (≤6.1% TLP), *Angelica sylvestris* (≤1% TLP) and *F. ulmaria* (≤1% TLP) recover slightly. The sedimentary context continues to be defined by silty peat with OM increasing to 60.7% prior to the deposition of the Katla AD 1500 tephra, after which OM is reduced to 53.5%.

3.4.4 HEL IV (14.25-6 cm. c. AD 1614-1850)

From AD 1614 Cyperaceae remains dominant (≤68.6% TLP) with a declining trend in contrast to Poaceae (≤25.6% TLP) and *T. alpinum* (≤18.1% TLP). Spore taxa i.e. Pteropsida (monolete) indet. (ferns) and *Equisetum* are also well represented (≤ 24.3% TLP and ≤110.3% TLP respectively) with some recovery in woody taxa i.e. *Betula* (≤8.8% TLP) and *Salix* (≤1.9% TLP). Microscopic charcoal values are very low (≤1% TLP) bar a single spike in values (180% TLP). CFS are absent. Sediments continue to be comprised of silty peats with OM recovering to ≤57% with corresponding declines in MS and DBD outwith disruption associated with the deposition of an undated Katla tephra (7.5 cm).

3.5 Ásbjarnarnes (Paper III)

Visual evaluation of the CONISS dendrogram allowed five LPAZ to be identified for ÁSB2. Ordination analysis reaffirmed this zonation with PCA separating ÁSB2 I from the later LPAZ and identifying *Betula* as particularly prominent. The later LPAZ present clear clusters but there are degrees of overlap between them, representing a transition from *E. nigrum* ÁSB2 II to Cyperaceae (ÁSB III & IV) to Poaceae in association with *T. alpinum,* and *S. selaginoides* (ÁSB2 V). Based upon pollen percentage values, detailed descriptions for each of the LPAZ are given as follows:

3.5.1 ÁSB2 I (49-41.25 cm. c. AD 550-913)

From AD 550 (ÁSB2 I) *Betula* is dominant (≤82.6% TLP) with the heath/wood component also comprised of *Salix* (≤9.3% TLP), Ericales (≤1.6% TLP), *E. nigrum* (≤2% TLP) and *Vaccinium*-type (≤2% TLP). Cyperaceae (≤28.8% TLP) is sub-dominant with Poaceae (≤3.8% TLP), *A. archangelica* (≤0.3% TLP), *A. sylvestris* (≤1% TLP) and *G. rivale* (≤2% TLP). Microscopic charcoal (≤14.9% TLP; above the LTL) and CFS (*Sordaria*-type HdV-55A) are present. The sedimentary context is defined by peat truncated only by the LTL. OM is relatively high (≤58%), but in decline.

3.5.2 ÁSB2 II (41.25-26.25 cm. c. AD 913-1101)

From AD 913 (ÁSB2 II) *Betula* values fluctuate between 7% TLP and 39.3% TLP with a declining trend matched by *Salix* (≤3% TLP), Ericales (≤2.3% TLP) and *E. nigrum* (≤3.2% TLP). *Vaccinium*-type virtually disappears as do the *Angelica* spp. and *F. ulmaria*. Cyperaceae values increase considerably (≤ 85.7% TLP). Poaceae also increases (≤6% TLP) with *T. alpinum* and *S. selaginoides* more persistent in the pollen assemblage than previously. Microscopic charcoal and CFS barely register. There is no significant alteration to the peat strata other than the deposition of the Katla AD 920 tephra.

3.5.3 ÁSB2 III (26.25-22.25 cm. c. AD 1101-1205)

From AD 1101 (ÁSB III) there is a recovery in *Betula* (≤26.4% TLP), Poaceae increases (≤9.7% TLP), while Cyperaceae falls (≤58.4% TLP). Increases are also observed in *R. acetosella* (≤2.2% TLP) and *T. alpinum* (≤3% TLP) while the pollen assemblage is now populated with Caryophyllaceae and *P. maritima*. CFS (*Sporormiella*-type HdV-113) values are low (< 1% TLP) while microscopic charcoal rises (≤7.2% TLP). Peat sediments become more minerogenic following the deposition of the Hekla AD 1104 tephra, clearly visible with regard to OM, DBD and MS, with the MS increase sustained into the longer term.

3.5.4 ÁSB2 IV (22.25-11.25 cm. c. AD 1205-1541)

From AD 1205 (ÁSB IV) Cyperaceae is dominant (≤89.1% TLP), Poaceae (≤7.7% TLP) and *Betula* decline (≤12.3% TLP) while *Salix*, Ericales and *E. nigrum* are low (<1% TLP). There is a general increase in microscopic charcoal (≤8.7% TLP). The CFS (*Podospora*-type HdV-368 and *Sporormiella*-type HdV-113) signal is relatively mute. With regard to sediments, there is greater fluctuation in MS, DBD and OM with an overall increase in minerogenic inputs.

3.5.5 ÁSB2 V (11.25-3 cm. c. AD 1541-1882)

From AD 1541 (ÁSB V) *Betula* (≤29.3% TLP), *Salix* (≤2.3% TLP), Ericales (≤5.9% TLP) and *E. nigrum* (≤ 1% TLP) are increasing with a decline in Cyperaceae (≤49.7% TLP). This trajectory is later reversed with Cyperaceae increasing again to 89.1% with a corresponding decline in in the tree and shrub taxa; *Betula* (≤5.3% TLP), *Salix* (≤0.2% TLP) and Ericales (≤0.4% TLP). Poaceae can also be seen to increase (≤11.8% TLP) in association with high values for *Equisetum* (≤26.8% TLP), *Lycopodium annotinum* (interrupted clubmoss; 5.9% TLP) and Pteropsida (monolete) indet. (≤19.1% TLP). The CFS signal becomes much stronger i.e. a consistent signal for *Sordaria*-type HdV-55A with *Sporormiella*-type HdV-113 attaining values of ≤3% TLP. Microscopic charcoal peaks at ≤52.3% TLP. In relation to sedimentary data, strata are significantly altered with bands of sand truncating the peat sequence with a general increase in minerogenic input (visible in OM, DBD and MS).

4 Discussion

4.1 The palynology of Landnám at four sites in Iceland (Papers I, II & III)

Although the emphasis of this study is upon medieval monasticism in Iceland, data incorporate material from other periods in Iceland's history and pre-history. The reason for this is to provide a foundation by which to compare later developments in the ecology and environment of the study sites in relation to monasticism. However, it also proffers an opportunity to make comparisons between these widely dispersed sites (**Papers I, II & III**), as well with others described in the palynological literature for Iceland. This relies upon a continuity in chronological frameworks and high resolution data and allows an opportunity to accrue insight into occupation patterns and land use, allowing theories attached to Landnám in particular to be evaluated (Erlendsson et al. 2006; Vésteinsson, 1998). Note that LPAZ/PZ will vary chronologically between sites, that the periods concerned may span more than a single LPAZ/PZ for a given site, and that the number of pollen samples and the sample resolution within a single LPAZ/PZ will differ between sites.

4.1.1 The pre-Landnám vegetation of four sites in Iceland

There is but a brief insight into the pre-Landnám pollen assemblage of Helgadalur (**Paper III**, HEL I) in the southwest as it encompasses less than 200 years (8th to 9th centuries). Nonetheless, it is possible to discern that the pollen assemblage for HEL I was representative of a Cyperaceae (≤61.7% TLP) and *Sphagnum* (≤172303 grains cm^{-3}) dominated wetland with herbaceous plants like *Angelica* indet. and *F. ulmaria* occupying the margins. Taxa such as *Betula* (≤17% TLP) and *E. nigrum* (≤30.5% TLP) were most likely associated with the steep slopes that surround the valley basin which may have encroached upon the margins and drier quarters of the mire. This scenario is very much in keeping with what is understood of south west Iceland at this time i.e. a wetland-heathland-woodland matrix (Erlendsson, 2007; Hallsdóttir, 1995). In the early 9th century, *Sphagnum* is considerably reduced (≥4299 grains cm^{-3}), Cyperaceae declines (≤53.1% TLP) and *E. nigrum* (≤5% TLP) is replaced by *Betula* (≤38% TLP). In effect, as *Betula* increases, it is probably encroaching further upon the wetland, hence the drying out of the mire as inferred by the decline in *Sphagnum*. There is no evidence to suggest that the drying out of the mire is related to any minerogenic influx (Arnalds, 2008; Erlendsson, 2007). Such raised pollen values for *Betula* are a recognised phenomenon from elsewhere in southwest Iceland, linked to a climate amelioration c. AD 600-800 (Erlendsson & Edwards, 2009; Hallsdóttir, 1987, 1995; Påhlsson, 1981).

Firmer evidence in support of a pre-Landnám climate amelioration is visible in the pollen assemblage from Helgafell (**Paper II**, HFK8 I & II) in the west. From the early 3rd century, the immediate surroundings and wider catchment of Helgafellsvatn were comprised of a vegetation matrix of *Betula* (≤49.2% TLP), Cyperaceae (≤21% TLP), and Poaceae (≤18.5% TLP). The presence of non-triporate *Betula* pollen, as evidence of hybridisation, asserts that both *B. pubescens* and *B. nana* were present (Karlsdóttir, 2014). *Betula* pollen grain size ($21^{\pm 2}$ µm) sits upon the cusp of the size distinguishing the two species (Karlsdóttir et al. 2007). From the mid-6th century until Landnám, *Betula* increases (≤57.4% TLP) at the expense of Poaceae (≤14% TLP) and Cyperaceae (≤18.6% TLP), in hand with a notable increase in pollen concentration across almost all terrestrial taxa. *Betula* pollen grain size is also greater ($23^{\pm 2}$ µm), closer to *B. pubescens*. *Betula* pollen grain size is subsequently reduced afterwards ($21^{\pm 1}$ µm HFK8 III). Within the aquatic context, concentration values for *Isoëtes* increase from ≤1500 to ≤5466 grains cm^{-3}. On the assumption that it is *Isoëtes echinospora* (spring quillwort) that is represented due to the oligotrophic conditions of the lake (Kristinsson, 1986; Langdon et al. 2008), environmental stability in the lake catchment is conveyed due to its preference for an undisturbed lakebed (Arts, 2002). An absence of any increase in minerogenic input to the lake at this time further suggests environmental stability. Here, expansion in *Betula*, increased grain size and raised pollen concentration values for almost all terrestrial taxa, would suggest a period of climate amelioration concurrent with similar vegetation change in south west Iceland c. AD 600-800 (Erlendsson & Edwards, 2009). Mild conditions and environmental stability are further asserted by the sedimentary context of the lake and increased growth in *Isoëtes* (Mørk et al. 2018; Rundgren, 1995).

In the north, at Þingeyrar (**Paper 1**, ÞING I), relatively high values (≤61.9% TLP) are maintained for *Betula* between the early 5th century and Landnám with a peak in the late 6th century. Higher values but a similar continuity for *Betula* applies to Ásbjarnarnes (**Paper III**, ÁSB2 I) between the mid-6th century until Landnám, with a peak (≤82.6% TLP) in the late 8th century. In terms of succession, this would suggest a level of habitat stability within a coastal context at both sites; certainly borne out by the stable sedimentary record for ÞING I, OM sustained (between 55.7% and 61.9%), but less so for ÁSB2 I where OM (58% to 40%) is declining prior to the deposition of the LTL. The low number of samples and resolution for ÞING I (4, c. 400 years) makes it difficult to place this LPAZ in any wider context in terms of vegetation development for the pre-Landnám period. However, with reference to ÁSB2 I (8 samples, 350 years), it is possible to discern an increase in *Betula* over time before it declines prior to Landnám.

The asynchronism between the habitat types of HEL and HFK8 in the southwest and west, and ÞING and ÁSB2 in the north, is to be expected given the disparate environmental contexts. Broadly, the nature of the differences conform with what would be expected for the time i.e. dwarf shrub communities in the north, a matrix of wetland, heath and woodland in the south (Hallsdóttir, 1995), both reflecting the climatological division of the island into low arctic (highlands and north coast) and cold tempered (lowland) zones (Jónsdóttir et al. 2005). There is a strong palaeoecological signal emanating from Helgafell (HFK8) in the west that is coincident with the climate amelioration c. AD 600-800 (Erlendsson & Edwards, 2009). There are also some palaeoecological indications that this might also apply at Helgadalur (HEL) in the south west, and at Ásbjarnarnes (ÁSB2) in the north. The signal from Þingeyrar (ÞING) is inconclusive. In relation to the coastal setting of ÞING and ÁSB2, studies from southern Iceland suggest that *Betula* was uncommon in coastal areas prior to settlement (Erlendsson & Edwards, 2009), although there are exceptions e.g. Påhlsson (1981). The most chronologically comparable coastal site in the north is Bungutjörn, Skagafjörður (56 km northeast of Þingeyrar) where *E. nigrum* is dominant over *B. nana* at this time (Eddudóttir, 2016). Based upon pollen grain size ($19^{\pm 1}$µm), it is possible to specifically identify *B. nana* for ÞING I, a species better adapted to exposed coastal areas than *B. pubescens* (Elkington, 1968) i.e. a dwarf shrub heath (Caseldine, 2001; Karlsdóttir et al. 2007; Mäkelä, 1996). Bungutjörn, ÞING and ÁSB2 are at a similar distance from the open sea (c. 5 km), but ÞING and ÁSB2 lie adjacent to salt water lagoons, while Bungutjörn lies within a hollow amid rock outcrops and glacial till. This difference in geomorphological context might favour *Betula*, particularly *B. nana*, over *E. nigrum* at ÞING and ÁSB2 due to the lagoon's mitigating the incidence and impact of low temperatures i.e. fewer night frosts, earlier snowmelt etc. which can sustain and enhance *B. nana* growth (Hollesen et al. 2015).

4.1.2 The impact of Landnám and patterns of occupation at four sites in Iceland vegetation of four sites in Iceland

There is consensus among archaeologists and palaeoecologists that the settlement of Iceland, Landnám, occurred in the late 9th century (Edwards et al. 2021; Karlsson, 2000; Vésteinsson, 1998). This is largely down to the fact that there is very limited physical evidence of settlement lying below the LTL, a tephra that has been dated to AD 871$^{\pm 2}$ based on its location within the Greenland GRIP ice core (Grönvold et al. 1995), more recently modified to AD 877$^{\pm 1}$ (Schmid et al. 2017). Can palynology contribute further to the understanding of settlement processes i.e. timing of impact, magnitude, and rates of occupation (Edwards, 2012; Edwards et al. 2011; Erlendsson et al. 2006; Vésteinsson, 1998; Vésteinsson & McGovern, 2012) for what is essentially a prehistoric period (Friðriksson & Vésteinsson, 2003)? In order to address these questions, we are concerned first with the immediacy of the Landnám moment c. AD 877. Secondly, the rate of palaeoecological change for each site as a means of ascertaining insight into rates of occupation and the timing of permanent settlement prior to the foundation of either a monastery, (12th century) or adoption into the monastic landholding (14th century), is investigated.

In terms of timing, human presence in Iceland around AD 877 arose simultaneously across all four sites considered in this study (north, southwest, and west). With reference to Erlendsson (2007), Edwards et al. (2011) and Edwards et al. (2021) this is demonstrable in a number of ways (Tables 3); 1) the alteration of vegetation communities i.e. expansion of Cyperaceae and Poaceae dominated habitats at the expense of *Betula*; 2) declines in grazing sensitive species e.g. *Salix*, *A. archangelica*, *A. sylvestris*, *F. ulmaria*, *Sphagnum* etc.; 3) the introduction of archaeophytes e.g. *P. aviculare* and *R. acetosella*; 4) increased values and consistency in the record for apophytes e.g. *Galium*, *P. maritima*, *R. acetosa*, *T. alpinum*, *S. selaginoides* etc.; 5) the appearance of microscopic charcoal in pollen assemblages; 6) altered sedimentary contexts e.g. increased minerogenic inputs (Dugmore et al. 2009; Gísladóttir et al. 2010). For Helgafell (HFK8), alterations to the aquatic plant community, might be added to this list (Lawson et al. 2006). That these indicators occur between disparate points in the compass and are comparable with evidence from a number of other sites across Iceland e.g. Einarsson (1963); Erlendsson (2007); Hallsdóttir (1987); Lawson et al. (2007); Riddell et al. (2018), lends weight to the suggestion that Iceland was occupied synchronously c. AD 877 (Edwards, 2012; Streeter et al. 2015; Vésteinsson & McGovern, 2012). However, with reference to Table 5, the sense of change in the ecology and environment at each of the four sampling sites at Landnám in terms of magnitude and rates of occupation is more nuanced (Edwards et al. 2011).

Table 5 Palaeoecological indicators of Landnám and rates of occupation.

Palaeoecological indicator	**HEL**	**HFK8**	**ÁSB2**	**ÞING**
Altered sediments (declining OM)	877	877	877	877
Altered *Betula*, Cyperaceae and Poaceae ratios	877	920	877	877
Grazing sensitive taxa (declining)	877	920	920	877
Arrival and/or increase in apophytes	877	920	1104	1104
Arrival of archaeophytes	877	920	1104	1104
Arrival of microscopic charcoal	877	910	877	n/a
Altered macrophytes (lacustrine)	n/a	920	n/a	n/a

For Helgadalur (**Paper III**, HEL) in southwest Iceland, the period between AD 877 and the late-14th century (when the farm became a tenancy of Viðeyjarklaustur) spans two LPAZ (HEL II & III). The arrival of the settlers c. AD 877 is immediate at Helgadalur; 1) there are influxes of minerogenic material into wetland sediments (OM ≤60.2% excluding declines associated with tephra deposits); 2) Cyperaceae has increased to a striking ≤84.4% TLP, Poaceae (≤19.5% TLP) values are also raised, while *Betula* is reduced (≤6.1%) compared with pre-Landnám values; 3) Grazing sensitive taxa e.g. *Sphagnum*, *A. archangelica* and *A. sylvestris* are disappearing or are in decline; 4) an archaeophyte *R. acetosella* appears; 5) Apophyte values increase or become more consistent in the pollen record (*P. maritima*, *R. acetosa*, *S. selaginoides*) with *T. alpinum* values increasing in particular (≤11.6% TLP). The latter is cited as a potential indicator of a wetland hay meadow (Fjordheim et al. 2018), an important feature of subsistence farming in medieval Iceland (Vésteinsson, 1998). Following the deposition of the AD 1226 tephra, the dominance of Cyperaceae is sustained (≤80.3% TLP) while Poaceae increases (≤23% TLP). *T. alpinum* levels increase again (≤13.1% TLP) i.e. a persisting hayfield which may also explain the reappearance of grazing sensitive species such as *A. archangelica*, *A. sylvestris* and *F. ulmaria* in the pollen assemblages. That CFS values are low might also lend support to this interpretation i.e. an absence of livestock. Microscopic charcoal is present throughout the LPAZ, further affirmation of a human presence from Landnám, representing either a domestic context (hearth, smithing, smelting) or a land management practice e.g. burning of leaf litter (*sinubruni*), fertilisation, or charcoal production (Church et al. 2007) etc. At Helgadalur, the entire range of indicators of human presence arise coincidentally c. AD 877 (Table 5), which underpins the relentless development of a pastoral landscape (possibly incorporating hayfields). This is a striking and rapid change that has been discussed previously in relation to palynological data from four other sites that Helgadalur shares a watershed with (Riddell et al. 2018). In contrast, with regard to the other three sites discussed here, there are varying degrees of protraction in terms of the manifestation of the various indicators (particularly with regard to the two sites on the north coast of Iceland).

At Helgafell in western Iceland the period between AD 877 and the early 12th century (when Helgafellsklaustur was founded) spans two LPAZ (**Paper II**, HFK8 II & III), the interpretation of which is complicated. Just prior to and coincident with the deposition of the LTL, there is an influx of wood fragments (≤2.5 cm long, ≤8 mm broad) and bark flakes (≤8 mm long) into the sediments of Helgafellsvatn. No such layer was identified anywhere else within the HFK8 core, neither above nor below. This material could intimate the clearance of wood and scrub at Helgafell by hand during settlement, the detritus subsequently washed into the lake, but this is uncertain (Edwards et al. 2021;

Smith, 1995). After the deposition of the LTL (and associated woody debris deposit), OM falls to below half that of earlier sediments (10.9%) in association with influxes of minerogenic material. This may either be a consequence of the LTL and/or human activity. It is not until c. AD 913 that the appearance of microscopic charcoal in the pollen assemblage represents more certain evidence of human activity (Edwards et al. 2011). From c. AD 920 (HFK8 III) the fuller suite of palynological indicators of anthropogenic activity, as observed with regard to Helgadalur (HEL), begin to appear. *Betula* drops to 43.3% TLP (on average), Cyperaceae (23.8% TLP on average) and Poaceae (18.8% TLP on average) increase, and apophytes (Lactuceae, *P. maritima*, and *T. alpinum*) present increased values or a more consistent presence in the pollen assemblage. Notably, a number of archaeophytes appear in the pollen record for the first time e.g. *Anthemis*-type, *Artemisia*-type, *C. carvi*, *C. majus*, *P. lanceolata*, *P. aviculare* and *R. acetosella*. From this point onwards, and similar to the pollen record for Helgadalur, the relentless development of a pastoral landscape ensues with the full suite of palaeoecological indicators present (Table 5).

The pollen record for Stóra Mörk in southern Iceland presents a subdued Landnám footprint akin to that of Helgafell with regard to terrestrial vegetation, said to be consistent with quasi-historical saga traditions stating that the farm was not settled until the early 10th century (Vickers et al. 2011). The delay in full occupation at Stóra Mörk is attributed to the labour demands required to clear large areas of *Betula* woodland (Smith, 1995; Vickers et al. 2011). At Helgafell (lit. holy mountain), adopting a similar approach, it is equally tempting to ascribe delay in full occupation to the sanctity of the eponymous hill as recounted in the Eyrbyggja Saga, (Sveinsson & Þórðarson, 1985). However, if it is accepted that the woody detritus associated with the LTL at Helgafell is a consequence of active *Betula* clearance, the reputed holiness of the hill becomes redundant and also challenges the notion that settlers baulked at clearing land by hand.

There are further, less definitive, points to consider with regard to Helgafell. With regard to aquatic taxa, *M. alterniflorum* is on the rise while *Isoëtes* experiences a declining trend. This could suggest an increase in nutrient levels within the lake following Landnám (Arts, 2002; Hiles et al. 2021; Lawson et al. 2007; Roelofs et al. 1984; Spierenburg et al. 2009). It might also explain increases in OM (21.2% on average) despite mineral influxes. These changes in the aquatic environment could be attributable to livestock grazing within the watershed of Helgafellsvatn, releasing nutrients that were previously stored in terrestrial vegetation into the wider environment via dung (Hiles et al. 2021; Lawson et al. 2006; Lawson et al. 2007; Spierenburg et al. 2009). The presence of livestock might be apparent via increased Pteropsida (monolete) indet., fossil spores, similarly released into the watershed by the trampling and erosion of terrestrial sediments (Gathorne-Hardy et al. 2009). However, a better indicator of livestock presence would be CFS (*Podospora*-type HdV-368, *Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113), the values of which also rise slightly and are more consistent. That said, greater CFS values would be expected.

Moving northwards, an even more protracted evolution of anthropogenic indicators (Table 5) applies to both Ásbjarnarnes (**Paper III**, ÁSB2) and Þingeyrar (**Paper I**, ÞING). Ásbjarnarnes lies a short distance to the southwest of Þingeyrar (c. 20 km), and became a tenancy of Þingeyraklaustur in the mid-14th century. For ÁSB2, the period between AD 877 and the mid-14th century spans four LPAZ (ÁSB I-IV). Human presence at ÁSB2 is ostensibly instant with *Betula* values halved (≤39.3% TLP) in association with an isolated spike in microscopic charcoal (14.9% TLP). Declining OM may simply be a continuation of an ongoing reduction initiated prior to Landnám and therefore difficult to definitively attribute as a response to human presence. It is not until after c. AD 920, that *Betula* declines further along with other grazing sensitive species e.g. *A. archangelica*, *A. sylvestris*, *F. ulmaria*, *Vaccinium*-type and *Salix*. CFS are completely absent prior to AD 1104 and microscopic charcoal only returns to the record in the late 11th century. Indeed, it is not until the early 12th century that the archaeophyte *R. acetosella* appears alongside an expansion in apophytic species e.g. *Galium, P. maritima* and *R. acetosa*, when Cyperaceae (85.7%) displaces *Betula* (≤7% TLP) almost entirely. Following AD 1104, while CFS might suggest a livestock presence, values are minimal. Overall, the rate of occupation is more prolonged at Ásbjarnarnes than at Helgafell even though initially there is a relatively strong signal c. AD 877 i.e. microscopic charcoal and *Betula* decline (Table 5). The immediacy of human presence followed by a relative absence of indicators between AD 877 and AD 1104 e.g. microscopic charcoal and CFS, might imply that Ásbjarnarnes was merely a beachhead c. AD 877 (Smith, 1995), with full occupation postponed due to the labour demands of *Betula* clearance (Vickers et al. 2011). It may even have been temporarily abandoned or used only seasonally (Vésteinsson, 1998). If Landnámabók and Laxdæla Saga are to be believed (Pálsson & Edwards, 1972; Sveinsson, 1934), this runs counter to what was understood of Ásbjarnarnes at the time the stories were written (centuries later). Perhaps the resource focus of Ásbjarnarnes after Landnám was predicated upon the maritime context rather than farming (although neither precludes the other) as implied by historical accounts from the 14th and 15th centuries (DI-II, 1857-1976, p. 376; DI-III, 1857-1976, p. 202; DI-V, 1857-1976, p. 85) in relation to shore rights (driftwood, whale wrecks, sealing and fishing).

At Þingeyrar, the period between AD 877 and the early 12th century (when Þingeyraklaustur was founded) spans a single LPAZ (**Paper I**, ÞING II). For ÞING II, there is a gradual, but fluctuating, decline in *B. nana* (≤60% TLP; size $19^{+/-1}$µm) from AD 877 until AD 1104 with a corresponding response in Cyperaceae (≤60% TLP) and Poaceae (≤5%). This is reflected in a gradual decline in OM (60% to 40%) and increasing MS and DBD. Grazing sensitive taxa (*Angelica* undiff., *F. ulmaria, Vaccinium*-type, *Salix*) also disappear while there is some expansion in heathland i.e. Ericales (≤5% TLP) and *E. nigrum* (≤6% TLP). CFS, as an indicator of livestock presence are absent while the archaeophytes and apophytes usually associated with the expansion of a pastoral landscape do not colonise the sampling area after c. AD 1104. There are a number of reasons, perhaps operating cumulatively, as to why the settlement signal is muted at Þingeyrar. First, the distance of the wetland coring site from the centres of farming activity may be a factor, either Trumbsvalir (c. 600 m) or Þingeyrar (c. 500 m), both locations with archaeology that pre-dates the deposition of the Hekla AD 1104 tephra (Hjartarson et al. 2017; Kristjánsdóttir et al. 2016). Second, domestic livestock may have been dispersed over a very large area and/or are limited in number (Davies, 2019). Third, prolonged transition might be a symptom of selective grazing; neither *B. nana* or *E. nigrum* are particularly favoured by domestic herbivores, perhaps hindering colonisation by apophytes associated with pasture (Hejcman et al. 2016; Tybirk et al. 2000).

Subject to this review of Landnám and the period that followed, it is possible to conclude that while Landnám was coincident across all four sites, rates of occupation varied between them. This is based upon the magnitude of environmental and ecological impact as inferred by a suite of palaeoecological indicators (Table 5). At Helgadalur (HEL), full occupation seems instantaneous, with all palaeoecological indicators arising in the sediment record simultaneously c. AD 877. The initial phase of Landnám at Helgafell (HFK8) is more ambiguous unless the influx of woody material into the sediments of Helgafellsvatn c. AD 877 is seen as anthropogenic in origin. Irrespective of this, any sense of complete occupation does not arise until c. AD 920. At Ásbjarnarnes (ÁSB2), a relatively strong signal c. AD 877 belies the fact that it is not until AD 1104 that the full suite of indicators is present in the pollen assemblage, a scenario that applies equally to Þingeyrar (ÞING1). The difference between these two sites lies in the interim, where a gradual progression in palaeoecological conditions can be seen at Ásbjarnarnes, whereas a step change applies to developments at Þingeyrar. More broadly, these four sites exhibit an ongoing north/south divide, rates of occupation possibly related to the climatological division of low arctic north coast and cold tempered south (Jónsdóttir et al. 2005), or at least, what the settlers may have understood of this division. Whatever the case, the inferred variation in rates of occupation as given here demonstrate that palynology continues to contribute to discussions on the pattern of colonisation of Iceland (Edwards, 2012; Erlendsson et al. 2006; Vésteinsson, 1998; Vésteinsson & McGovern, 2012).

CFS (Cugny et al. 2010; van Geel et al. 2003) as an indicator of the presence of domestic animals and humankind in Iceland (Edwards et al. 2011; Edwards et al. 2021; Erlendsson, 2007) have proven unreliable across all four sites compared with the other palaeoecological indicators (Table 5). This is primarily due to low values and an inconsistency in terms of presence within the pollen assemblages of the respective coring sites. The greatest difficulty arises when attempting to distinguish the presence of livestock from background levels attributable to the presence of wild birds; *Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113 are found in the dung of bird species indigenous to Iceland (Hallgrímsson & Eyjólfsdóttir, 2004). Without a significant spike in CFS values or a more consistent presence in the pollen assemblages it is hard to discern any change in conditions regarding livestock. Accepting this difficulty, the only alternative interpretation is that livestock only utilised a given area periodically, that numbers were low, and/or that they were dispersed over a large area (Davies, 2019). Where coring sites are distal to farm mounds, centres of human activity, CFS signals might also be more muted (Erlendsson, 2007). With regard to the lacustrine context of Helgafell (HFK8), low values might arise as a consequence of coring from near the centre of Helgafellsvatn as in-washed CFS tend to accumulate on lake margins (Lee et al. 2022).

4.1.3 Medicinal, culinary and utilitarian plants at Helgafell (Paper II)

The occurrence of single pollen grains of *Artemisia*-type (75.5 cm), *C. majus* (69.5 cm) and *C. carvi* (62.5 cm) in PZ HFK8 III (**Paper II**) are of particular interest as introduced plant species and for their medicinal and/or culinary applications (Edwards et al. 2011; Zielińska et al. 2018). *Artemisia vulgaris* (mugwort) is also used for dyeing wool (Guinot et al. 2006; Pluenneke, 2017).

While being discussed in a pre-monastic context here, it is worth noting that anemophilous (wind-dispersed) *Artemisia*-type pollen is found in later PZ’s from HFK8 (V and VI). *Artemisia*-type pollen has also been identified from an archaeological context (floor layer) from Helgafell (Undirtún) which, based upon ceramic artefacts, was dated to a period spanning AD 1850 to AD 1950 (Kristjánsdóttir & Gunnarsdóttir, 2014; Riddell & Erlendsson, 2015). Four instances of *Artemisia*-type pollen at a single locale could be down to the vagaries of the wind (Barney & DiTommaso, 2003), and it does appear in pre-Landnám pollen assemblages from Iceland e.g. Lawson et al. (2007). However, according to Einarsson (1962) and Hallsdóttir (1987), there are similar instances of *Artemisia*-type repeatedly occurring through time in Icelandic pollen assemblages i.e. Skálholt and Mosfell (Grímsnes). More recent incidences of *Artemisia*-type pollen at these locations (17th and 18th century) are also supported by written reports of *Artemisia* cultivation

(Thorarinsson, 1944). Furthermore, although it has never become naturalised, it has been argued that *Artemisia*-type pollen is representative of an archaeophyte, arriving in Iceland from Landnám (Edwards et al. 2011; Wasowicz et al. 2013). This may apply here, with *Artemisia*-type first arriving at Landnám and perhaps persisting into later periods through continued cultivation as at Skálholt and Mosfell (Grímsnes).

Although toxic, the entomophilous (insect dispersed pollen) *C. majus* is a plant long known to harbour medicinal properties (Zielińska et al. 2018) and its macrofossil remains have been found within archaeological contexts associated with medieval monasteries in England, Scotland, and Finland (Alanko & Uotila, 2015; Dickson, 1996; Gilchrist, 2020). Furthermore, relict populations of this plant are associated with monastic sites in Norway (Åsen, 2021) and Finland (Alanko & Uotila, 2015). There is no evidence to suggest that this plant has ever occurred in Iceland (Kristinsson et al. 2018; Wasowicz, 2018; Wasowicz et al. 2013) but it is not implausible given its widespread use elsewhere.

C. carvi (entomophilous) is an aromatic herb well known for its culinary applications (Åsen, 2021), and a naturalised archaeophyte in Iceland (Edwards et al. 2011; Kristinsson, 1986; Wasowicz, 2018; Wasowicz et al., 2013). *C. carvi* appears in the Icelandic pollen record from AD 1000 (Lawson et al. 2007). In specific relation to the cloister, recent plant surveys identify the presence of *C. carvi* at a number of monastery sites in Iceland i.e. Möðruvallaklaustur, Kirkjubæjarklaustur, Þykkvabæjarklaustur, Viðeyjarklaustur and Flateyjarklaustur (Åsen, 2021).

The appearance of these herbs in the pre-monastic pollen assemblages of HFK8 is perhaps surprising as the introduction of exotic plant species to Iceland has been identified as a feature of Icelandic monasticism (Åsen, 2021; Kristjánsdóttir, 2010a). In terms of context, with reference to Laxdæla Saga, (Sveinsson, 1934; Ch. 60, p. 179):

"*Fám nóttum síðar en Guðrún hafði heim komit heimti hún sonu sína til máls við sik í laukagarð sinn*"

"A few nights after Guðrún had returned home, she called her sons to speak with her in her kitchen garden" (author translation).

Likely nothing more than a narrative foil, that there was a "laukagarður" (literally onion/leek garden, figuratively a kitchen garden or vegetable plot) at Helgafell was plausible to the medieval Icelandic audience for whom the saga was written. There are also references to laukagarður in the Icelandic historical record e.g. the Bishop of Hólar is said to have died in a laukagarður in AD 1457 (Kristjánsdóttir et al. 2014). Furthermore, there is evidence from southern Scandinavia to show that medicinal plants were grown alongside culinary herbs in medieval kitchen gardens outwith ecclesiastical institutions (Helweg, 2020). Overall, there is no reason to preclude lay folk from the cultivation of medicinal herbs (Gilchrist, 2020), and there are certainly historical accounts of secular healers in Iceland in the medieval period e.g. Hrafn Sveinbjarnarson (Egilsdóttir, 2004; Kristjánsdóttir, 2023).

The occurrence of exotic tree pollen from Europe and North America in the HFK8 pollen assemblage i.e. *Abies* (fir), *Alnus* (alder), *Pinus* (pine), *Tsuga* (hemlock) and *Ulmus* (elm), is testament to the potential of pollen to reach Iceland from any quarter. This undermines the suggestion that exotic plant species were deliberately introduced to Helgafell, particularly where the utilitarian plants are represented by a single pollen grain. Nonetheless, collectively, it is hard to imagine that the manifestation of these utilitarian taxa and species at Helgafell is down to mere coincidence. Moreover, *C. majus* and *C.*

carvi are entomophilous, i.e. they depend upon insects rather than wind with regard to pollen dispersal. Plants that rely upon insects for pollen dispersal tend to produce less pollen than those that count upon the wind (Bakels, 2020; Moore et al. 1991) and in general, do not circulate their pollen as far afield due to large pollen grain size (Hjelle, 1997). Such factors therefore, reduce the chance that entomophilous pollen grains arrived in Iceland by accident.

4.2 Monasticism and land use in Medieval Iceland (Papers I & II)

Here, three particular objectives of this research project will be addressed with regard to the medieval Icelandic monasteries of Þingeyraklaustur and Helgafellsklaustur (**Papers I & II** respectively). These aims are as follows:

- Determine whether or not the introduction of monasticism to Iceland in the 12th century was accompanied by changes in the environment/ecology of the monastic landholding.

- Track the development of environmental/ecological change on the monastic landholding over time (12th century to 16th century) as a reflection of land use practices initiated by Icelandic monasteries.

- Discern the presence of European influences upon Icelandic monastic land use practices through the introduction of new plants and/or land use systems, and/or the intensification of established land use practices.

Further material pertaining to the impacts of climate, plague or Reformation will also be considered. Note that LPAZ/PZ will vary chronologically between sites, that the periods concerned may span more than a single LPAZ/PZ for a given site, and that the number of pollen samples and the sample resolution within a single LPAZ/PZ will differ between sites.

4.2.1 Pollen, plague and protestants at Þingeyraklaustur (Paper I)

Þingeyrar, the site of medieval Þingeyraklaustur (**Paper I**), is situated c. 13 km southwest of Blönduós, Austur Húnavatnssýsla, in northern Iceland (Fig. 1 & 2). Þingeyraklaustur was Iceland’s longest running monastery and among the earliest to be founded, either in AD 1112 or AD 1133, with consensus among historians favouring the latter date (DI-I, 1857-1976, p. 28; Jensson, 2021; Kristjánsdóttir, 2017 & 2023). The establishment of this Benedictine monastery was at the behest of Archbishop Össur Sveinsson of Lund, Sweden, and Bishop Jón Ögmundsson of Hólar, Iceland (Fig. 1; Jensson, 2021). From foundation, Þingeyraklaustur began to accumulate other properties, especially during the 14th century, in common with monasteries elsewhere in Iceland (Júlíusson, 2014; Kristjánsdóttir, 2023). By the 16th century, inventories reveal that the monastery owned 60 tenant farms across Austur and Vestur Húnavatnssýslur while the monastic landholding itself held a large number of livestock (DI-IX, 1857-1976, pp. 314-316; DI-XII, 1857-1976 pp. 451-452); Þingeyraklaustur was possibly the wealthiest monastery in Iceland. Ultimately, Þingeyraklaustur became famed for manuscript production (Jensson, 2021; Kristjánsdóttir, 2023).

With regard to palaeoecology, from AD 1104 (ÞING III), grazing sensitive taxa such as *Angelica* undiff. and *Vaccinium*-type finally disappear from the pollen assemblage. It is also clear that *Betula* (≤5% TLP; *Betula* pollen grain size $19^{\pm1}$ µm i.e. *B. nana* and referred to as such henceforth), *Salix*, Ericales and *E. nigrum* are experiencing ongoing declines i.e. scrub and heath type habitats are disappearing. The pollen record suggests that it is being replaced by Cyperaceae (≤90% TLP) and Poaceae (≤20% TLP) habitat types in association with an increased TLP or a consistent signal for herbaceous plants e.g. *L. viscaria*-type, *P. parnassia*, including the apophytes *Galium*, Lactuceae, *P. maritima, Rumex* spp., *S. selaginoides* and *T. alpinum* (≤5% TLP). CFS (*Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113) also appear for the first time in the pollen assemblage. Sedimentary data present an all-time low in OM (≥20%) with corresponding increases in MS and DBD. Overall, it is notable that major alterations to the ratios between *B. nana*, Cyperaceae and Poaceae, the definitive occupation of the landscape by apophytes, as well as a step reduction in OM, only occurs after AD 1104 rather than at Landnám c. AD 877 (Table 5).

As these palaeoecological changes are relatively coincident with the foundation of Þingeyraklaustur in the early 12th century, it is argued here that this represents clear evidence of the arrival of the monastery in the landscape; if for no other reason than it presents a significant contrast to what came before AD 1104 (ÞING I & II). That these changes might be arising prior to AD 1133 can be accounted for in two ways; 1) the margin of error attached to the age-depth model (unlikely given how close this data is to the fixed point of AD 1104); 2) that the palaeoecological data are picking up a signal that favours the earlier date for the establishment of Þingeyraklaustur in AD 1112. It is worth bearing in mind that construction and occupation of the monastic site could have arisen some decades prior to the formal consecration of the monastery in AD 1133 (and hence giving rise to the two dates in the historical record). Such activity would impose some demand upon the natural resources available in the surrounding landscape, and livestock grazing aside, most obviously for fuel for warmth, cooking, smelting and smithing (Vésteinsson & Simpson, 2001). This might be visible in the reduced presence of *B. nana* in the pollen assemblage, a species avoided by grazing animals (Hejcman et al. 2016). More broadly, while a pastoral landscape does appear to have been developing at Þingeyrar prior to AD 1104, a more concerted effort to remove unpalatable scrub e.g. *B. nana* and *E. nigrum* (Hejcman et al. 2016; Tybirk et al. 2000), might be underway with the establishment of the monastery. The expansion of grazing land and the clearance of *B. nana* at Þingeyraklaustur shares parallels with the foundation of the Augustinian house of Viðeyjarklaustur AD 1226 (Hallsdóttir, 1993) in southern Iceland, as well as with European monasteries (Table 1).

The development of a pastoral landscape at Þingeyrar continues into the 14th century (ÞING IV). However, from the beginning of the 15th century, there is a reversal in some of the trends discussed with regard to ÞING III i.e. an expansion in *B. nana* (≤20% TLP), the return of other grazing sensitive taxa e.g. *Angelica* undiff. and *F. ulmaria*, and a recovery in OM (≤55%). The prominence of *B. nana* in ÞING IV is especially significant as this is occurring during a period of climate cooling (Ogilvie & Jónsson, 2001). *B. nana* must therefore be benefitting from some other change in environmental conditions. In the 15th century, Iceland was beset by two plague epidemics (AD 1402 and AD 1495). There is some disagreement with regard to the exact nature of these epidemics, (Callow & Evans, 2016; Karlsson, 1996) but it is estimated that the first outbreak killed at least half the population of Iceland, with both epidemics leaving a number of farms abandoned by the 16th century (Júlíusson, 1997; Karlsson, 1996). At Þingeyraklaustur, the plague was just as devastating with the Abbot and all of the brethren bar one dying in AD 1402. As a result, the institution was devoid of a brotherhood for c. 22 years (Kristjánsdóttir, 2017). Þingeyraklaustur lost its Abbot again in AD 1495, but he was swiftly replaced, implying that some of the brethren survived this outbreak. It has been suggested that the later 15th century epidemic was not so virulent as the earlier one (Júlíusson, 1997; Karlsson, 1996; Kristjánsdóttir, 2017). Little is known of how these epidemics affected the laity of Þingeyraklaustur. Within the wider landscape, it is estimated that around 36% of the farms in tenure to the monastery were derelict by AD 1525 (Karlsson, 1996). On the European continent, instances of woodland recovery visible in the pollen record are considered to be symptomatic of demographic changes in human population arising from the Black Death (van Hoof et al. 2006; Yeloff & van Geel, 2007). It is posited here that this also applies to the recovery of *B. nana* at Þingeyrar in the 15th century.

Following the 15th century, there is a resumption in the development of a pastoral landscape at Þingeyrar (ÞING V), with a drop in *B. nana* (≤5% TLP) and increases in Cyperaceae (≤70% TLP) and Poaceae (≤20% TLP), while OM goes into a gradual decline from 60% (bearing in mind that there are only four pollen samples in this pollen assemblage). An inventory from Þingeyrarklaustur for AD 1525 suggests that there is a relatively large body of livestock present on the monastic landholding: 350 sheep, 56 cattle, and 11 horses (DI-IX, 1857-1976, p. 316). It is unknown as to whether or not these numbers were increasing or decreasing but the type of vegetation communities that are in ascendency at Þingeyrar, as suggested by the ÞING V, would be consistent with the presence of grazing animals.

This LPAZ also captures AD 1551, the date of the monastery's dissolution during the Lutheran Protestant Reformation, whereupon both fixed and movable property was transferred into the possession of the Danish Crown (Karlsson, 2000; Kristjánsdóttir, 2017). There is some evidence from the north of England to suggest that the dissolution of a monastery can initiate changes in vegetation due to the break-up of the monastic landholding (Wimble et al. 2000). Despite good sampling resolution (0.5 cm) for ÞING V, the changes in the vegetation at Þingeyrar in the 16th century could be attributable to either the monastery or the Danish Crown. This could suggest continuity in land management practices, irrespective of the overseeing institution, perhaps perpetuated by the fact that the monastic landholding was not divided up between various landowners but remained exclusively in the hands of the Danish Crown.

What follows in the 17th century into the 18th century (ÞING VI) is a culmination of centuries of effort in converting much of the landholding to pasture i.e. Poaceae ≤44%, Cyperaceae ≤40%, in association with raised values or greater consistency in apophyte presence e.g. *Oxyria*-type, *R. acetosa*, *R. acetosella*, *S. selaginoides* (≤5% TLP), and *T. alpinum* (≤15% TLP). CFS (*Sordaria*-type HdV-55A and *Sporormiella*-type HdV-113), as an indication of livestock presence, are also more consistent. Sedimentary conditions appear stable, with OM (≤50%) on the rise. This is a little surprising with reference to historical sources that identify inundations of sand at neighbouring farms (Geirastaðir and Trumbsvalir) north of Þingeyrar (Magnússon & Vídalín, 1926, Vol. VIII, pp. 247-251). The absence of depositions of sand in the sequence of ÞING VI might suggest that the documented events at nearby farms were localised, dictated by land use, prevailing wind direction, and proximity to coastal sands i.e. Þingeyrasandur.

4.2.2 A script born of sediments from Helgafellsklaustur (Paper II)

Helgafell, the site of medieval Helgafellsklaustur (**Paper II**), is situated on the north coast of Snæfellsnes, approximately 4 km south of Stykkishólmur, in western Iceland (Figs. 1 & 2). Helgafellsklaustur was established in AD 1184 when Abbot Ögmundur Kálfsson and three brethren relocated their nascent Augustinian institution (founded AD 1172) from the island of Flatey in Breiðafjörður to the uninhabited farm of Helgafell (DI-I 1857-1976 pp. 280-282; Drechsler, 2021; Kristjánsdóttir, 2017). The assets of the newly acquired landholding were extensive with ready access to marine resources (fish, seals, whale wrecks, seabirds, eggs, eiderdown and driftwood) and wood sourced from Drangaskógur. The brethren also brought a small number of domestic animals with them from Flatey to Helgafell; 30 cattle and c. 20 horses. Inventories for AD 1377/78 (DI-III, 1857-1976, p. 328) and AD 1397 (DI-IV, 1857-1976, p. 168) show that livestock numbers grew considerably (548 and 711 respectively), an important source of meat, dairy, vellum, hides and wool, as well as beasts of burden. The acquisition of tenant farms in the surrounding area began with the monastery's foundation in the 12th century (DI-I, 1857-1976, 280-282) although most were acquired during the 14th century (DI-III, 1857-1976, pp. 325-329). Rent was paid in fish, dairy, and woollen goods. By the time of the Lutheran Protestant Reformation in the 16th century, Helgafellsklaustur owned c. 95 farms across Snæfellsnes (Júlíusson, 2014). Upon dissolution c. AD 1544, Helgafellsklaustur and its assets became the property of the Danish Crown (DI-XI, 1857-1976, p. 168; Kristjánsdóttir, 2017), with the *caput* of the estate soon moving to Arnarstapi on the south coast of Snæfellsnes (AD 1550). Of the monastery itself, historical sources describe it as comprised of a number of buildings (DI-IV, 1857-1976, pp. 169-171), perhaps forming a cloister about a herb garden. Unfortunately, the exact location of this cloister at Helgafell remains elusive (Kristjánsdóttir, 2017). Archaeologists suspect that it was situated where the church and cemetery of Helgafell now stand. There are few artefacts that can be directly associated with the monastery (Kristjánsdóttir, 2017; Kristjánsdóttir & Gunnarsdóttir, 2014; Kristjánsdóttir et al. 2016). To date, the only tangible part of the monastery's legacy is a corpus of manuscripts written there in the 14th century (Drechsler, 2021; Kristjánsdóttir, 2023).

HFK8 IV (c. AD 1144-1407) encompasses the foundation (AD 1184) and first 250 years of Helgafellsklaustur. A step in the development of the agricultural landscape at Helgafell is obvious with regard to terrestrial vegetation communities. The archaeophytes *Hordeum*-type, and *P. aviculare* arrive at Helgafell and the incidence of the apophytes *P. lanceolata* and *P. maritima* ($\leq$2.9% and $\leq$0.9% TLP respectively) is stronger than previously (particularly the latter), while the archaeophytes *Anthemis*-type, *Artemisia*-type and *R. acetosella* recur. The occurrence of archaeophytes and apophytes seems bound to a slight expansion in Poaceae, while habitats associated with Cyperaceae and *Betula* are sustained ($\leq$26.7%, $\leq$24.9% and $\leq$55.3% TLP respectively). The average pollen grain size of *Betula* (Fig. 9; $22^{\pm1}$ µm) remains closer to *B. nana* (despite a slight increase in size) and infers heath. That Helgafellsklaustur was acquiring wood from beyond its immediate landholding from its foundation in AD 1184 also suggests *B. pubescens* was scant and lends strength to this interpretation (DI-I, 1857-1976, p. 282). The predominance of *B. nana* intimates selective grazing by livestock (Hejcman et al., 2016). Selective grazing may also apply in relation to the dominance of *E. nigrum* (2.7% TLP on average) over *Vaccinium*-type (1.3% TLP on average), the former also generally avoided by grazing animals (Tybirk et al. 2000).

Recurring *Artemisia*-type is a common feature of medieval Icelandic pollen assemblages as discussed previously with regard to Landnám. It has been associated with beer production in lieu of *Humulus lupulus* (hops; Edwards et al. 2021). Acknowledging that there are limits with regard to the number of pollen grains involved, it is interesting to see that *Artemisia*-type (57.5 cm) is populating the same PZ as *Hordeum*-type (55.5 cm and 49.5 cm); *Hordeum*-type may be under-represented due to the poor dispersal of its large pollen grains (Vuorela, 1973). Both the high social status attached to Helgafellsklaustur and its lowland coastal context favour cereal cultivation (Riddell et al. 2018), while beer production is a feature of the historical record of Helgafellsklaustur (Kristjánsdóttir, 2017). The possibility that *Hordeum*-type pollen might represent the native wild grass *Leymus arenaria* (lyme grass) is negated due to the absence of suitable habitat (Erlendsson, 2007; Mooney & Guðmundsdóttir, 2020; Riddell et al. 2018). Helgafell does lie in close proximity to the coast but the sand dune systems that *L. arenaria* thrives upon are absent within the immediate locale (Guðmundsson, 1996). Indications of long term erosion and the redeposition of terrestrial sediments, which might create conditions suitable for *L. arenaria*, are generally absent from the sedimentary record i.e. DBD and MS are declining while OM increases.

Indeed, the sediments of Helgafellsvatn infer stability in the surrounding environment as OM rises (27.1% on average) while DBD returns to pre-Landnám levels (range 0.22 to 0.09 g cm^{-3}). Increased OM may be a consequence of developments in the aquatic environment as amounts for *M. alterniflorum* (and to a lesser degree *M. spicatum*) also increase from 61 cm (9211 grains cm^{-3} on average) and reach a peak at 50.5 cm (21099 grains cm^{-3}) in the late 13th century. This might be due to ongoing nutrient enrichment which can result in a luxuriant growth of species such as *M. alterniflorum* in oligotrophic systems (Roelofs et al. 1984). The most obvious source of nutrients would be domestic livestock (Lawson et al. 2006; Lawson et al. 2007). A stronger and more consistent CFS signal verifies their presence (140 grains cm^{-3} on average), with *Podaspora* HdV-368 flourishing (in relative terms; ≤135 grains cm^{-3}) and BRN-7 cf. *Schizothecium conicum* (Feeser & O'Connell, 2010) appearing briefly (431 grains cm^{-3}), an ascomycete with a strong association with domestic mammals (Richardson, 2011). Nonetheless, greater values for CFS in HFK8 IV would be expected and if it were not for thriving *M. alterniflorum* and the historical record (DI-I, 1857-1976, p. 282; DI-III, 1857-1976, p. 328; DI-IV, 1857-1976, p. 168), the presence of livestock at Helgafell would be understated. In fact, the available historical data undermine any prospect that low amounts of CFS are a consequence of low livestock density. This therefore probably pertains to patterns of CFS deposition in lacustrine environments as discussed with regard to Landnám (Lee et al. 2022). HFK8 IV effectively terminates with a minor influx of minerogenic material at 46.5 cm (OM 20%; DBD 0.27 g cm^{-3}; MS 7.6 SI units, c. AD 1360) derived either from a volcanic or erosion event. If the latter, given what we understand with regard to livestock at Helgafell in the late 14th century, some disruption to terrestrial sediments is perhaps unsurprising (but remains minimal). It is interesting to note that the number of cattle in particular doubles between AD 1377 and AD 1398 when manuscript production was at its peak at Helgafell (Drechsler, 2021; Kristjánsdóttir, 2023).

As has been observed with regard to Þingeyraklaustur, and at Viðeyjarklaustur (Hallsdóttir, 1993), the palaeoecological data clearly reveal the arrival of Helgafellsklaustur in the landscape in the late 12th century. The contrast with previous PZ's is not as strong as at Þingeyraklaustur, but there is an expansion of open habitats (particularly grassland). This is associated with increases in apophytes and the arrival of a further suite of archaeophytes, and evidence of selective grazing by livestock i.e. increased values for *B. nana* and *E. nigrum* (Hejcman et al. 2016; Tybirk et al. 2000). Livestock are implicated in the eutrophication of Helgafellsvatn, apparent through increased *M. alterniflorum* values (Lawson et al. 2006; Lawson et al. 2007; Roelofs et al. 1984). Furthermore, the presence of *Hordeum*-type might infer cereal cultivation, and in association with *Artemisia*-type, beer production (Edwards et al. 2011). Documentary sources compliment this interpretation i.e. large numbers of livestock DI-III, 1857-1976, p. 328; DI-IV, 1857-1976, p. 168) and beer production (DI-III, 1857-1976, p. 445; DI-VI 1857-1976, pp. 35-36). Whether or not the land use practices associated with Helgafellsklaustur can be directly attributed to the influence of European monasticism remains open to question. In contrast to Þingeyraklaustur, and despite the clear shift in vegetation at Helgafell with the arrival of Helgafellsklaustur, this change is part of the continued development of a pastureland initiated c. AD 920 (Table 5). This trajectory is maintained for HFK8 V (c. AD 1407-1524) with yet further expansion in Poaceae and Cyperaceae habitat types at the expense of *Betula* (although the latter retains a strong presence), alongside the (subtle) arrival of another suite of apophytes, and the highest values for CFS yet (i.e. livestock presence). Such changes to the terrestrial vegetation are significant in their own right in terms of land use i.e. ongoing development of a pastoral economy, but it also asserts the continuity of a human presence during the plague epidemics of the 15th century. This is consistent with the historical view that neither of the plague epidemics in Iceland are believed to have had a significant impact at Helgafellsklaustur (Drechsler, 2021; Júlíusson, 1997; Karlsson, 1996; Kristjánsdóttir, 2017). Pollen analysis for HFK8 does not extend beyond AD 1524 so there is no way of discerning anything of the impact of the Lutheran Protestant Revolution upon the landholding Helgafellsklaustur. There is some intimation of change in the aquatic environment for HFK8 V i.e. a decline in *M. alterniflorum* values. If we accept that *M. alterniflorum* is a proxy for nutrient enrichment (Roelofs et al. 1984), a decline would suggest a change in the source of nutrients i.e. land use (Gauthier et al. 2010; Lawson et al. 2007). Alternatively, as the pollen assemblage conveys continuity in pastoralism at Helgafell, it is possible that the decline in *M. alterniflorum* is due to climate cooling as the later phase of the LIA ensues (c. AD 1500).

4.3 Monasticism and tenancy in Medieval Iceland (Paper III)

The monastic tenancies of Helgadalur and Ásbjarnarnes (**Paper III**), will be discussed in order to address the final objective of the research project, given as follows:

- Assess the manner in which farm tenants on monastic landholdings responded to the introduction of monastic ownership i.e. societal change identifiable via altered land management practices expressed through environmental/ecological change (**Paper III**).

Material pertaining to the impacts of climate, plague or Reformation will also be considered alongside post-Reformation material.

4.3.1 Tenancy and making hay at Helgagdalur

The earliest historical reference to Helgadalur comes from an inventory for AD 1395 (DI-III, 1857-1976, p. 598) where it is stated that it came into the ownership of the Augustinian house of Viðeyjarklaustur (Fig. 1) during the rule of Abbot Páll Magnússon (AD 1379-1403) i.e. within the 16 years between the Abbot's ordination in AD 1379 (Kristjánsdóttir, 2017) and the compilation of the inventory. Representatives of the Danish Crown attacked Viðeyjarklaustur in the name of Lutheran Protestant Reformation on Whitsun AD 1539 (DI-X, 1857-1976, pp. 451-459). Following dissolution, Viðeyjarklaustur, Helgadalur and another c. 60 tenancies (Júlíusson, 2014), effectively became a fiefdom of the Danish Crown, remaining so into the 18th century (Magnússon & Vídalín, 1926, Vol. III, pp. 316-317). The period of monastic oversight is encompassed by LPAZ HEL III (c. AD 1235-1614) which has already been discussed with regard to Landnám and the pre-monastic period at Helgadalur. By the time of its acquisition by Viðeyjarklaustur in AD 1395, the part of Helgadalur associated with the sampling site seems to have been managed as a hayfield as Cyperaceae is dominant in the pollen assemblage (≤80.3% TLP), Poaceae is rising (≤23% TLP), with relatively high *T. alpinum* (≤13.1% TLP), as well as a recovery of grazing sensitive species *A. sylvestris* and *F. ulmaria*. OM values are also increasing (≤60.7%). There is absolutely no break in the continuity of the pollen and sedimentary record between AD 1235 and AD 1614 other than the deposition of the Katla AD 1500 tephra. This suggests that there was no change in the management regime at Helgadalur under the auspices of Viðeyjarklaustur and later, the Danish Crown following the Lutheran Protestant Reformation c. AD 1539.

4.3.2 Tenancy, hay, and the Danish Crown at Helgadalur

The final LPAZ of Helgadalur (HEL IV) encompasses the time period c. AD 1614-1850. It is readily apparent that the cultivation of a hayfield at Helgadalur is sustained into the modern period. The only real change is an increase in Poaceae (≤25.6% TLP) at the expense of Cyperaceae (which retains prominence; ≤68.6% TLP). *T. alpinum* continues to increase (≤18.1% TLP). CFS are absent. The presumed exclusion of livestock may be allowing some recovery in woody taxa (*Betula* and *Salix*). Sediments continue to be comprised of silty peats with OM recovering to ≤57% with corresponding declines in MS and DBD outwith disruption associated with the deposition of an undated Katla tephra (7.5 cm). It would appear that the Danish Crown exerted little change at Helgadalur, the development of the hayfield a culmination of land management practices initiated at Landnám c. AD 877.

4.3.3 Tenancy and the Nesskógar at Ásbjarnarnes

Reference to Ásbjarnarnes in historical sources (also known as *Nes í Víðidalur*, *Nes í Vestur Hóp*, *Ásbjarnarnes í Þverárhreppi*) begins in the early 14th century in association with the Benedictine monastery of Þingeyraklaustur. This material is concerned with shore rights such as sealing and beached whales (DI-II, 1857-1976, p. 376). In AD 1361, half of the Ásbjarnarnes landholding, including the home farm and an extensive area of woodland, was bequeathed to Þingeyraklaustur by the farmer Árni Bárðarsson (DI-III, 1857-1976, pp. 179-181). Later inventories (DI-VIII, 1857-1976, p. 131; DI-IX, 1857-1976, p. 314; DI-XII, 1857-1976, p. 453) show that this portion of Ásbjarnarnes remained a tenancy of Þingeyraklaustur, along with around 62 other tenancies (Júlíusson 2014), until the Lutheran Protestant Reformation and the dissolution of the monastery.

This period is encompassed by LPAZ ÁSB2 IV (c. AD 1205-1541), largely defined by high Cyperaceae values (≤89.1% TLP) in association with some degree of environmental disturbance i.e. increased minerogenic input. What is of particular interest are the declining values for *Betula* (≤12.3% TLP) in light of historical descriptions of Ásbjarnarnes. The original deed of sale from AD 1361 describes an extensive area of *skóg* (woodland) extending from the lagoon of Hóp to the east of Ásbjarnarnes across the ridge of Bjargaás to the west (a span of c. 2 km). With reference to later sources (AD 1669), the name of this woodland was "Nesskógur" (Þorsteinsson, 1922-1932, p. 384). In AD 1705, by clearly distinguishing between woodland, trees and scrub in their description of Ásbjarnarnes, Magnússon & Vídalín (1926, Vol. VIII, pp. 216-217) thought that the Nesskógur survived down to the mid-17th century. Based upon this small body of historical information it may be inferred that a proportion of the *Betula* pollen grains counted for ÁSB2 IV represent *B. pubescens* (presumably applying to earlier and later pollen assemblages from ÁSB2 as well). One would expect *Betula* pollen values to be greater than 12% TLP in the presence of a *B. pubescens* woodland. It is possible that there is a parallel here with Holocene studies that identify the presence of *B. pubescens* woodland via macrofossils even though pollen values are low (Eddudóttir et al. 2016). This is attributed to low temperatures associated with altitude suppressing *B. pubescens* pollen productivity (Kuoppamaa et al. 2009). At Ásbjarnarnes, it may be that *B. pubescens* is experiencing temperature stress and reduced pollen production induced by the LIA (Eiríksson et al. 2000; Larsen et al. 2012; Ogilvie & Jónsson, 2001).

In a 16th century inventory for Þingeyraklaustur, Ásbjarnarnes is conspicuous as the only tenant farm of 62 that pays its rent to the monastery with charcoal. Charcoal production was also a feature of Ásbjarnarnes in the late 17th century (Magnússon & Vídalín, 1926, Vol. VIII, pp. 216-217). Raised microscopic charcoal values for ÁSB2 IV might be capturing this activity from the 15th century (≤8.7% TLP; the signal stronger with regard to concentration), although there is a consistent microscopic charcoal signal from the 11th century (ÁSB2 II). The continuity in microscopic charcoal coincident with woodland may represent an established practice at Ásbjarnarnes prior to tenancy. Some interrelationship between charcoal and *Betula* values might be expected but there is none. It is speculated here that this might be a consequence of the *ad hoc* coppicing of *Betula*, shrouding oscillations in the palynomorph signal that would conventionally be attached to such activity. Of course, nothing is actually known of the impact of coppicing on pollen production in Iceland, and little is understood of it elsewhere (Bunting et al. 2016). Woodland in Iceland was seen as an important source of timber (rafters), wood fuel, charcoal (iron smelting and smithing), leaf fodder, winter grazing and shelter for livestock (Church et al. 2007; Hejcman et al. 2016; Magnússon & Vídalín, 1926, Vol. VIII, pp. 216-217; Vésteinsson & Simpson, 2001); clear incentives to nurture woodlands. That woodland survived at Ásbjarnarnes down to at least the 17th century (Magnússon & Vídalín, 1926, Vol. VIII, pp. 216-217), is perhaps as a direct consequence of a land use strategy imposed by Þingeyraklaustur and a demand for charcoal.

There is a slight recovery in *Betula* toward the end of the 15th century, and it is tempting to attribute this to plague given what has already been discussed on this matter with regard to the landowner i.e. Þingeyraklaustur (van Hoof et al. 2006; Yeloff & van Geel, 2007). However, coincident increases in microscopic charcoal suggest otherwise (irrespective of whether or not this is from charcoal production or household activities). Some Icelandic farms were untouched by plague (Karlsson, 1996) and *Betula* recovery in the late 15th century could represent altered land management practices as a response to plague rather than outright abandonment (Streeter et al. 2012).

4.3.4 An end to the Nesskógar at Ásbjarnarnes

The final LPAZ of Ásbjarnarnes (ÁSB2 V) encompasses the time period c. AD 1541-1882. The Lutheran Protestant Reformation seems to have had little impact at Ásbjarnarnes following the dissolution of Þingeyrarklaustur. Woody taxa are on the increase i.e. *Betula* (≤29.3% TLP), *Salix* (≤2.3% TLP), Ericales (≤5.9% TLP) and *E. nigrum* (≤ 1% TLP) with a decline in Cyperaceae (≤49.7% TLP). Scrub encroachment could infer dereliction but microscopic charcoal suggests continued occupation and/or activity (Edwards et al. 2011). This trajectory is later reversed with Cyperaceae increasing again to 89.1% with a corresponding decline in in the tree and shrub taxa; *Betula* (≤5.3% TLP), *Salix* (≤0.2% TLP) and Ericales (≤0.4% TLP). It is notable that this arises following the appearance of bands of sand in the sedimentary sequence and increased minerogenic input in general (visible in OM, DBD and MS). Magnússon & Vídalín (1926, Vol. VIII, pp. 216-217) describe the poor condition of the surviving trees at Ásbjarnarnes in the early 18th century, in hand with descriptions of sandstorms. It is possible that these sand deposits are linked to increased storminess during the LIA (Clarke & Rendell, 2009; Dawson et al. 2003), the material derived from Þingeyrasandur.

4.4 Consilience, palaeoecology and monasticism in Iceland (Papers I, II & III)

An aspect of this study was to marry palaeoecological data with information derived from historical sources. This was aided by the ability to attribute historic events to specific times and places, primarily via the *Diplomatarium Islandicum* (DI-I-XVI, 1857-1976) and Jarðabók (Magnússon & Vídalín, 1926). High pollen sampling resolution was a further contributing factor while the fixed dates attached to tephra layers offset the imprecision of ^{14}C dates. The effectiveness of this approach did vary between the four sites investigated. A suite of tephra layers at Þingeyrar (**Paper I**) allowed for good chronological resolution that allowed for a direct comparison between historical sources and palaeoecological data. In particular, insight was garnered with regard to the foundation of the Þingeyraklaustur, there was parity between sources with regard to the plague epidemics of the 15th century, while nuance was detected with regard to inundations of sand in the centuries following the Reformation. In comparison, the chronological resolution for Helgafell (**Paper II**) was less constrained, relying on two tephra layers and a 20th century date (Pu), that left some margin of error with regard to pinpointing specific historical and palaeoecological events. This resulted in a more general discussion pertaining to pollen zones rather than specific events. Nonetheless, it was possible to determine the arrival of Helgafellsklaustur at Helgafell in the late 12th century and something of the impact of livestock on the aquatic and terrestrial environments there in subsequent centuries. Similar difficulties applied to Ásbjarnarnes (**Paper III**) which was particularly reliant on ^{14}C dates in the later part of the chronological sequence. Nonetheless, even a broad brush analysis allowed historical reference to woodland at Ásbjarnarnes to be evaluated palaeoecologically, perhaps even revealing some subtlety with regard to the nature of the woodland, possibly linked to climate (low *Betula* values). Finally, the rigour of the chronology for Helgadalur (**Paper II**) and the high resolution of pollen sampling made it possible to conclude that Viðeyjarklaustur was not exerting any direct influence on land use once the farm became a part of its landholding. There was absolutely no break in palaeoecological continuity c. AD 1395. On the basis of these findings, there is clearly merit in applying this approach to palaeoecological data sets.

5 Conclusion

With regard to the specific objectives identified for this research project, it is possible to conclude that; 1) The arrival of both Þingeyraklaustur and Helgafellsklaustur is visible in their respective pollen assemblages (**Papers I & II**). This is particularly obvious in relation to Þingeyraklaustur if for no other reason than it presents a significant contrast to what came before AD 1104. Nonetheless, a suite of features at Helgafell also reveal a step change in in the pollen assemblage and lake sediments around the time that the monastery was founded there; 2) Under the aegis of Þingeyraklaustur (**Paper I**), a pastoral landscape was perpetuated with evidence suggesting the active clearance of *B. nana*, either as a deliberate effort to expand pasture area, or by default through gathering material for fuel. A similar approach to land use applies at Helgafellsklaustur (**Paper II**) with the added (tentative) possibility that cereals were cultivated; 3) While there are parallels at Þingeyraklaustur (**Paper I**) with European monasticism i.e. assarting, and at Helgafellsklaustur (**Paper II**) regarding cultivation, it is impossible to assert that what was happening in Iceland was a specific derivative of European monasticism. Nor is there any evidence of imported plant species for medicinal, culinary, or other utilitarian purposes in association with either monastery with potential taxa already present in the pollen assemblage prior to monasticism.; 4) In relation to the influence that monasteries brought to bear upon the tenant farms of Helgadalur and Ásbjarnarnes (**Paper III**), evidence is limited to the possibility that Þingeyraklaustur was attempting to nurture woodland at Ásbjarnarnes. At Helgadalur, there is absolute continuity in land use i.e. a hayfield, following the acquisition of the farm by Viðeyjarklaustur.

Further to the specific objectives of this research project, data reveal parity between the palaeoecological record and historical sources with regard to the plague epidemics of the 15th century at Þingeyrarklaustur (**Paper I**: *Betula* recovery) and Helgafellsklaustur (**Paper II:** continuity). There was no evidence of any disruption to land use at monastery and tenancy sites (**Papers I, II & III**) in relation to the Lutheran Protestant Reformation in the early 16th century. This is probably because the land units remained intact in the hands of the Danish Crown rather than being broken up between a number of new landowners. Climate impacts associated with the LIA might be visible in the aquatic pollen assemblage (declining *M. alterniflorum*) from Helgafell (**Paper II**) and in the *Betula* and sedimentary record (reduced pollen production and sandstorms) of Ásbjarnarnes (**Paper III**).

Consideration of pre-Landnám vegetation and the impact of Landnám upon vegetation was also informative. In particular; 1) All four sites (**Papers I, II & III**) were evaluated in relation to a climate amelioration c. AD 600-800, with findings potentially contributing to further discourse on climate impacts on Icelandic vegetation in the past (and future); 2) All four sites (**Papers I, II & III**) were evaluated in relation to Landnám, identifying synchronicity of human presence in Iceland c. AD 877 but also demonstrating variation between sites in terms of the magnitude of human impact and/or the rate at which land was occupied; 3) The pollen assemblage for Helgafell (**Paper II**) included evidence for the introduction of exotic plant taxa (medicinal, culinary, or utilitarian applications) at Helgafell prior to the foundation of Helgafellsklaustur.

Overall, the targeting of specific sites for palaeoecological analysis in relation to the historical record (consilience) has proven informative in terms of monastic presence, land use, plague, and Reformation. Contradiction between data sources has been equally informative e.g. with regard to the birch woods of Ásbjarnarnes. With the latter site and Helgadalur in mind, a first step has been made palaeoecologically to understand the relationship between landowners and their tenants, which in this instance, infers a light touch.

More broadly, this suite of pollen assemblages makes a further contribution to the growing canon of pollen studies pertaining to the Holocene, Landnám, and the Medieval period in Iceland first initiated in the early 20th century by geographer Sigurður Thorarinsson (1944). With that in mind, palynology and palaeoecology in general continues to enhance our understanding of natural resource utilisation in the past (Erlendsson et al. 2006; Vésteinsson, 1998), and how the ecosystems that underpinned it, can be sustained into the future (Edwards et al. 2019).

References

Aaby, B., & Berglund, B. E. (1986). Characterisation of lake and peat deposits. In *Handbook of Holocene Palaeoecology and Palaeohydrology*. Chichester: John Wiley & Sons Ltd.

Alanko, T., & Uotila, K. (2015). Gardening and consumption of plants in Naantali cloister (SW Finland) before and after the Reformation. *Journal of Nordic Archaeological Science*.

Andersen, S. T. (1979). Identification of wild grass and cereal pollen. *Danmarks Geologiske Undersøgelse Årbog,* 25, 491-518.

Arnalds, Ó. (2004). Volcanic soils of Iceland. *Catena,* 56(1-3), 3-20.

Arnalds, Ó. (2008). The Soils of Iceland. *Jökull* 58, 409–421.

Arts, G. H. (2002). Deterioration of Atlantic soft water macrophyte communities by acidification, eutrophication and alkalinisation. *Aquatic Botany,* 73(4), 373-393.

Åsen, P. A. (2021). Medieval Monastery Gardens in Iceland and Norway. *Religions,* 12(5), 317.

Aston, M. (2000). *Monasteries in the Landscape*. Stroud: Tempus.

Bakels, C. (2020). Pollen and Archaeology. In A. Henry (Ed.), *Handbook for the Analysis of Micro-Particles in Archaeological Samples*. Switzerland: Springer, 203-224.

Barney, J., & DiTommaso, A. (2003). The biology of Canadian weeds. 118. *Artemisia vulgaris* L. *Canadian journal of plant science,* 83(1), 205-215.

Bates, R., Erlendsson, E., Eddudóttir, S. D., Möckel, S. C., Tinganelli, L., & Gísladóttir, G. (2022). Landnám, Land Use and Landscape Change at Kagaðarhóll in Northwest Iceland. *Environmental Archaeology,* 27(2), 211-227.

Benediktsson, J. (1968). Íslendingabók, Landnámabók, Íslenzk fornrit I. *Reykjavik: Hið íslenzka fornritafélag*.

Berglund, B. E. (1985). Early agriculture in Scandinavia: research problems related to pollen-analytical studies. *Norwegian Archaeological Review,* 18(1-2), 77-90.

Birks, H. J. B., & Birks, H. H. (1980). *Quaternary palaeoecology*. London: Edward Arnold.

Björck, S., Ingólfsson, Ó., Haflidason, H., Hallsdóttir, M., & Anderson, N. J. (1992). Lake Torfadalsvatn: a high resolution record of the North Atlantic ash zone I and the last glacial-interglacial environmental changes in Iceland. *Boreas,* 21(1), 15-22.

Björck, S., Persson, T., & Kristersson, I. (1978). Comparison of two concentration methods for pollen in minerogenic sediments. *Geologiska Föreningen i Stockholm Förhandlingar,* 100(1), 107-111.

Blaauw, M. (2010). Methods and code for 'classical' age-modelling of radiocarbon sequences. *Quaternary Geochronology,* 5, 512-518.

Blaauw, M., & Christen, J. A. (2011). Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis,* 6(3), 457-474.

Bolender, D., Johnson, E., & Bello, G. (2020). Tenancy, finance, and access to commercial goods: Interpreting impoverished assemblages in Skagafjörður, Iceland, CE 1300–1900. *Journal of Anthropological Archaeology,* 60, 101227.

Bond, J. (2004). *Monastic Landscapes*. Stroud: Tempus.

Bonny, A. P. (1972). A method for determing absolute pollen frequencies in lake sediments. *New Phytologist,* 71, 393-405.

Brady, N. C., & Weil, R. R. (1996). *Elements of the nature and properties of soils*. Upper Saddle River Pearson Prentice-Hall

Breitenlechner, E., Hilber, M., Lutz, J., Kathrein, Y., Unterkircher, A., & Oeggl, K. (2010). The impact of mining activities on the environment reflected by pollen, charcoal and geochemical analyses. *Journal of Archaeological Science,* 37(7), 1458-1467.

Buckland, P., Edwards, K., Blackford, J., Dugmore, A., Sadler, J., & Sveinbjarnardóttir, G. (1995). A question of Landnám: pollen, charcoal and insect studies on Papey, eastern Iceland. In R. Butlin & N. Roberts (Eds.), *Ecological relations in historical times: Human impact and adaption*. Oxford: Blackwell, 245-264.

Bunting, M. J., Grant, M. J., & Waller, M. (2016). Approaches to quantitative reconstruction of woody vegetation in managed woodlands from pollen records. *Review of Palaeobotany and Palynology,* 225, 53-66.

Callow, C., & Evans, C. (2016). The mystery of plague in medieval Iceland *Journal of Medieval History,* 42(2), 254-284.

Caseldine, C. (2001). Changes in *Betula* in the Holocene record from Iceland—a palaeoclimatic record or evidence for early Holocene hybridisation? *Review of Palaeobotany and Palynology,* 117(1-3), 139-152.

Caseldine, C., & Hatton, J. (1994). Interpretation of Holocene climatic change for the Eyjaförður area of northern Iceland from pollen-analytical data: Comments and preliminary results. *Environmental Change in Iceland: Münchener Geographische Abhandlungen, Reihe B,* 12, 41-62.

Caseldine, C., Langdon, P., & Holmes, N. (2006). Early Holocene climate variability and the timing and extent of the Holocene thermal maximum (HTM) in northern Iceland. *Quaternary Science Reviews,* 25(17-18), 2314-2331.

Church, M., Dugmore, A., Mairs, K., Millard, A., Cook, G., Sveinbjarnardóttir, G., Ascough, P.A. & Roucoux, K.H. (2007). Charcoal production during the norse and early medieval periods in Eyjafjallahreppur, southern Iceland. *Radiocarbon,* 49(2), 659-672.

Clark, J. G. (2021). The Making of Nordic Monasticism, c. 1076–c. 1350. *Religions,* 12(8), 581.

Clarke, M. L., & Rendell, H. M. (2009). The impact of North Atlantic storminess on western European coasts: a review. *Quaternary International,* 195(1-2), 31-41.

Cugny, C., Mazier, F., & Galop, D. (2010). Modern and fossil non-pollen palynomorphs from the Basque mountains (western Pyrenees, France): the use of coprophilous fungi to reconstruct pastoral activity. *Vegetation History and Archaeobotany,* 19(5-6), 391-408.

Davies, A. L. (2019). Dung fungi as an indicator of large herbivore dynamics in peatlands. *Review of Palaeobotany and Palynology,* 271, 104108.

Dawson, A. G., Elliott, L., Mayewski, P., Lockett, P., Noone, S., Hickey, K., . . . Foster, I. (2003). Late-Holocene North Atlantic climate ‘seesaws’, storminess changes and Greenland ice sheet (GISP2) palaeoclimates. *Holocene,* 13(3), 381-392.

Dearing, J. (1994). *Environmental Magnetic Susceptibility*. Kenilworth: Chi Publishing.

DI-I-XVI. (1857-1976). *Diplomatarium Islandicum: Íslenzkt fornbréfasafn*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

DI-I. (1857-1976). *Diplomatarium Islandicum: Íslenzkt fornbréfasafn*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

DI-II. (1857-1976). *Diplomatarium Islandicum: Íslenzkt fornbréfasafn*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

DI-III. (1857-1976). *Diplomatarium Islandicum: Íslenzkt fornbréfasafn*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

DI-IV. (1857-1976). *Diplomatarium Islandicum: Íslenzkt fornbréfasafn*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

DI-V. (1857-1976). *Diplomatarium Islandicum: Íslenzkt fornbréfasafn*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

DI-VIII. (1857-1976). *Diplomatarium Islandicum: Íslenzkt fornbréfasafn*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

DI-IX. (1857-1976). *Diplomatarium Islandicum: Íslenzkt fornbréfasafn*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

DI-X. (1857-1976). *Diplomatarium Islandicum: Íslenzkt fornbréfasafn*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

DI-XI. (1857-1976). *Diplomatarium Islandicum: Íslenzkt fornbréfasafn*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

DI-XII. (1857-1976). *Diplomatarium Islandicum: Íslenzkt fornbréfasafn*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

Dickson, C. (1996). Food, medicinal and other plants from the 15th century drains of Paisley Abbey, Scotland. *Vegetation history and Archaeobotany,* 5(1), 25-31.

Drechsler, S. (2021). *Illuminated manuscript productionin Medieval Iceland: literary and artistic activities of the monastery at Helgafell in the fourteenth century*. Turnhout, Belgium: Brepols.

Dugmore, A. J., Gísladóttir, G., Simpson, I. A., & Newton, A. (2009). Conceptual models of 1200 years of Icelandic soil erosion reconstructed using tephrochronology. *Journal of the North Atlantic,* 2(1), 1-18.

Dugmore, A. J., Larsen, G., & Newton, A. J. (1995). Seven tephra isochrones in Scotland. *Holocene,* 5(3), 257-266.

Dumayne, L., Stoneman, R., Barber, K., & Harkness, D. (1995). Problems associated with correlating calibrated radiocarbon-dated pollen diagrams with historical events. *Holocene,* 5(1), 118-123.

Eddudóttir, S. D. (2016). *Holocene environmental change in Northwest Iceland.* (PhD), University of Iceland, Reykjavík.

Eddudóttir, S. D., Erlendsson, E., & Gísladóttir, G. (2015). Life on the periphery is tough: Vegetation in Northwest Iceland and its responses to early-Holocene warmth and later climate fluctuations. *Holocene,* 25(9), 1437-1453.

Eddudóttir, S. D., Erlendsson, E., & Gísladóttir, G. (2017). Effects of the Hekla 4 tephra on vegetation in Northwest Iceland. *Vegetation History and Archaeobotany,* 26(4), 389-402.

Eddudóttir, S. D., Erlendsson, E., Tinganelli, L., & Gísladóttir, G. (2016). Climate change and human impact in a sensitive ecosystem: the Holocene environment of the Northwest Icelandic highland margin. *Boreas,* 45(4), 715-728.

Edwards, K. J. (2012). Was the peopling of Iceland a trickle, a steady stream or a deluge? *Norwegian Archaeological Review,* 45(2), 220-223.

Edwards, K. J., Bennett, K., & Davies, A. L. (2019). Palaeoecological perspectives on Holocene environmental change in Scotland. *Earth and Environmental Science Transactions of the Royal Society Edinburgh,* 110(1-2), 199-217.

Edwards, K. J., Erlendsson, E., & Schofield, J. E. (2011). Is there a Norse 'footprint' in North Atlantic pollen records? In S. Sigmundsson (Ed.), *Viking settlements and Viking society; papers from Proceedings of the 16th Viking Congress, Reykjavík* *and Reykholt, 16th-23rd August 2009*. Reykjavík: Hið íslenzka fornleifafélag and Háskóli Íslands, 65-82.

Edwards, K. J., Erlendsson, E., & Schofield, J. E. (2021). Landnám and the North Atlantic flora. In E. Panagiotakopulu & J.P. Saler (Eds), *Biogeography in the Sub-Arctic: The Past and Future of North Atlantic Biota*, Oxford: Jon Wiley & Sons, 185-214.

Egilsdóttir, Á. (2004). Hrafn Sveinbjarnarson, pilgrim and martyr. In G. Williams & P. Bibire (Eds), *Sagas, saints and settlements*, Leiden: Brill, 29-39.

Einarsson, Þ. (1962). Vitnisburður frógreiningar um gróður, veðurfar og landnám á Íslandi. *Saga,* 3, 442-469.

Einarsson, Þ. (1963). Pollen-analytical studies on the vegetation and climate history of Iceland in late and post-glacial times. In Á. Löve & D. Löve (Eds.)*, North Atlantic Biota and their History*. Oxford: Pergamon, 255-365.

Eiríksson, J., Knudsen, K. L., Haflidason, H., & Heinemeier, J. (2000). Chronology of late Holocene climatic events in the northern North Atlantic based on AMS 14C dates and tephra markers from the volcano Hekla, Iceland. *Journal of Quaternary Science,* 15(6), 573-580.

Elkington, T. (1968). Introgressive hybridization between Betula nana L. and B. pubescens Ehrh. in North-West Iceland. *New Phytologist,* 67(1), 109-118.

Erlendsson, E. (2007). *Environmental change around the time of the Norse settlement of Iceland.* (PhD), University of Aberdeen, Aberdeen.

Erlendsson, E., & Edwards, K. J. (2009). The timing and causes of the final pre-settlement expansion of *Betula pubescens* in Iceland. *Holocene,* 19(7), 1083-1091.

Erlendsson, E., Edwards, K. J., & Buckland, P. C. (2009). Vegetational response to human colonisation of the coastal and volcanic environments of Ketilsstaðir, southern Iceland. *Quaternary Research,* 72(2), 174-187.

Erlendsson, E., Edwards, K. J., Lawson, I., & Vésteinsson, O. (2006). Can there be a correspondence between Icelandic palynological and settlement evidence. In J. Arneborg & B. Grønnow (Eds)*, The Dynamics of Northern Societies (Proceedings of the SILA/NABO 2004 Conference).* Copenhagen: Greenland Research Centre & National Museum of Denmark, 345-351.

Feeser, I., & O'Connell, M. (2010). Late Holocene land-use and vegetation dynamics in an upland karst region based on pollen and coprophilous fungal spore analyses: an example from the Burren, western Ireland. *Vegetation History and Archaeobotany,* 19(5), 409-426.

Fjordheim, K., Moen, A., Hjelle, K. L., Bjune, A. E., & Birks, H. H. (2018). Modern pollen–vegetation relationships in traditionally mown and unmanaged boreal rich-fen communities in central Norway. *Review of Palaeobotany and Palynology,* 251, 14-27.

Friðriksson, A., & Vésteinsson, O. (2003). Creating a Past: A Historiography of the Settlement of Iceland. In J. H. Bennett (Ed.)*, Contact, Continuity, & Collapse: The Norse Colonisation of the North Atlantic*. Belgium: Brepols, 139-161.

Gathorne-Hardy, F. J., Erlendsson, E., Langdon, P. G., & Edwards, K. J. (2009). Lake sediment evidence for late Holocene climate change and landscape erosion in western Iceland. *Journal of Paleolimnology,* 42(3), 413-426.

Gauthier, E., Bichet, V., Massa, C., Petit, C., Vannière, B., & Richard, H. (2010). Pollen and non-pollen palynomorph evidence of medieval farming activities in southwestern Greenland. *Vegetation History and Archaeobotany,* 19(5), 427-438.

Gilchrist, R. (2014). Monastic and church archaeology. *Annual Review of Anthropology,* 43, 235-250.

Gilchrist, R. (2020). The materiality of magic: the ritual lives of people and things. In R. Gilchrist (Ed.), *Spirit, mind and body: the archaeology of monastic healing*. Cambridge: Cambridge University Press, 110-144.

Gísladóttir, G., Erlendsson, E., & Lal, R. (2011). Soil evidence for historical human-induced land degradation in West Iceland. *Applied Geochemistry,* 26, S28-S31.

Gísladóttir, G., Erlendsson, E., Lal, R., & Bigham, J. (2010). Erosional effects on terrestrial resources over the last millennium in Reykjanes, southwest Iceland. *Quaternary Research*, 73(1), 20-32.

Grimm, E. C. (2011). Tilia 1.7.16. Springfield: Illinois State Museum.

Grønlie, S. (2006). *Íslendingabók, Kristni saga: The Book of the Icelanders, The Story of the Conversion*: London: Viking Society for Northern Research, University College London.

Grönvold, K., Óskarsson, N., Johnsen, S. J., Clausen, H. B., Hammer, C. U., Bond, G., & Bard, E. (1995). Ash layers from Iceland in the Greenland GRIP ice core correlated with oceanic and land sediments. *Earth and Planetary Science Letters,* 135(1-4), 149-155.

Guðmundsson, G. (1996). Gathering and processing of lyme-grass (*Elymus arenarius* L.) in Iceland: an ethnohistorical account. *Vegetation History and Archaeobotany,* 5(1), 13-23.

Guinot, P., Rogé, A., Gargadennec, A., Garcia, M., Dupont, D., Lecoeur, E., Candelier, L. & Andary, C. (2006). Dyeing plants screening: an approach to combine past heritage and present development. *Coloration Technology,* 122(2), 93-101.

Haflidason, H., Larsen, G., & Olafsson, G. (1992). The recent sedimentation history of Thingvallavatn, Iceland. *Oikos,* 80-95.

Haldon, J., Mordechai, L., Newfield, T. P., Chase, A. F., Izdebski, A., Guzowski, P., Labuhn, I. & Roberts, N. (2018). History meets palaeoscience: Consilience and collaboration in studying past societal responses to environmental change. *Proceedings of the National Academy of Sciences,* 115(13), 3210-3218.

Hall, D. (2006). *Scottish Monastic Landscapes*. Stroud: Tempus.

Hallgrímsson, H., & Eyjólfsdóttir, G. G. (2004). Íslenskt sveppatal I smásveppir. *Fjölrit Náttúrufræðistofnunar,* 45, 1-194.

Hallsdóttir, M. (1987). *Pollen analytical studies of human influence on vegetation in relation to the Landnám tephra layer in southwest Iceland.* (PhD), University of Lund, Lund.

Hallsdóttir, M. (1993). *Frjórannsókn á mósniðum úr Viðey*. Reykjavík: Raunvísindastofnun Háskólans.

Hallsdóttir, M. (1995). On the pre-settlement history of Icelandic vegetation. *Búvísindi,* 9, 19-29.

Hallsdóttir, M., & Caseldine, C. J. (2005). The Holocene vegetation history of Iceland, state-of-the-art and future research. In Caseldine, C., Russell, A., Harðardóttir, J. & Knudsen, O. (Eds) *Iceland-Modern Processes and Past Environments*. Elsevier, 319-334.

Harrison, R. (2014). Connecting the Land to the Sea at Gásir: International Exchange and Long-Term Eyjafjörður Ecodynamics in Medieval Iceland. In Amundsen, C., Bond, J.M., Dockrill, S.J., Dugmore, A., Gibson, J., Hicks, M., Kendall, A., McGovern, T.H., Smiarowski, K. & Streeter, R. (Eds) *Human Ecodynamics in the North Atlantic: A Collaborative Model of Humans and Nature through Space and Time*. Maryland: Lexington, 117-136.

Harrison, R., Roberts, H. M., & Adderley, W. P. (2008). Gásir in Eyjafjörður: international exchange and local economy in medieval Iceland. *Journal of the North Atlantic,* 1(1), 99-119.

Hättestrand, M., Jensen, C., Hallsdóttir, M., & Vorren, K.-D. (2008). Modern pollen accumulation rates at the north-western fringe of the European boreal forest. *Review of Palaeobotany and Palynology,* 151(3-4), 90-109.

Heiri, O., Lotter, A. F., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology,* 25(1), 101-110.

Hejcman, M., Hejcmanová, P., Pavlů, V., & Thorhallsdottir, A. G. (2016). Forage quality of leaf fodder from the main woody species in Iceland and its potential use for livestock in the past and present. *Grass Forage Science,* 71, 649-658.

Helweg, K. K. (2020). Gardening at medieval farmsteads: Archaeobotanical indications of horticulture in Denmark and southern Sweden, AD 1000–500. *Archaeobotanical studies of past plant cultivation in northern Europe,* 5, 119-130.

Hiles, W., Lawson, I. T., Roucoux, K. H., & Streeter, R. T. (2021). Late survival of woodland contrasts with rapid limnological changes following settlement at Kalmanstjörn, Mývatnssveit, northeast Iceland. *Boreas,* 50(4), 1209-1227.

Hjartarson, H. J., Kristjánsdóttir, S., & Walser-Wallace III, J. (2017). *Kortlagning klaustra á Íslandi: Þingeyrar*. Vettvangsskýrsla XXV. Klaustur á Íslandi/Monasticism in Iceland. Reykjavík.

Hjelle, K. L. (1997). Relationships between pollen and plants in human-influenced vegetation types using presence-absence data in western Norway. *Review of Palaeobotany and Palynology,* 99(1), 1-16.

Hjelle, K. L., Halvorsen, L. S., & Overland, A. (2010). Heathland development and relationship between humans and environment along the coast of western Norway through time. *Quaternary International,* 220(1), 133-146.

Hollesen, J., Buchwal, A., Rachlewicz, G., Hansen, B. U., Hansen, M. O., Stecher, O., & Elberling, B. (2015). Winter warming as an important co-driver for Betula nana growth in western Greenland during the past century. *Global Change Biology,* 21(6), 2410-2423.

Icelandic Meteorological Office. (2007). Monthly Averages (Mánaðameðaltöl).

Jakobsson, S. (2013). From Reciprocity to Manorialism: On the peasant mode of production in Medieval Iceland. *Scandinavian Journal of History, 38*(3), 273-295.

Jensson, G. (2021). Þingeyrar Abbey in Northern Iceland: A Benedictine Powerhouse of Cultural Heritage. *Religions,* 12(6), 423.

Jóhannesson, H. E. S. (1988). Krísuvíkureldar I. Aldur Ögmundarhrauns og Miðaldalagsins. *Jökull,* 38, 71-87.

Jónsdóttir, I. S., Magnusson, B., Gudmundsson, J., Elmarsdottir, A., & Hjartarson, H. (2005). Variable sensitivity of plant communities in Iceland to experimental warming. *Global Change Biology,* 11(4), 553-563.

Júlíusson, Á. D. (1997). *Bønder i prestens tid: landbrugg, godsdrift og social konflikt i semiddelalderens Islandske bondesamfund.* (PhD), University of Copenhagen, Copenhagen.

Júlíusson, Á. D. (2007). *Peasants, aristocracy and state power in Iceland 1400-1650.* Reykjavík: Center for Agrarian Historical Dynamics.

Júlíusson, Á. D. (2010). Signs of power: manorial demesnes in Medieval Iceland. *Viking and Medieval Scandinavia,* 6, 1-29.

Júlíusson, Á. D. (2014). *Jarðeignir kirkjunnar og tekjur af þeim 1000-1550*. Reykjavík: Center for Agrarian Historical Dynamics.

Júlíusson, Á. D., Lárusdóttir, B., Lucas, G., & Pálsson, G. (2020). Episcopal economics: Property and power in post-reformation Iceland. *Scandinavian Journal of History,* 45(1), 95-120.

Karlsdóttir, L. (2014). *Hybridisation of Icelandic birch in the Holocene reflected in pollen.* (PhD) University of Iceland/Háskóli Íslands, Reykjavík.

Karlsdóttir, L., Hallsdottir, M., Thorsson, A. T., & Anamthawat-Jonsson, K. (2009). Evidence of hybridisation between Betula pubescens and B. nana in Iceland during the early Holocene. *Review of Palaeobotany and Palynology,* 156(3-4), 350-357.

Karlsdóttir, L., Thórsson, Æ. T., Hallsdóttir, M., Sigurgeirsson, A., Eysteinsson, T., & Anamthawat-Jónsson, K. (2007). Differentiating pollen of *Betula* species from Iceland. *Grana,* 46(2), 78-84.

Karlsson, G. (1996). Plague without rats: the case of fifteenth-century Iceland. *J Mediev Hist*, 22(3), 263-284.

Karlsson, G. (2000). *Iceland's 1100 years: the history of a marginal society*. London: C. Hurst & Co.

Karlsson, G. (2019). *The settlement of Iceland: a story from the ninth and tenth centuries*. Reykjavík: Mal og Menning.

Ketterer, M. E., Hafer, K. M., Jones, V. J., & Appleby, P. G. (2004). Rapid dating of recent sediments in Loch Ness: inductively coupled plasma mass spectrometric measurements of global fallout plutonium. *Science of the Total Environment,* 322(1-3), 221-229.

Ketterer, M. E., Watson, B. R., Matisoff, G., & Wilson, C. G. (2002). Rapid dating of recent aquatic sediments using Pu activities and 240Pu/239Pu as determined by quadrupole inductively coupled plasma mass spectrometry. *Environmental science & technology,* 36(6), 1307-1311.

Tybirk, K., Nilsson, M.-C., Michelsen, A., Lakkenborg Kristensen, H., Shevtsova, A., Strandberg, M. T., Johansson, M., Nielsen, K.E., Riis-Nielsen, T., Strandberg, B. & Johnsen, I. (2000). Nordic *Empetrum* Dominated Ecosystems: Function and Susceptibility to Environmental Changes. *AMBIO: A Journal of the Human Environment*, 29(2), 90-97.

Kristinsson, H. (1986). *A guide to flowering plants and ferns of Iceland*. Reykjavík: Mál og Menning.

Kristinsson, H., Hlíðberg, J. B., & Þórhallsdóttir, Þ. E. (2018). *Flóra Íslands: blómplöntur og byrkningar*: Vaka: Helgafell.

Kristjánsdóttir, G. B., Stoner, J. S., Jennings, A. E., Andrews, J. T., & Grönvold, K. (2007). Geochemistry of Holocene cryptotephras from the North Iceland Shelf (MD99-2269): intercalibration with radiocarbon and palaeomagnetic chronostratigraphies. *Holocene*, 17(2), 155-176.

Kristjánsdóttir, S. (2010a). Icelandic Evidence for a Late-medieval Hospital: Excavations at Skriðuklaustur. *Medievieval Archaeology,* 54(1), 371-381.

Kristjánsdóttir, S. (2010b). The Tip of the Iceberg: The Material of Skriðuklaustur Monastery and Hospital. *Norwegian Archaeological Review,* 43(1), 44-62.

Kristjánsdóttir, S. (2017). *Leitin að klaustrunum – klausturhald á Íslandi í fimm aldir*. Reykjavík: Forlagið.

Kristjánsdóttir, S. (2023). *Monastic Iceland*. Routledge: Abingdon.

Kristjánsdóttir, S., & Gunnarsdóttir, V. (2014). *Kortlagning klaustra á Íslandi: Helgafell*. Klaustur á Íslandi/Monasticism in Iceland. Reykjavík.

Kristjánsdóttir, S., Gunnarsdóttir, V. & Jónsdóttir, H. (2016). *Kortlagning klaustra á Íslandi: Þingeyrar*. Klaustur á Íslandi/Monasticism in Iceland. Reykjavík.

Kristjánsdóttir, S., Larsson, I., & Åsen, P. A. (2014). The Icelandic medieval monastic garden-did it exist? *Scandinavian Journal of History*, 39(5), 560-579.

Kristjánsdóttir, S., Gunnarsdóttir, V. & Jónsdóttir, H. (2016). *Kortlagning klaustra á Íslandi: Helgafell*. Klaustur á Íslandi/Monasticism in Iceland. Reykjavík.

Kuoppamaa, M., Huusko, A., & Hicks, S. (2009). *Pinus* and *Betula* pollen accumulation rates from the northern boreal forest as a record of interannual variation in July temperature. *Journal of Quaternary Science: Published for the Quaternary Research Association,* 24(5), 513-521.

Laine, A., Gauthier, E., Garcia, J.-P., Petit, C., Cruz, F., & Richard, H. (2010). A three-thousand-year history of vegetation and human impact in Burgundy (France) reconstructed from pollen and non-pollen palynomophs analysis. *Comptes Rendus Biologies,* 333(11-12), 850-857.

Langdon, P. G., Holmes, N., & Caseldine, C. J. (2008). Environmental controls on modern chironomid faunas from NW Iceland and implications for reconstructing climate change. *Journal of Paleolimnology,* 40(1), 273-293.

Larsen, D. J., Miller, G. H., Geirsdóttir, Á., & Ólafsdóttir, S. (2012). Non-linear Holocene climate evolution in the North Atlantic: a high-resolution, multi-proxy record of glacier activity and environmental change from Hvítárvatn, central Iceland. *Quaternary Science Review,* 39, 14-25.

Larsen, G., Eiríksson, J., Knudsen, K.L. & Heinemeier, J. (2002) Correlation of late Holocene terrestrial and marine tephramarkers, north Iceland; implications for reservoir age changes. *Polar Research*, 21(2), 283-290.

Larsen, G., & Eiríksson, J. (2008). Holocene tephra archives and tephrochronology in Iceland–a brief overview. *Jökull,* 58(2005), 229-250.

Larsen, G., Róbertsdóttir, B. G., Óladóttir, B. A., & Eiriksson, J. (2020). A shift in eruption mode of Hekla volcano, Iceland, 3000 years ago: two-coloured Hekla tephra series, characteristics, dispersal and age. *Journal of Quaternary Science,* 35(1-2), 143-154.

Lawson, I. T., Gathorne-Hardy, F. J., Church, M. J., Einarsson, A., Edwards, K. J., Perdikaris, S., McGovern, T.H., Amundsen, C. & Sveinbjarnardottir, G. (2006). Human impact on freshwater environments in Norse and early medieval Iceland. In J. Arneborg & B. Grønnow (Eds), *The Dynamics of northern societies: proceedings of the SILA/NABO Conference on Arctic and North Atlantic Archaeology, May 10th-14th, 2004*. Aarhus University Press: Copenhagen, 375-382.

Lawson, I. T., Gathorne-Hardy, F. J., Church, M. J., Newton, A. J., Edwards, K. J., Dugmore, A. J., & Einarsson, A. (2007). Environmental impacts of the Norse settlement: palaeoenvironmental data from Myvatnssveit, northern Iceland. *Boreas,* 36(1), 1-19.

Lee, C. M., van Geel, B., & Gosling, W. D. (2022). On the Use of Spores of Coprophilous Fungi Preserved in Sediments to Indicate Past Herbivore Presence. *Quaternary,* 5(3).

Loftsdóttir, K. (2019). *Crisis and Coloniality at Europe's Margins: Creating Exotic Iceland*: Taylor & Francis.

Lomas-Clarke, S. H., & Barber, K. E. (2004). Palaeoecology of human impact during the historic period: palynology and geochemistry of a peat deposit at Abbeyknockmoy, Co. Galway, Ireland. *Holocene,* 14(5), 721-731.

Lowe, D. J. (2011). Tephrochronology and its application: a review. *Quaternary Geochronology,* 6(2), 107-153.

Lucas, G. (2012). Later historical archaeology in Iceland: A review. *International Journal of History and Archaeology,* 16(3), 437-454.

Magnússon, Á., & Vídalín, P. (1926). *Jarðabók.* (Vol. I-XIII). Kaupmannahöfn: Hin íslensk fræðafelagið í Kaupmannahöfn & Möller, S.L.

Magnússon, Á., & Vídalín, P. (1926). *Jarðabók* (Vol. III). Kaupmannahöfn: Hin íslensk fræðafelagið í Kaupmannahöfn & Möller, S.L.

Magnússon, Á., & Vídalín, P. (1926). *Jarðabók* (Vol. VIII). Kaupmannahöfn: Hin íslensk fræðafelagið í Kaupmannahöfn & Möller, S.L.

Mäkelä, E. (1996). 1996: Size distinctions between *Betula* pollen types–a review. Grana 35, 248–256.

Mann, M. E. (2002a). Medieval Climatic Optimum. In T. Munn (Ed.), *Encyclopedia of Global Environmental Change* (Vol. 1). Chichester: John Wiley & Sons Ltd., 514-516.

Mann, M. E. (2002b). Little Ice Age. In T. Munn (Ed.), *Encyclopedia of Global Environmental Change* (Vol. 1). Chichester: John Wiley & Sons Ltd., 504-509.

McGovern, T., Smairowski, K., Hambrecht, G., Brewington, S., Harrison, R., Hicks, M., Feeley, F.J., Prehal, B. & Woollett, J. (2017). *Zooarchaeology of the Scandinavian settlements in Iceland and Greenland: diverging pathways*. New York: City University of New York

Mensing, S., Schoolman, E. M., Palli, J., & Piovesan, G. (2020). A consilience-driven approach to land use history in relation to reconstructing forest land use legacies. *Landscape Ecology,* 35(12), 2645-2658.

Mensing, S., Tunno, I., Cifani, G., Passigli, S., Noble, P., Archer, C., & Piovesan, G. (2016). Human and climatically induced environmental change in the Mediterranean during the Medieval Climate Anomaly and Little Ice Age: A case from central Italy. *Anthropocene,* 15, 49-59.

Möckel, S. C., Erlendsson, E., & Gísladóttir, G. (2017). Holocene environmental change and development of the nutrient budget of histosols in North Iceland. *Plant and Soil,* 418(1-2), 437-457.

Möckel, S. C., Erlendsson, E., Prater, I., & Gísladóttir, G. (2021). Tephra deposits and carbon dynamics in peatlands of a volcanic region: Lessons from the Hekla 4 eruption. *Land Degradation & Development,* 32(2), 654-669.

Mooney, D. E., & Guðmundsdóttir, L. (2020). Barley cultivation in Viking Age Iceland in light of evidence from Lækjargata 10–12, Reykjavík. *Archaeobotanical studies of past plant cultivation in northern Europe, 5*, 5.

Moore, P. D., Webb, J. A., & Collison, M. E. (1991). *Pollen Analysis*. Oxford: Blackwell Scientific Publications.

Mørk, O., Kragh, T., Kristensen, E., & Sand-Jensen, K. (2018). Adaptation and growth performance of four endangered amphibious freshwater species. *Aquatic Botany,* 150, 16-22.

Munsell Soil Color Charts. (2009). *Munsell Soil Color Charts*. Grand Rapids: Xrite.

Nakagawa, T., Brugiapaglia, E., Digerfeldt, G., Reille, M., Beaulieu, J. L. d., & Yasuda, Y. (1998). Dense-media separation as a more efficient pollen extraction method for use with organic sediment/deposit samples: comparison with the conventional method. *Boreas,* 27(1), 15-24.

Noël, H., Garbolino, E., Brauer, A., Lallier-Vergès, E., De Beaulieu, J.-L., & Disnar, J.-R. (2001). Human impact and soil erosion during the last 5000 yrs as recorded in lacustrine sedimentary organic matter at Lac d'Annecy, the French Alps. *Journal of Paleolimnology,* 25(2), 229-244.

Ogilvie, A. E. J., & Jónsson, T. (2001). "Little Ice Age" research: A perspective from Iceland. *Climate Change,* 48(1), 9-52.

Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P. & Stevens, M. (2016). vegan: Community Ecology Package. R package version 2.4-3.

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

Ottósson, J. G., Sveinsdóttir, A., & Harðardóttir, M. (2016, 15/02/21). Vistgerðir á Íslandi. Retrieved from http://vistgerdakort.ni.is/

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

Pálsson, G. (2018). Storied lines: Network perspectives on land use in early modern Iceland. *Norwegian Archaeological Review,* 51(1-2), 112-141.

Pálsson, H., & Edwards, P. (1972). *The Book of Settlements: Landnámabók.* Manitoba: University of Manitoba Press.

Patterson III, W. A., Edwards, K. J., & Maguire, D. J. (1987). Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Review,* 6(1), 3-23.

Pluenneke, M. (2017). *Shift in Icelandic Plant Populations Due to Climate Change: Through the Lens of Natural Dyes*. Independent Study Project (ISP) Collection. 2751.

Reimer, P. J., Austin, W. E., Bard, E., Bayliss, A., Blackwell, P. G., Ramsey, C. B., Butzin, M., Cheng, H., Edwards, R.L., Friedrich, M. & Grootes, P.M. (2020). The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon,* 62(4), 725-757.

Riddell, S., & Erlendsson, E. (2015). *Helgafell Pollen Analysis: Sample KLI-2014-16-02.* Klaustur á Íslandi/Monasticism in Iceland. Reykjavík.

Riddell, S., Erlendsson, E., Gísladóttir, G., Edwards, K. J., Byock, J., & Zori, D. (2018). Cereal cultivation as a correlate of high social status in medieval Iceland. *Vegetation History and Archaeobotany,* 27(5), 679-696.

Roelofs, J., Schuurkes, J., & Smits, A. (1984). Impact of acidification and eutrophication on macrophyte communities in soft waters. II. Experimental studies. *Aquatic Botany,* 18(4), 389-411.

Roy, N., Woollett, J., Bhiry, N., Haemmerli, G., Forbes, V., & Pienitz, R. (2018). Perspective of landscape change following early settlement (landnám) in Svalbarðstunga, northeastern Iceland. *Boreas,* 47(2), 671-686.

Rundgren, M. (1995). Biostratigraphic evidence of the Allerød-Younger Dryas-Preboreal oscillation in northern Iceland. *Quaternary Research,* 44(3), 405-416.

Rundgren, M. (1998). Early-Holocene vegetation of northern Iceland: pollen and plant macrofossil evidence from the Skagi peninsula. *Holocene,* 8(5), 553-564.

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

Schmid, M. M., Zori, D., Erlendsson, E., Batt, C., Damiata, B. N., & Byock, J. (2017). A Bayesian approach to linking archaeological, paleoenvironmental and documentary datasets relating to the settlement of Iceland (Landnám). *Holocene,* 28(1), 19-33.

Sigurmundsson, F. S., Gísladóttir, G., & Óskarsson, H. (2014). Decline of birch woodland cover in Þjórsárdalur Iceland from 1587 to 1938. *Human Ecology,* 42(4), 577-590.

Smith, K. P. (1995). Landnám: the settlement of Iceland in archaeological and historical perspective. *World Archaeology,* 26(3), 319-347.

Spierenburg, P., Lucassen, E., Lotter, A., & Roelofs, J. (2009). Could rising aquatic carbon dioxide concentrations favour the invasion of elodeids in isoetid-dominated softwater lakes? *Freshwater Biology,* 54(9), 1819-1831.

Stockmarr, J. (1971). Tablets with spores used in absolute pollen analysis. *Pollen et Spores,* 13, 614-621.

Stolz, C., & Grunert, J. (2010). Late Pleistocene and Holocene landscape history of the central Palatinate forest (Pfälzerwald, south-western Germany). *Quaternary International,* 222(1-2), 129-142.

Streeter, R., Dugmore, A. J., Lawson, I. T., Erlendsson, E., & Edwards, K. J. (2015). The onset of the palaeoanthropocene in Iceland: Changes in complex natural systems. *Holocene,* 25(10), 1662-1675.

Streeter, R., Dugmore, A. J., & Vésteinsson, O. (2012). Plague and landscape resilience in premodern Iceland. *Proceedings of the National Academy of Sciences*., 109(10), 3664-3669.

Striberger, J., Björck, S., Holmgren, S., & Hamerlík, L. (2012). The sediments of Lake Lögurinn–A unique proxy record of Holocene glacial meltwater variability in eastern Iceland. *Quaternary Science Reviews,* 38, 76-88.

Sveinsson, E. (1934). *Laxdœla Saga*. Reykjavík: Hið íslenzka fornritafélag.

Sveinsson, E., & Þórðarson, M. (1985). *Eyrbyggja Saga*. Reykjavík: Hið íslenzka fornritafélag.

Sverrisdottir, G. (2007). Hybrid magma generation preceding Plinian silicic eruptions at Hekla, Iceland: evidence from mineralogy and chemistry of two zoned deposits. *Geological Magazine,* 144(4), 643-659.

Thorarinsson, S. (1944). Tefrokronologiska studier på Island: Þjórsárdalur och dess förödelse. *Geografiska annaler, 26*(1-2), 1-217.

Thorarinsson, S. (1967). The eruptions of Hekla in historical times: a tephrochronological study. In *The eruption of Hekla 1947-1948* (pp. 1-177). Reykjavík: Societas Scientiarum Islandica.

Þorsteinsson, H. (1922-1932). *Annales Islandici Posterium Sæculorum (Annálar 1400-1800)* (Vol. I). Reykjavík: Hinu íslenzka bókmenntafélag.

Tipping, R. (1997). Medieval woodland history from the Scottish Southern Uplands: fine spatial-scale pollen data from a small woodland hollow. In C. Smout (Ed.), *Scottish Woodland History*. Dalkeith: Scottish Cultural Press, 51-74.

Tipping, R. (2004). Palaeoecology and political history: evaluating driving forces in historic landscape change in southern Scotland. *Society, Landscape and Environment in Upland Britain. Exeter: University of Exeter Press.*

Tipping, R. (2010). *Bowmont: an environmental history of the Bowmont Valley and the northern Cheviot Hills, 10000 BC-AD 2000*. Edinburgh: Society of Antiquaries of Scotland.

Tisdall, E., Barclay, R., Nichol, A., McCulloch, R., Simpson, I., Smith, H., & Vésteinsson, O. (2018). Palaeoenvironmental evidence for woodland conservation in Northern Iceland from settlement to the twentieth century. *Environmental Archaeology,* 23(3), 205-216.

Troels-Smith, J. (1955). Karakterisering af lose jordarter. Characterization of unconsolidated sediments. *Danmarks Geologiske Undersøgelse Årbog,* 3(10).

van Geel, B., Buurman, J., Brinkkemper, O., Schelvis, J., Aptroot, A., van Reenen, G., & Hakbijl, T. (2003). Environmental reconstruction of a Roman Period settlement site in Uitgeest (The Netherlands), with special reference to coprophilous fungi. *Journal of Archaeological Science,* 30(7), 873-883.

van Hoof, T. B., Bunnik, F. P. M., Waucomont, J. G. M., Kürschner, W. M., & Visscher, H. (2006). Forest re-growth on medieval farmland after the Black Death pandemic - implications for atmospheric CO_2 levels. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 237(2-4), 396-411.

Verhoeven, K., Louwye, S., & Eiríksson, J. (2013). Plio-Pleistocene landscape and vegetation reconstruction of the coastal area of the Tjörnes Peninsula, Northern Iceland. *Boreas,* 42(1), 108-122.

Vésteinsson, O. (1998). Patterns of settlement in Iceland: a study in prehistory. *Saga book-Viking Society for Northern Research,* 25, 1-29.

Vésteinsson, O. (2007). A divided society: Peasants and the aristocracy in medieval Iceland. *Viking and Medieval Scandinavia,* 3, 117-139.

Vésteinsson, O., & McGovern, T. H. (2012). The peopling of Iceland. *Norwegian Archaeological Review,* 45(2), 206-218.

Vésteinsson, O., & Simpson, I. A. (2001). *Fuel utilisation in pre-industrial Iceland. A micro-morphological and historical analysis.* In Vésteinsson, O., Simpson, I. & Guðmundsson, G. (Eds) Current Issues in Nordic Archaeology (Proceedings of the 21st Conference of Nordic Archaeologists), Reykjavik: Society of Icelandic Archaeologists, 181-187.

Vickers, K., Erlendsson, E., Church, M. J., Edwards, K. J., & Bending, J. (2011). 1000 years of environmental change and human impact at Stóra-Mörk, southern Iceland: a multiproxy study of a dynamic and vulnerable landscape. *Holocene,* 21(6), 979-995.

Vuorela, I. (1973). Relative pollen rain around cultivated fields. *Acta Botanica Fennica,* 102, 1-27.

Wasowicz, P. (2018). The first attempt to list the archaeophytes of Iceland. *Acta Societatis Botanicorum Poloniae,* 87(4).

Wasowicz, P., Przedpelska-Wasowicz, E. M., & Kristinsson, H. (2013). Alien vascular plants in Iceland: diversity, spatial patterns, temporal trends, and the impact of climate change. *Flora-Morphology, Distribution, Functional Ecology of Plants,* 208(10-12), 648-673.

Wastl, M., Stötter, J., & Caseldine, C. (2001). Reconstruction of Holocene variations of the upper limit of tree or shrub birch growth in northern Iceland based on evidence from Vesturárdalur-Skíðadalur, Tröllaskagi. *Arctic, Antarctic, and Alpine Research,* 33(2), 191-203.

Wimble, G., Wells, C. E., & Hodgkinson, D. (2000). Human impact on mid-and late Holocene vegetation in south Cumbria, UK. *Vegetation History and Archaeobotany,* 9(1), 17-30.

Yeloff, D., & van Geel, B. (2007). Abandonment of farmland and vegetation succession following the Eurasian plague pandemic of AD 1347–52. *Journal of Biogeography,* 34, 575–582.

Zielińska, S., Jezierska-Domaradzka, A., Wójciak-Kosior, M., Sowa, I., Junka, A., & Matkowski, A. M. (2018). Greater Celandine's Ups and Downs−21 Centuries of Medicinal Uses of *Chelidonium majus* From the Viewpoint of Today's Pharmacology. *Frontiers in Pharmacology,* 9(299), 1-29.

Zori, D., Byock, J., Erlendsson, E., Martin, S., Wake, T., & Edwards, K. J. (2013). Feasting in Viking Age Iceland: sustaining a chiefly political economy in a marginal environment. *Antiquity,* 87(335), 150-165.

Zori, D., & Byock, J. L. (2014). *Viking Archaeology in Iceland: Mosfell Archaeological Project*. Turnhout: Brepols.

Paper I

ENVIRONMENTAL ARCHAEOLOGY
2022, VOL. 27, NO. 2, 193–210
https://doi.org/10.1080/14614103.2018.1531191

Pollen, Plague & Protestants: The Medieval Monastery of Þingeyrar (Þingeyraklaustur) in Northern Iceland

Scott J. Riddell [a], Egill Erlendsson [a], Sigrún D. Eddudóttir [a], Guðrún Gísladóttir [a,b] and Steinunn Kristjánsdóttir [c]

[a]Institute of Life and Environmental Sciences, University of Iceland, Reykjavík, Iceland; [b]Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland; [c]National Museum of Iceland, University of Iceland, Reykjavík, Iceland

ABSTRACT

Until recently, Icelandic monasticism has been considered remote from European monasticism and that it had little impact upon medieval Icelandic society. Focussing upon a monastic site in northern Iceland (Þingeyraklaustur), palaeoecological data is utilised to explore the role of Icelandic monasticism with regard to land use in order to discern whether or not the aforementioned conventions hold true. In particular, are changes in land use associated with the eleventh century revival of European monasticism apparent in Iceland? Further consideration is given to changes in land use arising due to the challenges of plague, Reformation, and the prevailing climate regime for the Medieval period in Iceland. At Þingeyraklaustur, the clearance of *Betula* seems to be associated with the foundation of the monastery in the early twelfth century. The impact of plague is observed in the recovery of *Betula* during the fifteenth century. On both counts, events at Þingeyraklaustur reflect those encountered in the palaeoecological archive for monasteries elsewhere in Europe. Overall, there is a broad transition from dwarf shrub wetland to a grassland dominated landscape from the time of Iceland's settlement, through the monastic period (AD 1133–1551), and beyond the sixteenth century Reformation into the eighteenth century.

ARTICLE HISTORY
Received 22 May 2018
Revised 12 September 2018
Accepted 27 September 2018

KEYWORDS
Iceland; medieval; monasticism; land use; plague; reformation

Introduction

Þingeyrar, northern Iceland (Figure 1), is the former site of a medieval monastery (Þingeyraklaustur). This palynological study seeks to investigate whether or not ecological and socio-political changes are visible in the palaeoecological archive of the site for the term of the monastery (AD 1133–1551). This encapsulates change initiated by the monastery itself, e.g. land management practices, as well as challenges imposed upon it; either by society (e.g. Reformation), or by the environment (e.g. climate and volcanism). Of particular interest is whether or not the initiation of change under the aegis of the monastery, or responses to change imposed by external forces, reflect the experience of European monasteries.

It has been said that monasteries in Iceland were little more than retirement homes for the wealthy (Vésteinsson 2000); unique, eccentric, peripheral and remote from European monasticism. This ignores the fact that thirteen of Iceland's fourteen monasteries were founded between the eleventh and thirteenth centuries; concomitant with a well-documented renaissance in monasticism across Europe (Aston 2001; Bond 2004; Kristjánsdóttir 2017). Some obvious links between Iceland's monasteries and the world beyond its shores include the presence of foreign abbots (England) and the import of foreign goods such as alabaster (Midlands, England) and ceramics (Utrecht, Netherlands) (Kristjánsdóttir 2010a, 2017). However, more intellectual, philosophical and technical associations are apparent. Archaeological excavation at Skriðuklaustur (Figure 1) revealed a monastery that encapsulated all of the architectural elements that would be expected of an Augustinian monastery on the continent; church, cemetery, garden, well, Abbot's lodgings, chapter house, dormitory, refectory, kitchen, store rooms etc., as well as an infirmary. This latter feature, along with surgical instruments, evidence of medicinal plants (some introduced), and skeletal pathology (burials), infer an element of medical care; beyond that required for the aged and again, in keeping with the European monastic mission (Kristjánsdóttir 2008, 2010a, 2010b; Kristjánsdóttir, Larsson, and Åsen 2014). This evidence would suggest that Icelandic monasteries were very much a part of the wider Roman Catholic world.

The European revival in monasticism has been observed to have had a significant impact on land use (Aston 2000, 2001; Bond 2004; Hall 2006; Gilchrist 2014) through the development of mining, salt panning, water management (mill complexes, fishponds etc.), and centralised farms (granges) (Bond 2004; Hall 2006; Gilchrist 2014). Although the point was made in reference to Scotland, it may still stand that

CONTACT Scott J. Riddell sjr3@hi.is Institute of Life and Environmental Sciences, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland

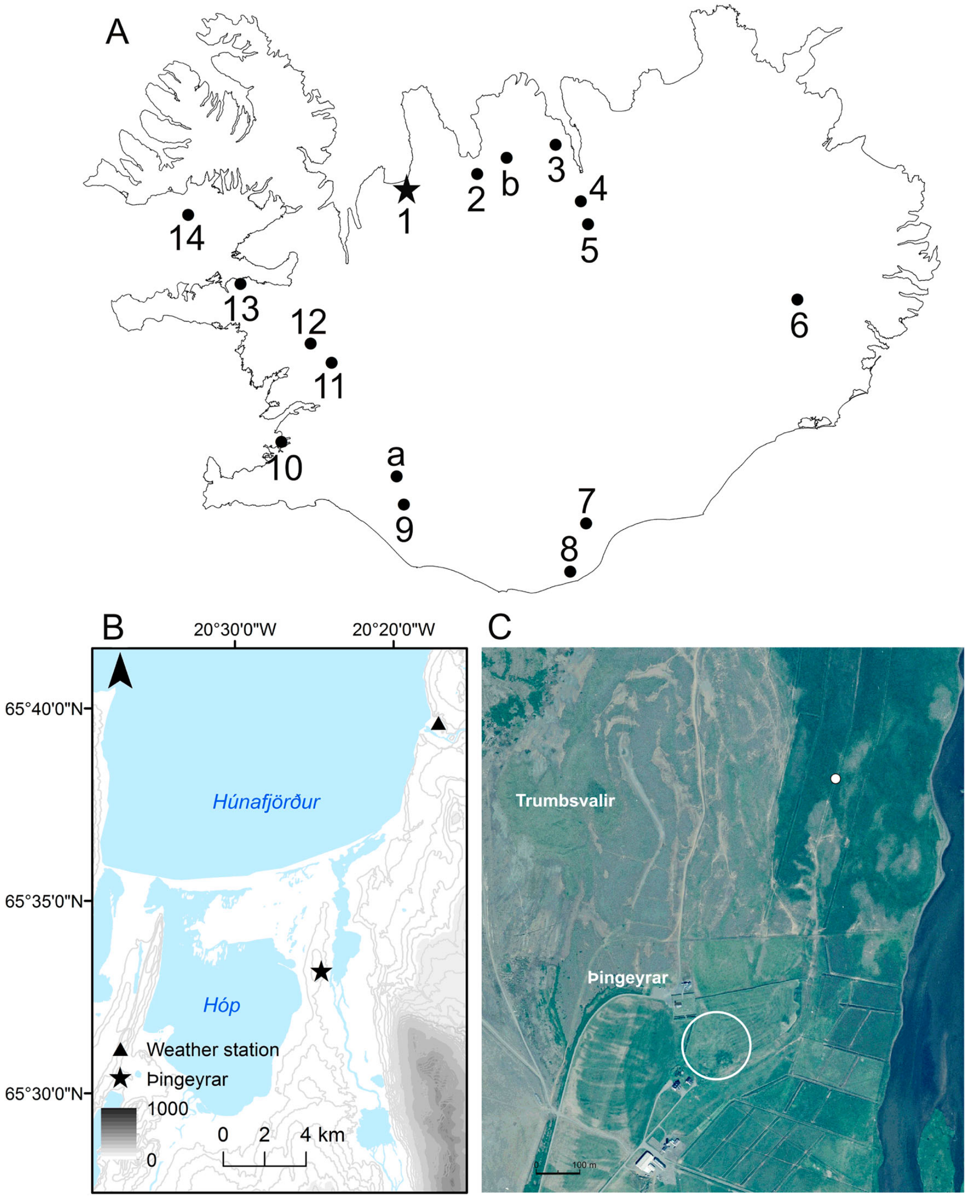


Figure 1. A) Monasteries of Iceland: 1) Þingeyraklaustur (AD 1133–1551), 2) Reynistaðarklaustur (AD 1295–1551), 3) Möðruvallaklaustur (AD 1295–1547), 4) Munkaþverárklaustur (AD 1155–1551), 5) Saurbæjarklaustur (AD 1200–1224), 6) Skriðuklaustur (AD 1493–1554), 7) Kirkjubæjarklaustur (AD 1186–1542), 8) Þykkvabæjarklaustur (AD 1168–1548), 9) Keldnaklaustur (AD 1193–1222), 10) Viðeyjarklaustur (AD 1226–1539), 11) Bæjarklaustur (1030–1049), 12) Hítardalsklaustur (AD 1166–1201/1237), 13) Helgafellsklaustur (AD 1184–1543), 14) Flateyjarklaustur (AD 1172–1184). a) Skálholt (1096) and b) Hólar (1106) represent the two episcopal seats of Iceland, south and north respectively. B) Þingeyrar and weather station (Blönduós). C) Þingeyrar and environs, site of monastic complex (encircled) and coring site (Image: Loftmyndir ehf 2006). For the interpretation of colour maps, please refer to the online version of this article.

in Europe, medieval monasticism initiated an agricultural revolution on a par with that of the Neolithic (Hall 2006). In accordance with God's will, European monasticism sought to bring order where there was disorder, to demonstrably impose an anthropogenic conformity upon (either real or contrived) desert and wilderness (Hoffmann 2014). Palaeoecological investigation has shown that across Europe, monastic orders were implicated in land clearance, the development of both arable and pastoral landscapes (Wimble, Wells, and Hodgkinson 2000; Noël et al. 2001; Lomas-Clarke and Barber 2004; Breitenlechner et al. 2010; Hjelle, Halvorsen, and Overland 2010; Stolz and Grunert 2010), and technological innovation, e.g. the introduction of new agricultural species (Tipping 1997). This may also be apparent in Iceland. Although there are late twelfth century references to cereal cultivation on the island of Viðey (Ólsen 1910) in south west Iceland, it is not until the foundation of the Augustinian monastery there in AD 1226 (Figure 1; Viðeyjarklaustur) that it appears in the palaeoecological record (Hallsdóttir 1993). This is interesting given that cereal cultivation was largely being abandoned elsewhere in south-western Iceland at that time (Riddell et al. 2018). This observation alone is sufficient to justify asking the question of what exactly was the relationship between monasticism and the Icelandic landscape? Were Iceland's monasteries importing new ideas on agriculture from Europe along with abbots, altars and architecture?

Þingeyrar: Assembly, Monastery and Farms

The *þing* (pron: thing) element of the place name Þingeyrar is indicative of a former site of political assembly (Karlsson 2000). Unfortunately, there is no written account of any political gathering at this place by which to support this inference. Furthermore, there is a longstanding belief that some of the archaeological remains at Þingeyrar are that of a *dómhringur* (law court) but this is looking increasingly unlikely. A geo-electrical (resistivity) survey has revealed the presence of a structure within the dómhringur and it is now proposed that the remains are of an early medieval church enclosure (Coolen and Mehler 2015; Kristjánsdóttir 2017).

The establishment of the Benedictine monastery at Þingeyrar was initiated, at the behest of the Archbishop Össur Sveinsson of Lund (Sweden), by the Bishop Jón Ögmundsson of Hólar (Jensson 2016). There are two dates for the foundation of Þingeyraklaustur, AD 1112 and AD 1133, with consensus favouring the latter date when its first Abbot, Vilmundur Þórólfsson, was ordained (Karlsson 2000; Kristjánsdóttir 2017). Following foundation, Þingeyraklaustur progressively began to acquire further properties, especially from the fourteenth century, in common with monasteries elsewhere in Iceland (Júlíusson 2014). By the sixteenth century, inventories reveal that there were 60 tenant farms across (Austur and Vestur) Húnavatnssýslur belonging to Þingeyraklaustur while the monastic landholding itself supported a relatively large body of livestock (Júlíusson 2014). Indeed, Þingeyraklaustur was possibly the wealthiest monastery in Iceland (Coolen and Mehler 2015). Over time, Þingeyraklaustur also gained fame as a literary centre, a place where regal, ecclesiastical and family sagas were written and transcribed (Kristjánsdóttir 2017). One of the most significant events in the history of the monastery occurred in the fifteenth century when two plague epidemics beset Iceland (AD 1402 and AD 1495) (Kristjánsdóttir 2017). However, it was in the following century that the Protestant Reformation effected the demise of the monastery at Þingeyrar (AD 1551). This witnessed the transfer of both the fixed and moveable assets of Þingeyraklaustur to the Danish state, subsequently administered by stewards thereof into the modern period (Karlsson 2000; Kristjánsdóttir 2017).

Recent archaeological investigation by the *Klaustur á Íslandi* (Monasticism in Iceland) project has revealed evidence of human activity at Þingeyrar prior to the establishment of the monastery (Kristjánsdóttir et al. 2016; Hjartarson et al. 2017). Material remains situated beneath the Hekla AD 1104 tephra include the presence of a possible smithy with floor layers incorporating charcoal and slag, a post hole, as well as human bone dated to c. AD 962–1040 (1030 ± 30 BP; Beta Analytic 473011, Hjartarson et al. 2017). A structure at nearby Trumbsvalir (Figure 1) was also present prior to the deposition of the Hekla AD 1104 tephra layer (Kristjánsdóttir and Gunnarsdóttir 2014). The precise nature of the relationship between Trumbsvalir and Þingeyraklaustur is unclear. Within a collection of medieval papers known as Diplomatarium Islandicum (DI I-XVI)), an inventory of AD 1525 identifies Trumbsvalir as an abandoned tenancy of the monastery (DI IX, p. 314), while it is absent from a later inventory for AD 1552 (DI XII, p. 451–454). Both inventories identify the adjacent farms of Geirastaðir (north) and Leysingjastaðir (south) as active tenancies of Þingeyraklaustur in the sixteenth century (DI IX, p. 314; DI XII, p. 451–454).

The Environment of Þingeyrar

Þingeyrar is situated approximately 13 km southwest of the town of Blönduós, Austur-Húnavatnssýsla, in northern Iceland (Figure 1). The ridge of Þingeyrar is orientated on a north–south axis bounded by the estuaries of Húnavatn and Hóp (east and west respectively). The underlying geology is comprised of tertiary basalts overlain by Holocene sand deposits (Thordarson and Hoskuldsson 2002). The northern end of the ridge terminates in an extensive gravel beach known as Þingeyrasandur which branches both east and west to confine the aforementioned estuaries as semi-saline lagoons (Guðmundsson 2007). The place name of Þingeyrar probably once applied to the entire area between the two estuaries but now refers specifically to the farm, church, and former monastery site, situated upon the summit of the ridge (Figure 1). The immediate vicinity of the farm is comprised of land converted from wetland into pasture via a network of drainage ditches. The primary land use is grazing for horses and hay fields. Progressing northwards along the ridge, the impact of soil erosion develops from considerable, to severe, to extreme (Arnalds et al. 2001); partially due to the dynamic coastal context

Table 1. Climate data for Blönduós, Austur-Húnavatnssýsla (Icelandic Meteorological Office 2018).

Recording period	1961–1990
Elevation (m a.s.l)	8
Avg. temp. °C tritherm	9.4
Avg. temp. °C July	8.7
Avg. temp. °C January	−2.5
Avg. pptn. mm yr^{-1}	458

rather than land use. Where vegetation survives, it is comprised of heathland, wetland and coastal plant communities. Nitrogen-fixing Alaskan lupin (*Lupinus nootkatensis*) has been introduced as a soil conservation measure (Ottósson, Sveinsdóttir, and Harðardóttir 2016). Land to the south consists of heath, wetland and modified wetlands, i.e. sheep pasture. Erosion is largely absent. Temperature and precipitation data for Austur-Húnavatnssýsla is available from a weather station at Blönduós (Figure 1; Table 1).

Methods and Materials

Historical Palaeoecology

In Iceland, palynology has been primarily utilised to discern the development of vegetation cover during the Holocene (e.g. Hallsdóttir 1995; Hallsdóttir and Caseldine 2005; Eddudóttir, Erlendsson, and Gísladóttir 2015, 2016, 2018; Eddudóttir 2016) or has focussed upon the impact of the human settlement on plant communities during the late ninth century (e.g. Einarsson 1962; Hallsdóttir 1987; Erlendsson 2007). Both represent prehistoric contexts (Friðriksson and Vésteinsson 2003), and with regard to the latter, rather than simply representing a marker of human colonisation, changes in the palynological record for Iceland may also shed light upon the allocation and utilisation of land in the medieval period (Vésteinsson 1998; Erlendsson et al. 2006). The present study acknowledges this potential but is situated within a context that allows palaeoecological data to be cross-referenced with the Icelandic historical archive, primarily Diplomatarium Islandicum (DI I-XVI) and Jarðabók (Magnússon and Vídalín 1926a). Difficulties with comparing the inexact chronologies of palaeoecological data with the refined timescales of documentary sources are recognised (Dumayne et al. 1995; Tipping 2004). However, in this instance, the application of tephrochronology proffers a degree of relief given that historic tephra isochrones can allow for direct comparison with the documentary archive, situated as they are, at fixed points in time (Thorarinsson 1967; Lomas-Clarke and Barber 2004).

Site Selection and Sampling

Potential sampling sites were identified via a field survey of the environs of the modern farm of Þingeyrar, either by test coring, or by cleaning the banks of existing ditches. Factors influencing the proximity of the sampling site to the monastic complex were the availability of an anaerobic context, an undisturbed sequence of sediments and a suite of potentially identifiable tephra layers. A core (c. 75 cm long) was extracted from a cleaned section (ISN93: N65° 33.594 W20°23.854) of ditch bank from within a wetland (now being developed as a plantation woodland) approximately 500 m from the remains of the monastic complex (Figure 1). The extracted core was protected in plastic guttering, wrapped in plastic film to inhibit contamination and moisture loss, and stored under cool conditions (4°C) prior to laboratory analysis.

Sedimentology

In order to detect influxes of minerogenic material into the sedimentary sequence, the entire column was measured at intervals of 1 cm for magnetic susceptibility (MS) with a Bartington MS2 meter and MS2E probe, with an enhanced resolution of 0.5 cm for the section 5 cm to 30 cm depth (Dearing 1994). Soil moisture content (SMC), dry bulk density (DBD) and organic matter (OM; by loss on ignition) were measured contiguously at 1 cm intervals. Dry weight was obtained by heating samples at 105°C for 24 hrs. with soil moisture calculated as percentage of dry soil weight (Burt 2004). DBD (g/cm^3) was calculated by dividing the dry weight of a sample by sample volume (1.2 cm^3) (Brady and Weil 1996). OM was measured by combusting 1.2 cm^3 sample of sediment at 550°C for 4 hrs. with loss on ignition (LOI) calculated according to Heiri, Lotter, and Lemcke (2001).

Age Determination

The chronological sequence is based upon tephrochronology. Tephra samples were extracted from all visible tephra horizons in the sediment profile, cleaned, sieved (63 μm), mounted, polished, and carbon-coated for analysis. MS detected a further tephra (23.5–25.5 cm), which was also sampled. To verify the sources of the tephra samples, their geochemistry was analysed at the University of Iceland using JEOL JXA-8230 electron probe micro-analyser (EPMA). Acceleration voltage was 15 kV, beam current 10 nA and beam diameter 10 μm. To verify consistency in analytical conditions, the standard A99 was measured before and after each session of analysis. The dataset was inspected for, and cleaned of, anomalies and analyses with sums of <96%. A radiocarbon date was sought from wood macro-fossils (1.5 mg) derived from a depth of 24.5–25.5 cm, situated within the tephra horizon at 23–25.5 cm depth. The arising material was analysed by ETH Zurich, Switzerland. Linear age-depth modelling of chronological data was performed with the Clam package in ‘R’ (Blaauw 2010).

Palynology

The volume (1–2 cm^3) of 36 individual pollen samples was determined by displacement in 10% HCl (Bonny 1972). One *Lycopodium clavatum* tablet (Batch no. 177745) was added to each sample as a control for the calculation of palynomorph concentrations (Stockmarr 1971). Pre-treatment consisted of rinsing samples in 10% HCl, 10% NaOH, acetolysis mixture, and sieving (150 µm) to remove coarse material (Moore, Webb, and Collison 1991). Dense media separation (LST fastfloat, 1.9 g/ml) was used to remove minerogenic material (Björck, Persson, and Kristersson 1978; Nakagawa et al. 1998). Pollen grains were slide-mounted with silicone oil of 12,500 cSt. viscosity (Moore, Webb, and Collison 1991). Using Moore, Webb, and Collison (1991) as the primary key, pollen counts were conducted using a microscope at 400–1000x magnification. At least 300 native land pollen (total land pollen, TLP) were counted for each sub-sample. Where Cyperaceae (sedge) pollen was overly dominant, counting was continued until a minimum of 100 pollen, excluding Cyperaceae, was attained. All Poaceae (grass) pollen were evaluated as potential cereal-type, i.e. mean grain diameter >37 µm, annulus diameter >8 µm (Andersen 1979). All *Betula* (birch) pollen grains were measured in order to distinguish between *Betula nana* and *Betula pubescens* as a means of differentiating dwarf birch heath from birch woodland (Mäkelä 1996; Caseldine 2001; Erlendsson and Edwards 2009). Following Karlsdóttir (2014), the mean size of *B. nana* pollen grains is 20.4 µm while that of *B. pubescens* is 24.2 µm. Pteridophyte spores, microscopic charcoal and spores from coprophilous (dung-loving) fungi (van Geel et al. 2003; Cugny, Mazier, and Galop 2010) were also recorded. Both charcoal and coprophilous fungi are recognised environmental proxies for human activity and the presence of livestock in Iceland from the time of colonisation (Edwards, Erlendsson, and Schofield 2011). Count data were entered into TILIA (version 2.0.41) and subjected to a Total Sum of Squares Analysis (CONISS), producing a stratigraphically constrained dendrogram to aid zonation (Grimm 2011). Plant nomenclature follows Kristinsson (1986). Pollen and spore taxonomy follows Moore, Webb, and Collison (1991) but is amended to better reflect the Icelandic flora (Erlendsson 2007).

Ordination Analysis

Ordination analyses were utilised in order to better understand the relationship between past pollen assemblages arising within the immediate vicinity of the sample site. Detrended Correspondence Analysis (DCA) revealed a linear response of 1.5925 on the first axis of the pollen dataset (Hill and Gauch 1980). Principal Component Analysis (PCA) was therefore applied to Hellinger transformed data consisting of pollen taxa with percentages >1%. Both DCA and PCA were applied using the vegan package in ‘R’ (Oksanen et al. 2016).

Results

Chronology

With reference to Figure 2 and Table 2, the two lowermost tephra layers in the stratigraphy have been identified as Hekla 4 (47.5 cm) and Hekla 3 (38.5 cm) (Dugmore et al. 1995). A Veiðivötn tephra is interpreted here as the Landnám Tephra Layer (LTL) AD 877 ± 1 (Schmid et al. 2017) due to its chemical composition (Table 2) and stratigraphic position (25.5 cm) in relation to the Hekla 3 and Hekla AD 1104 (20.5 cm) tephra layers (Eiríksson et al. 2000). The uppermost tephra (6 cm) is considered to be the Hekla AD 1766 tephra due to its geochemistry and dispersal range (Thorarinsson 1967; Sverrisdottir 2007). These findings are consistent with other tephra sequences identified in palaeoenvironmental studies from northern Iceland, e.g. Steinberg, Bolender, and Damiata (2016) and Möckel, Erlendsson, and Gísladóttir (2017).

The radiocarbon data is presented (Table 3, Figure 2) but it has not been incorporated into the chronological sequence as it does not conform with

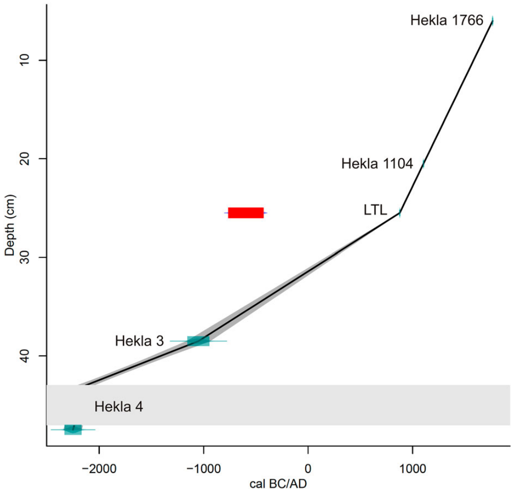


Figure 2. Age-depth model for the Þingeyrar core. Blue horizontal lines indicate the depth of the tephra layers and the red horizontal line indicates the radiocarbon date. The horizontal band denotes the thickness of the Hekla 4 tephra layer. For the interpretation of references to colour in this chart, please refer to the online version of this article.

Table 2. Major elements (wt%) of glass shards in tephra layers observed in Þingeyrar profile.

Profile and depth (cm)	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
THING 6–7	60.17	1.14	15.36	9.86	0.25	1.45	5.15	3.17	1.61	0.48	98.63
THING 6–7	59.86	1.20	15.36	9.83	0.24	1.54	5.11	4.18	1.49	0.34	99.15
THING 6–7	59.80	1.17	15.23	9.90	0.34	1.57	5.05	4.31	1.59	0.38	99.35
THING 6–7	59.22	1.36	15.39	9.95	0.28	1.82	5.55	3.89	1.55	0.50	99.51
THING 6–7	58.57	1.38	15.48	10.00	0.25	1.95	5.56	4.17	1.52	0.56	99.44
THING 6–7	57.94	1.45	15.27	10.62	0.29	2.06	5.92	4.06	1.52	0.61	99.74
THING 6–7	57.90	1.54	15.49	10.62	0.24	1.99	5.72	4.02	1.43	0.57	99.52
THING 6–7	57.86	1.49	15.35	10.68	0.27	2.08	5.48	3.47	1.40	0.61	98.69
THING 6–7	57.83	1.49	15.27	10.45	0.24	1.97	5.81	3.75	1.43	0.65	98.89
THING 6–7	57.66	1.53	15.07	10.40	0.23	2.06	5.73	4.08	1.53	0.64	98.93
THING 6–7	57.64	1.55	14.89	10.76	0.26	2.06	5.80	3.77	1.51	0.63	98.87
THING 6–7	57.57	1.42	15.34	10.52	0.20	2.08	5.59	3.97	1.54	0.59	98.83
THING 20–21	72.17	0.22	14.59	3.11	0.12	0.10	1.99	4.03	2.67	0.02	99.02
THING 20–21	72.15	0.21	14.42	3.18	0.11	0.10	2.06	4.10	2.60	0.08	99.01
THING 20–21	71.90	0.22	14.28	3.24	0.10	0.12	1.92	4.29	2.42	0.06	98.55
THING 20–21	71.87	0.18	14.26	3.13	0.11	0.10	1.92	4.12	2.74	0.05	98.48
THING 20–21	71.80	0.21	14.07	3.21	0.13	0.12	1.92	2.66	2.69	0.04	96.85
THING 20–21	71.77	0.19	13.97	3.26	0.11	0.12	1.97	2.88	2.50	0.00	96.78
THING 20–21	71.75	0.20	14.29	3.09	0.14	0.09	1.85	4.16	2.61	0.06	98.24
THING 20–21	71.51	0.17	14.41	3.22	0.10	0.09	1.96	4.36	2.67	0.01	98.50
THING 20–21	71.39	0.17	14.18	3.23	0.11	0.12	1.91	3.34	2.70	0.05	97.20
THING 20–21	71.14	0.26	14.07	3.19	0.10	0.12	1.89	3.09	2.58	0.02	96.46
THING 25–25.5	49.64	1.76	13.74	12.02	0.20	6.78	11.72	2.40	0.24	0.15	98.65
THING 25–25.5	50.95	1.69	13.90	11.73	0.22	6.31	10.88	2.68	0.32	0.12	98.79
THING 25–25.5	49.50	1.72	13.60	11.99	0.23	6.99	11.90	2.28	0.20	0.20	98.60
THING 25–25.5	48.97	1.71	13.90	12.05	0.22	7.11	12.01	2.26	0.20	0.19	98.61
THING 25–25.5	49.24	1.70	13.92	12.06	0.20	7.08	11.76	2.23	0.21	0.17	98.57
THING 25–25.5	49.37	1.74	13.72	11.89	0.21	7.12	11.80	2.34	0.20	0.19	98.58
THING 25–25.5	48.92	1.79	13.61	12.33	0.22	6.86	11.89	2.35	0.20	0.18	98.36
THING 25–25.5	49.44	1.74	13.78	12.25	0.23	6.96	11.64	2.47	0.21	0.19	98.91
THING 25–25.5	49.57	1.76	13.93	11.94	0.22	7.07	11.67	2.37	0.18	0.16	98.87
THING 25–25.5	49.15	1.67	13.82	11.81	0.21	7.45	12.16	2.35	0.18	0.15	98.94
THING 25–25.5	49.85	1.85	13.87	12.09	0.20	6.81	11.45	2.37	0.24	0.20	98.93
THING 25–25.5	50.11	1.76	13.87	11.92	0.20	7.08	11.89	2.48	0.22	0.17	99.69
THING 25–25.5	49.19	1.75	13.79	12.31	0.21	6.97	12.04	2.33	0.19	0.16	98.94
THING 25–25.5	49.55	1.89	13.70	12.50	0.20	6.86	11.80	2.34	0.19	0.12	99.15
THING 25–25.5	49.32	1.71	13.85	12.08	0.20	7.10	11.88	2.40	0.19	0.13	98.86
THING 38–38.5	73.91	0.13	13.27	2.02	0.12	0.02	1.31	2.85	2.79	0.00	96.42
THING 38–38.5	72.12	0.22	14.47	3.06	0.10	0.14	2.03	4.36	2.47	0.05	99.03
THING 38–38.5	66.02	0.50	15.18	6.27	0.21	0.50	3.70	3.06	1.92	0.07	97.43
THING 38–38.5	65.99	0.41	15.43	5.89	0.14	0.40	3.27	3.04	2.06	0.10	96.71
THING 38–38.5	64.05	0.87	16.04	6.82	0.19	1.21	4.24	4.01	1.65	0.31	99.40
THING 38–38.5	63.69	0.62	15.12	7.74	0.21	0.79	3.96	4.21	1.86	0.23	98.44
THING 38–38.5	63.62	0.96	15.73	7.00	0.22	1.26	4.32	4.15	1.62	0.26	99.13
THING 38–38.5	63.49	0.65	15.62	8.12	0.22	0.84	4.33	2.87	1.74	0.27	98.15
THING 44.5–45.5	75.39	0.07	13.43	1.93	0.10	0.02	1.29	3.10	2.83	0.03	98.19
THING 44.5–45.5	75.13	0.12	13.42	1.95	0.09	0.01	1.29	4.41	2.78	0.00	99.20
THING 44.5–45.5	74.94	0.13	13.34	1.89	0.14	0.01	1.30	2.69	2.84	0.01	97.28
THING 44.5–45.5	74.51	0.13	13.21	2.02	0.08	0.01	1.36	3.18	2.88	0.00	97.37
THING 44.5–45.5	74.40	0.10	13.26	2.06	0.09	0.01	1.39	4.25	2.84	0.00	98.40
THING 44.5–45.5	74.32	0.10	12.92	1.94	0.07	0.02	1.28	2.95	2.71	0.00	96.31
THING 44.5–45.5	74.29	0.09	13.22	1.95	0.09	0.02	1.28	4.10	2.74	0.01	97.79
THING 44.5–45.5	74.21	0.10	13.37	1.92	0.06	0.02	1.30	2.84	2.76	0.01	96.59
THING 44.5–45.5	73.99	0.09	13.30	2.00	0.10	0.01	1.38	2.65	2.70	0.01	96.23
THING 44.5–45.5	73.78	0.12	13.46	2.00	0.08	0.00	1.28	2.91	2.72	0.01	96.37
THING 44.5–45.5	73.70	0.13	13.31	2.04	0.10	0.01	1.31	4.04	2.76	0.02	97.42
THING 44.5–45.5	73.57	0.07	13.34	2.02	0.09	0.00	1.28	4.16	2.80	0.00	97.34

the tephrochronological elements of the age-depth model. This could be attributed to a hiatus in the stratigraphy. However, both visual assessment of the sediment core and a consideration of sedimentary properties (Figure 3) presents a clear continuity in strata development between H4 (43 cm) and H1 (21 cm).

Palynology and Sedimentology

Interpretation of pollen data is based primarily upon pollen percentages (Figure 4) as a means of ascertaining the relative proportions of pollen and spore taxa within a sample (Birks and Birks 1980). As percentage values are co-dependent, e.g. high values in Cyperaceae may

Table 3. Radiocarbon date from the Þingeyrar core.

Sample	Depth (cm)	^{14}C Date (BP)	Error 1σ	$\delta\ ^{13}C$ (‰)	Calibrated age (BC) 2σ	Weight (mg)	Material
Þingeyrar (ETH-82940)	24.5–25.5	2463	35	−30.2	762–429	1.5	Wood

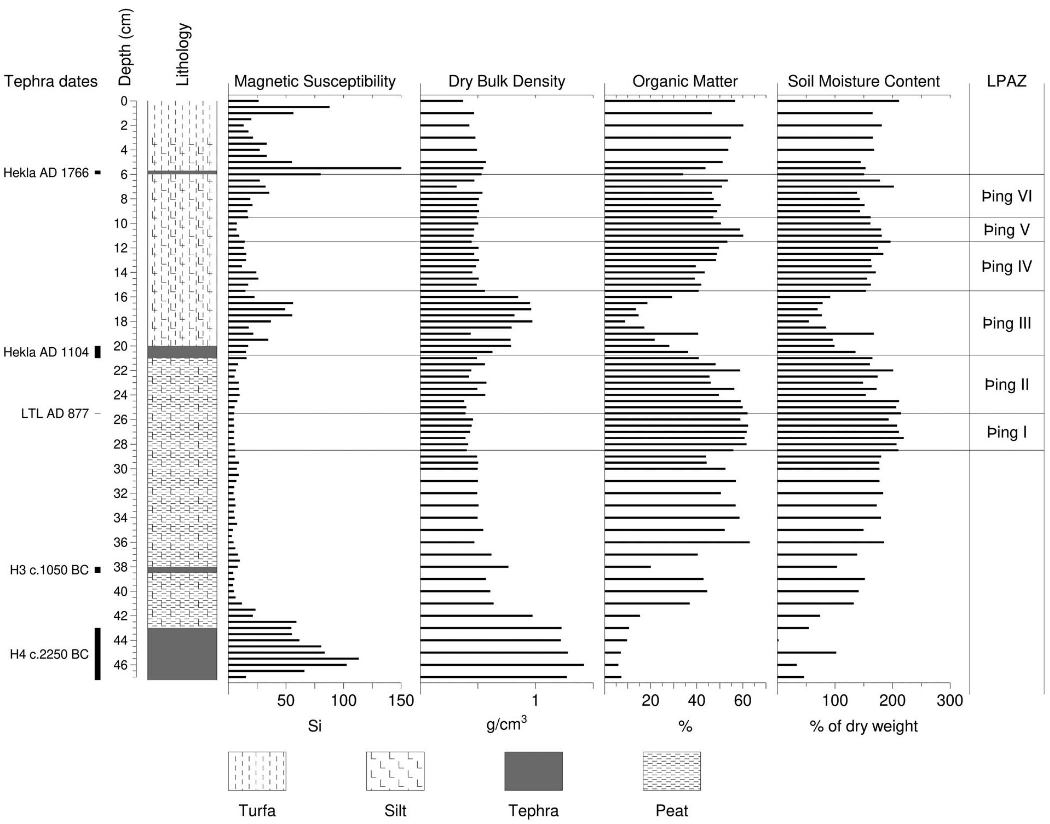


Figure 3. Sediment properties of the Þingeyrar core (MS, DBD, SMC, OM).

suppress values for other taxa, data are presented (Figure 5) that exclude Cyperaceae from the percentage calculation in order to aid interpretation (Moore, Webb, and Collison 1991). Alternative clarification can also be sought with reference to absolute data expressed as pollen concentration (Figure 6). The palynological data are divided into six Local Pollen Assemblage Zones (LPAZ; Þing I-VI) based upon the visual examination of the various datasets and consultation with the dendrogram (Figure 4). Interpolated dates are derived from the age-depth model (Figure 2). Corprophilous fungi encompasses *Sordaria*-type (HdV 55A), *Sporomiella-type* (HdV 113) and *Delitschia* spp. (Figures 4–6).

Þing I (Figure 4; 28.5–25.5 cm; AD c. 432 to 877) infers an environment where *Betula* and Cyperaceae are co-dominant (60% and 40% respectively). Based upon *Betula* pollen grain size (Figure 8), it is thought that *Betula nana* is the principal species concerned and *Betula* is henceforth considered to mostly represent *B. nana* (Mäkelä 1996; Caseldine 2001; Erlendsson and Edwards 2009; Karlsdóttir 2014). Of the other taxa, *Salix* (willows) is prominent (5%) along with Pteropsida (monol.) indet. (ferns; 5%) and Poaceae (6%). These values are reflected in Cyperaceae-excluded percentages and pollen concentrations (Figures 5 and 6). There are no significant alterations to the sedimentary data (Figure 3).

Þing II (Figure 4; 25.5–20.75 cm; AD 877 to 1104) presents an environment where *Betula* and Cyperaceae values are gradually dropping (to <40% and <30% respectively). This decline is also mirrored by *Salix* (<5%), perhaps more notably given the decline in pollen concentration for this taxon (Figure 6), from ~4000 to ~1000 pollen grains/cm^3. *Angelica* (Angelicas), Brassicaceae (crucifers), *Filipendula ulmaria* (Meadowsweet) and *Vaccinium*-type (e.g. Bilberry) appear similarly affected. Ericales (encompassing Ericaceae and Empetraceae) and *Empetrum nigrum* (Crowberry) values are increasing from <1% up to 5% and 6% respectively. Poaceae values remain relatively consistent. Overall, similar trends are also observed in Cyperaceae-excluded percentages and pollen concentrations (Figures 5 and 6). Sedimentary trends (Figure 3) show a progressive decline in SMC and OM values with an increase in DBD and MS values.

Þing III (Figure 4; 20.75–15.5 cm; AD 1104 to c. 1332) witnesses a considerable reduction in *Betula* (5%) while *Salix*, Ericales, *Empetrum nigrum* and *Angelica* fall to zero values. There is an increase in Poaceae values

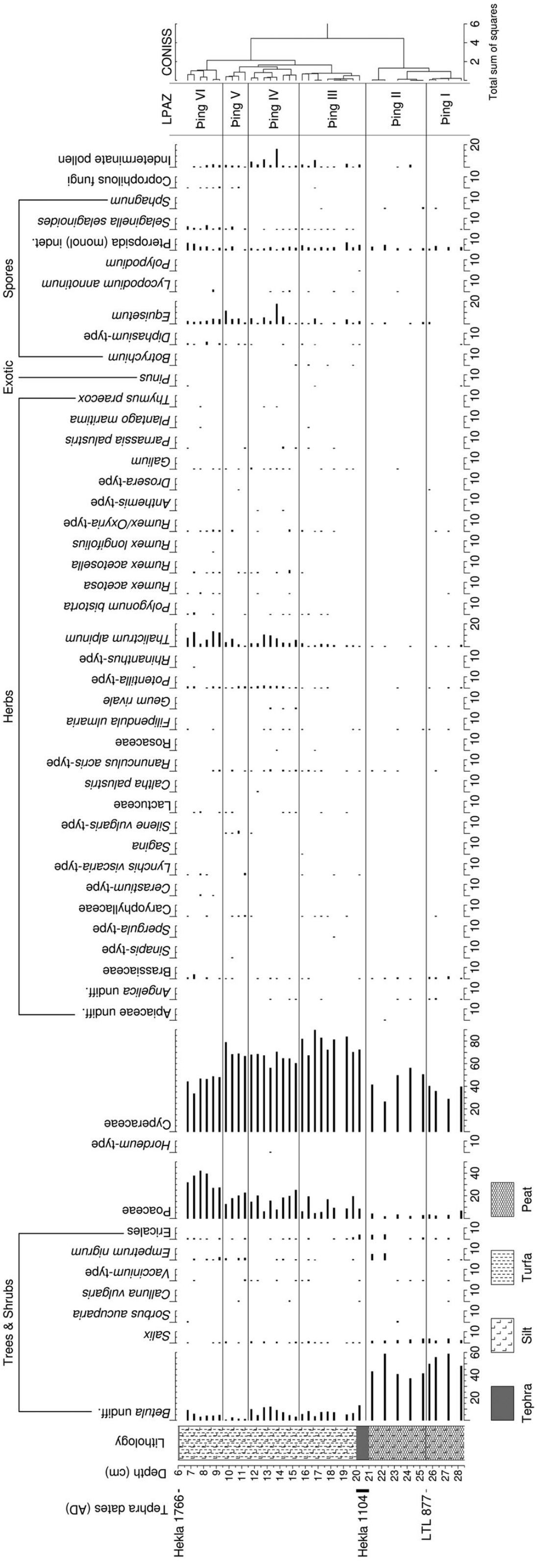


Figure 4. Pollen percentage diagram for the Þingeyrar core with LPAZ dendrogram.

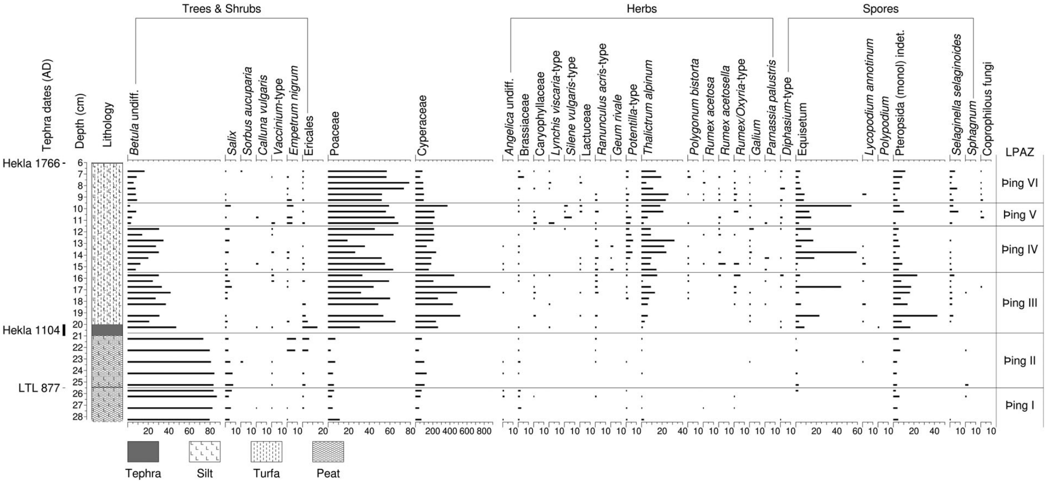


Figure 5. Pollen percentage diagram for the Þingeyrar core for all taxa and species ≥1% TLP and with Cyperaceae excluded from the percentage calculation.

(20%) and Cyperaceae becomes almost completely dominant (90%). A consistent signal for *Selaginella selaginoides* (Lesser clubmoss) arises, *Equisetum* (horsetail) increases (6%) and there is a tentative increase in the prominence of *Thalictrum alpinum* (Alpine meadow rue; 5%). A greater variety of herbaceous species and taxa also begin to be recorded for this LPAZ along with coprophilous fungi (16.75 cm). Similar trends are apparent in Cyperaceae-excluded percentages and pollen concentrations (Figures 5 and 6). Sedimentary data (Figure 3) display the lowest values for OM and SMC and corresponding peaks in values for DBD and MS.

Þing IV (Figure 4; 15.5–11.5 cm; AD c. 1332 to c. 1515) reveals a recovery of *Betula* (maximum 20%) at the expense of Poaceae (minimum 10%) and Cyperaceae (briefly falling to 55%). Of the grasses, a single *Hordeum*-type pollen is present (13.25 cm). *Potentilla*-type (cinquefoils; 2%), *Thalictrum alpinum* (12%) and *Equisetum* (19%) are increasingly prominent and the signal for *Rumex* spp. (sorrels) is stronger than in previous LPAZ. Similar trends can be seen in Cyperaceae-excluded percentages and pollen concentrations (Figures 5 and 6). Sedimentological data reveals a recovery in SMC with values similar to those of the pre-Landnám LPAZ (Þing I). OM values are increasing while those of DBD and MS decline (Figure 3).

Þing V (Figure 4; 11.5–9.5 cm; AD c. 1515 to c. 1606) suggests another significant reduction in *Betula* (<5%) and a corresponding increase in Poaceae (maximum 20%). A slight recovery in *Empetrum nigrum* values is apparent (2%). Cyperaceae and *Equisetum* remain fairly

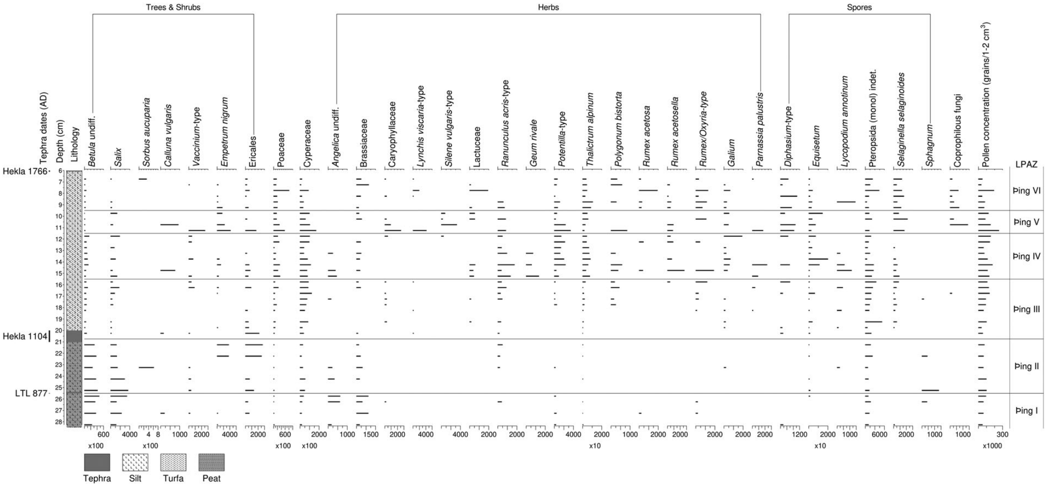


Figure 6. Pollen concentration diagram for the Þingeyrar core for all taxa and species ≥1% TLP.

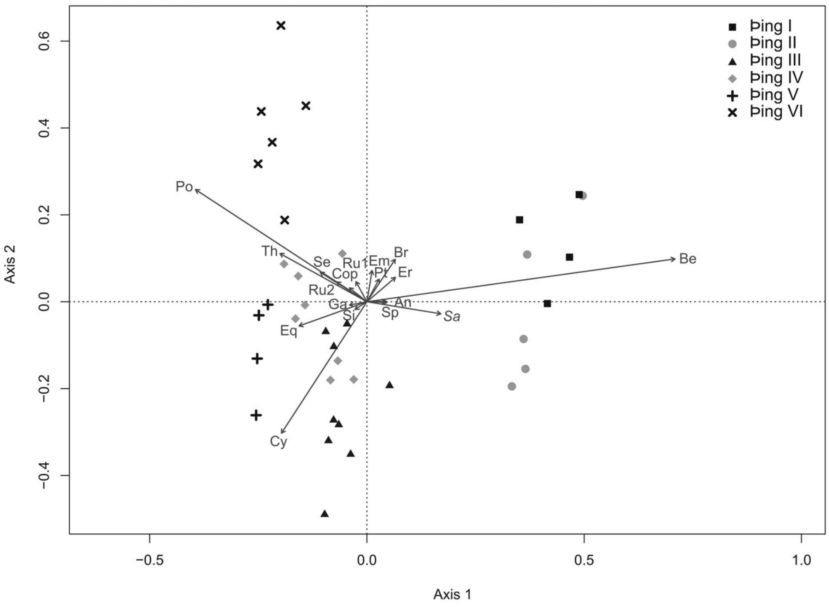


Figure 7. Principal component analysis (PCA). Note that only a selection of taxa and species are presented; An (*Angelica* undifferentiated), (*Betula* undifferentiated), Br (Brassicaceae), Cop (Coprophilous fungi), Cy (Cyperaceae), Em (*Empetrum nigrum*), Er (Ericales), Eq (*Equisetum*), Ga (*Galium*); Po (Poaceae), Ru1 (*Rumex acetosa*), Ru2 (*Rumex acetosella*), Sa (*Salix*), Se (*Selaginella selaginoides*), Si (*Silene vulgaris*-type), Sp (*Sphagnum*), Th (*Thalictrum alpinum*).

stable with the PCA intimating that Cyperaceae remains dominant (Figure 7). Coprophilous fungi are present (from 10.75 cm). These patterns are mirrored in Cyperaceae-excluded percentages and pollen concentrations (Figures 5 and 6). MS values show a slight decline while those of DBD remain relatively stable (Figure 3). OM and SMC values (Figure 3) are akin to pre-Landnám values (Þing I) before declining slightly.

Þing VI (Figure 4; 9.5–6 cm; AD c. 1606 to 1766) observes Poaceae reach its maximum value (44%) at the expense of Cyperaceae (minimum 30%); a decline mirrored by *Equisetum* (<5%). PCA (Figure 7) reveals that Poaceae is now dominant. *Thalictrum alpinum* (maximum 15%) reasserts its presence and there is a stronger manifestation of *Rumex* spp., *Selaginella selaginoides* (5%) and *Diphasium*-type (e.g. *Diphasium alpinum*; 3%) compared with previous LPAZ. The presence of coprophilous fungi is also more consistent than before. Of final note is the slight recovery of *Betula* (10%). Cyperaceae-excluded percentages and pollen concentrations demonstrate comparable trends (Figures 5 and 6). Sedimentary data (Figure 3) identify a relative stability in SMC and OM, with both increasing toward the onset of the eighteenth century (7–6 cm). DBD values remain fairly stable while an increase in MS is associated with the Hekla AD 1766 tephra.

Ordination Analysis

PCA (Figure 7) verifies the pollen zonation (Figures 4–6) and the transition from pre-Landnám vegetation cover (Þing I), to the decline in *Betula* from Landnám (Þing II) from the late ninth century, to the establishment of an open landscape dominated by Cyperaceae (Þing III) in the early twelfth century. Open habitats persist with a shift toward Poaceae from Cyperaceae inferred for the fourteenth century (Þing IV). Cyperaceae reasserts its presence (Þing V) in the sixteenth century before ultimately submitting to Poaceae, by the eighteenth century. Apophytes and coprophilous fungi are also a strong feature of the latter pollen zone (Figure 8).

Discussion

The following interpretation is set within a climatological framework that in time came to be dominated by what is known as the Little Ice Age (LIA) (Mann 2002a) c. AD 1500–1900 and preceded by the Medieval Climatic Optimum (MCO or Medieval Warm Period) from c. AD 900 (Mann 2002b). Palaeoecological data from the Greenland Sea (north of Iceland) suggests that the MCO spanned the period AD 800–1350 followed by the LIA which persisted until AD 1900 (Eiríksson et al. 2000). This corresponds broadly with lacustrine palaeoenvironmental data from the Icelandic highlands (Larsen et al. 2012). A review of palaeoecological and historical data infers a more nuanced interpretation of the LIA in Iceland, subsequently proposed to have spanned the period c. AD 1250–1900 and broadly separated into two phases (Ogilvie and Jónsson 2001). The earlier phase was relatively mild but punctuated by short periods of harsh

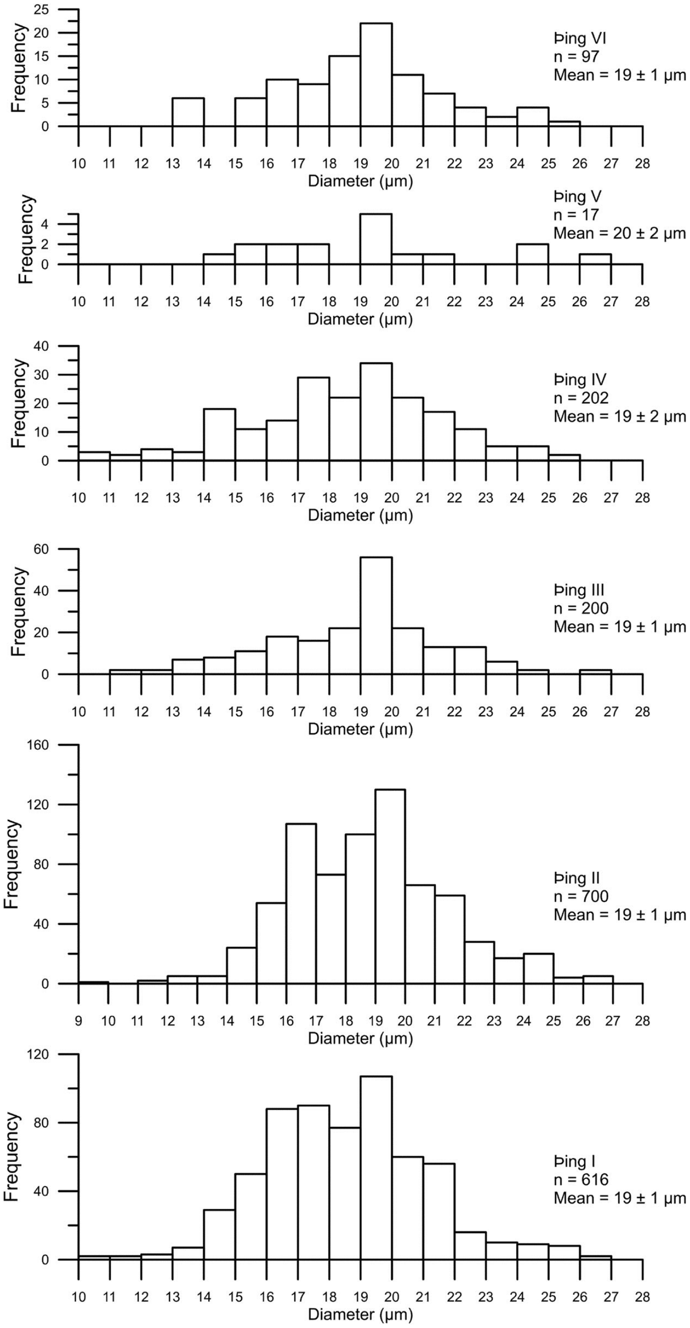


Figure 8. Measured diameters (µm) of *Betula* pollen grains for Þing I-VI.

climate until c. AD 1500 whereupon the incidence of severe conditions increased before abating c. AD 1900. Both the settlement of Iceland (Landnám) and the foundation of Þingeyraklaustur occurred within the span of the MCO and negative impacts upon vegetation at Þingeyrar for these periods are more likely to be anthropogenic in origin (cf. Eddudóttir et al. 2016; Tinganelli et al. 2018).

Þingeyrar: Pre-Landnám (Þing I, c. AD 432–877)

The earliest data sequence represents a pre-Landnám context dominated by *B. nana* and Cyperaceae (Figures 4–7); essentially a wetland. It is unlikely that any habitats in Iceland today are unmodified by human activity and are probably unrepresentative of habitats found in Iceland prior to human settlement. However, it is possible that this vegetation community could have been akin to a Boreal black sedge-brown moss fen (Icelandic vegetation classification: D4.162); a *B. nana* dominated wetland habitat that is still found at Þingeyrar (Ottósson, Sveinsdóttir, and Harðardóttir 2016). It is perhaps testament to the resilience of *B. nana* that it has apparently never disappeared entirely from Þingeyrar in the last 1000 or so years despite pressure from humans (fuel), coastal context (Thórsson et al. 2007; Möckel, Erlendsson, and Gísladóttir 2017), volcanic eruptions (Eddudóttir, Erlendsson, and Gísladóttir 2017) and climate (De Groot, Thomas, and Wein 1997).

Þingeyrar: Landnám (Þing II, c. AD 877–1104)

The arrival of people at Þingeyrar is muted (Figures 4–6) compared to the Landnám signal found elsewhere in Iceland, e.g. Reykholtsdalur, Reykjavík, Mosfellsdalur, Grímsnes, Skálholt and Stóra-Mörk (Einarsson 1962; Hallsdóttir 1987; Vickers et al. 2011; Riddell et al. 2018; Erlendsson et al. 2018) as well as within Austur-Húnavatnssýsla (Eddudóttir et al. 2016; Tinganelli et al. 2018). This is not unprecedented (Erlendsson 2007; Erlendsson, Edwards, and Buckland 2009) and spatial complexity must be recognised (Streeter et al. 2015). In this instance, the simplest explanation is that the sample site is relatively remote from the centres of human activity at Þingeyrar and Trumbsvalir (Figure 1) during the Landnám period. The absence of charcoal throughout the sedimentary record emphasises this, as does the intermittent and late arrival of coprophilous fungi.

B. nana is not a plant that is particularly favoured by livestock as fodder, only ever grazed during the winter months; if at all (Hejcman et al. 2016). It is possible therefore that its decline arises as a result of settlers directly clearing scrub in order to increase grazing area or to harvest fuel (or both). Firm evidence (macro-fossils) for the use of *Betula* spp. as a source of fuel comes from the hearth, floors and midden of a Viking Age farmstead at Vatnsfjörður, north west Iceland (Mooney 2009). Even during the MCO, it has been estimated that a Viking Age household in Iceland might require a minimum area of c. 11 m^2 per day in order to supply its fuel (cooking and heat) needs (Trbojevic, Mooney, and Bell 2011).

Livestock remain implicated given the decline in *Salix*, a plant that is very palatable to domestic animals (Hejcman et al. 2016), and the rise in values for the comparatively unpalatable *Empetrum nigrum* (Knud et al. 2000). Indeed, a subtle transition to an *Empetrum nigrum* dominated wetland appears to be underway in the short term (Figure 4; c.11th century).

Þingeyraklaustur: Foundation (Þing III, c. AD 1104–1332)

In contrast to the initial colonisation of Þingeyrar, the arrival of the monastery in the landscape clearly had an impact on the character of the vegetation and environment. Indeed, many of the signals one would expect of Landnám are present (Figures 4–7), i.e. the development of a landscape increasingly characterised by open wetland (Cyperaceae) and grassland (Poaceae and *Selaginella selaginoides*), the signal for apophytic plants is stronger (e.g. Caryophyllaceae, *Ranunculus acris*-type, *Galium*, and *Rumex* spp.) and the, albeit tentative, presence of coprophilous fungi. Soil conditions are also altered (Figure 3). Considering that there are two dates given in the historical archive for the establishment of the monastery at Þingeyrar, these environmental changes would be more consistent with the earlier date of AD 1112. It is therefore worth bearing in mind that the construction and occupation of Þingeyraklaustur probably began decades before its formal inauguration in AD 1133 (and hence the variance in dates regarding foundation). European parallels of such environmental change can be drawn with respect to palaeoecological evidence from the monasteries of Abbeyknockmoy (Ireland), Melrose (Scotland), Furness (England), Annecy (France) and St. Georgenberg-Fiecht (Austria), all implicated in the development of pastoral landscapes during the twelfth century (Wimble, Wells, and Hodgkinson 2000; Noël et al. 2001; Lomas-Clarke and Barber 2004; Breitenlechner et al. 2010; Tipping 2010). It is a further drop in *Salix* and the incidence of coprophilous fungi from the late thirteenth century (Figures 4–6, 16.75 cm) that perhaps intimates the agent of overall change at Þingeyrar, i.e. livestock. Sustaining livestock at a monastery may either be linked with food or manuscript production (or both). Zooarchaeological evidence from Skriðuklaustur revealed that a relatively high number of the cattle bones found there were of neonatal or very young calves (c. 13%) suggesting an emphasis on dairy farming or vellum (calfskin) production (Hamilton-Dyer 2010).

Another factor worth considering is that the construction of a monastery at Þingeyrar is likely to have made some demand upon the landscape in its immediate vicinity, most obviously for fuel for cooking and warmth. This may be apparent in the retreat of *B. nana* (Figures 4–6), a feature also observed in the pollen record for Viðeyjarklaustur (Figure 1) at the time of its establishment c. 1226 (Hallsdóttir 1993). Furthermore, as charcoal is absent from the micro-fossil record at Þingeyrar, it is possible to infer that fire was not used to clear the land of *B. nana* in this instance (Smith 1995). There remains the possibility that the deposition of the Hekla AD 1104 tephra had a negative impact upon *B. nana* (and other vegetation).

However, there is evidence available that would suggest that *B. nana* is relatively resilient to burial arising from the deposition of minerogenic material ≤10 cm thick (Vilmundardóttir et al. 2009). Allowing for compaction of strata over time, in Austur-Húnavatnssýsla, the Hekla AD 1104 tephra deposits are usually ≤2 cm thick (Larsen and Thorarinsson 1977).

Þingeyraklaustur: Plague (Þing IV, c. AD 1332–1515)

Iceland was beset by two outbreaks of 'plague', first in AD 1402, followed by another in AD 1495. There is an ongoing debate regarding the exact nature of these plague events (Karlsson 1996; Callow and Evans 2016), but there is no doubt about their impact in Iceland. It is estimated that the first outbreak killed at least half of the population of the island and both events are thought to have left at least some farms deserted (Karlsson 1996; Júlíusson 1997). With regard to Þingeyraklaustur, the plague was just as devastating; the Abbot and all of the monastery's brethren, bar one, died in the AD 1402 outbreak. The impact of this loss was sufficient enough to leave the institution devoid of a brotherhood for approximately 22 years (Kristjánsdóttir 2017). The later epidemic again took Þingeyraklaustur's Abbot, although he was swiftly replaced. This would suggest that at least some of the brethren survived this outbreak and it has been inferred that the second epidemic was not as virulent as that of AD 1402 (Karlsson 1996; Júlíusson 1997; Kristjánsdóttir 2017). With regard to the lay population at Þingeyraklaustur, nothing is known with regard to either epidemic. Within the wider landscape, it has been noted that around 36% of the farms tenured to Þingeyraklaustur had been abandoned by AD 1525, perhaps as a direct consequence of the two plagues (Karlsson 1996). On the continent, it is thought that instances of woodland recovery could be symptomatic of demographic change arising due to the Black Death (van Hoof et al. 2006; Yeloff and van Geel 2007). Given the timing of the resurgence of *B. nana* during the early LIA (Ogilvie and Jónsson 2001), and an absence of coprophilous fungi (i.e. livestock), similar demographic change affected by plague is the most plausible explanation for the recovery of *B. nana*, *Angelica* undiff., *Filipendula ulmaria*, SMC and OM, at Þingeyrar (Figures 4–6; 14 cm, c. AD 1401 ± 2 and 12 cm, c. AD 1492 ± 1). The earlier event seems to have initiated a relatively prolonged period (decades) of recovery while the second event (bearing in mind the limits of dataset) seems to have been comparatively short-lived. Perhaps the scale of recovery in each instance reflects the degree of impact of plague upon the human population? It has been suggested that woodland recovery in Iceland during the fifteenth century may embody a response to plague but not necessarily due to abandonment (Streeter, Dugmore, and Vésteinsson 2012); it may actually represent a change in land management regimes in response to declining population. There is some historical evidence to suggest that peasants resisted utilising outlying areas despite the demands of landowners (Júlíusson 1997). Similarly, not all abandonment may have been due to plague; climate cooling, volcanism and famine may all be implicated (Callow and Evans 2016). Nonetheless, the historical testimony for a period of desertion at Þingeyraklaustur due to plague in the fifteenth century is hard to ignore.

Due to an absence of other arable indicators (Erlendsson, Edwards, and Gísladóttir 2014; Riddell et al. 2018), and the coastal context, the single incidence of *Hordeum*-type pollen (Figure 4) is attributed to the presence of lyme grass (*Elymus arenarius*) at Þingeyrar; not cereal cultivation. Given the possible correlation between cereal cultivation and the establishment of the monastery at Viðey (Hallsdóttir 1993), the absence of evidence for cereal cultivation at Þingeyrar is perhaps a little surprising. The coastal location (mitigates frost) and presumably, high status of the monastery, intimate the potential for cereal cultivation despite the cooling climate regime (Riddell et al. 2018). As with charcoal and the intermittent signal for coprophilous fungi (already discussed with regard to Þing II), not to mention the poor dispersal ability of cereal pollen (Tweddle et al. 2005), the absence of pollen from cereal and arable weed taxa could be a consequence of the sample site being remote from the monastery/home farm.

Þingeyraklaustur: Erosion, the LIA and the Reformation (Þing V, c. AD 1515–1606)

The early sixteenth century witnesses a change in vegetation not seen at Þingeyrar since the foundation of the monastery c. 400 years earlier. Although a Cyperaceae dominated wetland prevails (Figure 7), *B. nana* gives way almost entirely to Poaceae (i.e. grassland), and to a somewhat lesser degree, an *Empetrum nigrum* wetland (Figures 4–6). The relatively strong representation of Caryophyllaceae (pinks) and *Silene vulgaris*-type (catchflies) could infer the presence of *Silene uniflora* (Sea campion), a species that favours a gravelly and sandy substrate (Kristinsson 1986; Ottósson, Sveinsdóttir, and Harðardóttir 2016). This implies either some degree of erosion or is associated with the re-deposition of coastal sands due to increasing storminess arising during the LIA (Ogilvie and Jónsson 2001). Soil degradation is a recognised feature of sixteenth century in Iceland, attributed to land management practices (grazing) originating during Landnám, persisting into the modern period, and exacerbated by deteriorating climate conditions (Dugmore et al. 2009; Gísladóttir et al. 2010). However, the sedimentary data for

Þingeyrar suggest stability for this period, with no additional influxes of minerogenic material (Figure 3). Notably, the coprophilous fungi reveal that livestock have returned to the landscape (Figures 4–6). An inventory for the monastery from AD 1525 suggests that a large body of livestock was present on the landholding, summarised as 56 cattle, 350 sheep and 11 horses (DI IX, p. 314). Whether or not this represents an increase on previous livestock numbers is unknown but this could explain the altered character of the vegetation and the possible inception of erosion. Meanwhile, the decline in *B. nana* may simply be revealing an increased demand for fuel for warmth in response to the LIA or ongoing scrub clearance for pasture (Figures 4–6). By AD 1552, Þingeyrarklaustur is receiving charcoal for fuel as a rental payment from its tenancy at Ásbjarnarnes (DI XII p. 451–454).

The sixteenth century also encompasses the Lutheran Reformation (AD 1551) whereupon Þingeyraklaustur fell into the hands of the Danish state. Ecological responses to the dynamic sixteenth century Protestant Reformation have been observed in Europe. For example, the pastoral hinterland of Furness Abbey evolved into one of mixed-arable farming due to the division of the monastic landholding between freeholders (Wimble, Wells, and Hodgkinson 2000). If a single sample can be trusted, a very slight increase in *B. nana* values at the expense of *Empetrum nigrum* wetland (Figure 4, 10.25 cm, c. AD 1561) could suggest some element of reduced human population, i.e. the dispersal of the brethren and lay community of Þingeyraklaustur, following AD 1551 (Ísleifsdóttir 2013). Otherwise, it appears that the general trajectory of vegetation change (from wetland to grassland) at Þingeyrar simply persists post-Reformation under the new administration of the Danish state.

Early Modern Þingeyrar (Þing VI, c. AD 1606–1766)

From the early seventeenth century, Þingeyrar remains in the hands of the Danish state within a colonial regime of trade monopoly and royal absolutism (Karlsson 2000). The landscape of Þingeyrar has become increasingly dominated by grassland (Poaceae) and associated apophytes (e.g. *Selaginella selaginoides*, *Rumex* spp. and *Diphasium*-type) at the expense of Cyperaceae dominated wetland (Figures 4–7). Coprophilous fungi (i.e. livestock) have become an almost permanent feature (Figures 4–6). Despite this, and the LIA, the sedimentary data suggest increasingly stable environmental conditions (Figure 3).

It is possible that such stability and the expansion of grassland habitats are a consequence of a considered land management policy introduced by the representatives of the Danish state in the face of a deteriorating climate. However, agricultural improvement is not thought to have arrived in Iceland until the latter part of the eighteenth century (Lucas 2012) and so far, has only been expressed archaeologically through stock breeding (Hambrecht 2009) and palaeoecologically via cereal pollen (Einarsson 1962) at the episcopal seat of Skálholt. The land register (AD 1702) known as Jarðabók (Magnússon and Vídalín 1926b) comments upon inundations of sand for Geirastaðir and abandoned Trumbsvalir (now within the landholding of Þingeyrar), both to the north of Þingeyrar. It therefore remains a possibility that the redeposition of minerogenic material by the wind is responsible for the drier ground conditions favoured by Poaceae at the sample site. Yet these inundation events do not appear in the sampled strata (Figure 3). Nor are there any further references in Jarðabók to inundations of sand at Þingeyrar or Neðri Vatnsdalshreppur (Lower Vatnsdalur) to the south (Magnússon and Vídalín 1926b). This would suggest that the documented events were localised, dictated by aspect with regard to wind direction and by proximity to the coast (perhaps arising in response to increasing storminess during the LIA). Þingeyrar is relatively remote from inland erosion areas and the active volcanic belt of Iceland which may further explain the relative stability in sedimentary conditions (Möckel, Erlendsson, and Gísladóttir 2017).

Jarðabók (Magnússon and Vídalín 1926b) remarks upon the limited availability of *hrísrif* (woody shrubs) at Þingeyrar. Again, *B. nana* data contradict this somewhat although it is possible that while it was available, it was not considered sufficient to be worth the effort of harvesting for fuel.

Conclusion

Interpreting palaeoecological data in hand with historical sources is common practice (e.g. Lomas-Clarke and Barber 2004; Tipping 2004) and at Þingeyrar there is a degree of parity between the two archives with regard to the establishment of the monastery. However, it is shown here that palaeoecological data are able to discern land use activities during the historical period that are invisible in documentary record, practices perhaps considered too base or humdrum by the medieval scribe to be worthy of mention. For example, the pollen record for Þingeyrar shows that from foundation the monastery was active in altering the character of its immediate environs, probably through livestock grazing, perhaps by deliberate scrub clearance by hand, but also through other forms of resource use, e.g. *B. nana* for fuel. Furthermore, this altered landscape can be seen to reflect monastic activity observed in the pollen record elsewhere in Europe, e.g. woodland clearance and conversion to pastoral landscapes. Conversely, recourse to the historical archive does allow the recovery of *B. nana* scrub during a period of climate cooling to be understood, i.e. the Icelandic plague events of the fifteenth century (and again in common with the effect plague had on vegetation on the continent). Where contradictions between the two sources of data arise, it is seen here as an interpretation opportunity where differences are seen to represent a more nuanced suite of circumstances, e.g. insights into the distribution of the influx of coastal sands during the LIA, or the availability of *hrísrif* for fuel as described in Jarðabók. It may even shed light on the documentary disparity over the foundation date of the monastery. It has not been possible to confidently attribute any specific changes in land use to the sixteenth century Protestant Reformation.

Overall, there is a gradual transition from *B. nana* dominated wetland to a pastoral landscape, initiated by settlers c. AD 877, consolidated by the monastery from the twelfth century, and intensified initially by the monastery and then by the Danish state from the sixteenth century. Although the proportions between the different habitat types have changed, ecological equilibrium was sustained throughout (Hallsdóttir 1987), i.e. there is little evidence for erosion on a large scale and vegetation cover is maintained. The inferred transition appears to be led by human activity, perhaps enhanced by a deterioration in climate conditions, especially from c. AD 1500. Documented influxes of coastal sands during the eighteenth century appear to be localised.

Acknowledgements

First and foremost, we wish to thank Ingimundur Sigfússon (1938–2018) of Þingeyrar and his family for their kind support and hospitality during fieldwork. The editorial team of Environmental Archaeology are thanked for inviting us to contribute to this special issue. The constructive feedback from two reviewers was also greatly appreciated. Fríðþór Sófus Sigurmundsson and Olga Kolbrún Vilmundardóttir are thanked for insights into the Icelandic historical archive and plant ecology, respectively.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The Icelandic Research Fund (grant numbers 140983-051, 163290-051, 141842-051) and the Landsvirkjun Energy Research Fund (grant numbers NÝR-05-2017 and NÝR-05-2016) financed this research.

ORCID

Scott J. Riddell http://orcid.org/0000-0003-4589-3925
Egill Erlendsson http://orcid.org/0000-0002-2264-3504
Sigrún D Eddudóttir http://orcid.org/0000-0002-8632-8191
Guðrún Gísladóttir http://orcid.org/0000-0002-4309-2414
Steinunn Kristjánsdóttir http://orcid.org/0000-0002-2872-0160

References

Andersen, S.Th. 1979. “Identification of Wild Grass and Cereal Pollen.” *Danmarks Geologiske Undersøgelse Årbog* 25: 491–518.

Arnalds, Ó, E. F. Þorarinsdóttir, S. Metúsalemsson, Á Jónsson, E. Grétarsson, and Á Árnason. 2001. *Soil Erosion in Iceland*. Iceland: Soil Conservation Service and the Agricultural Research Institute.

Aston, M. 2000. *Monasteries in the Landscape*. Stroud: Tempus.

Aston, M. 2001. “The Expansion of the Monastic and Religious Orders in Europe from the Eleventh Century.” In *Monastic Archaeology*, edited by G. Keevill, M. Aston, and T. Hall, 9–36. Oxford: Oxbow Books.

Birks, H. J. B., and H. H. Birks. 1980. *Quaternary Palaeoecology*. London: Edward Arnold.

Björck, S., T. Persson, and I. Kristersson. 1978. “Comparison of Two Concentration Methods for Pollen in Minerogenic Sediments.” *Geologiska Föreningen i Stockholm Förhandlingar* 100 (1): 107–111.

Blaauw, M. 2010. “Methods and Code for ‘Classical’ Age-Modelling of Radiocarbon Sequences.” *Quaternary Geochronology* 5: 512–518.

Bond, J. 2004. *Monastic Landscapes*. Stroud: Tempus.

Bonny, A. P. 1972. “A Method for Determining Absolute Pollen Frequencies in Lake Sediments.” *New Phytologist* 71: 393–405.

Brady, N. C., and R. R. Weil. 1996. *Elements of the Nature and Properties of Soils*. Upper Saddle River: Pearson Prentice-Hall.

Breitenlechner, E., M. Hilber, J. Lutz, Y. Kathrein, A. Unterkircher, and K. Oeggl. 2010. “The Impact of Mining Activities on the Environment Reflected by Pollen, Charcoal and Geochemical Analyses.” *Journal of Archaeological Science* 37: 1458–1467.

Burt, R. 2004. *Soil Survey Laboratory Methods Manual, Soil Survey Investigation Report*. Nebraska: USDA-NRCA.

Callow, C., and C. Evans. 2016. “The Mystery of Plague in Medieval Iceland.” *Journal of Medieval History* 42 (2): 254–284.

Caseldine, C. 2001. “Changes in *Betula* in the Holocene Record from Iceland—A Palaeoclimatic Record or Evidence for Early Holocene Hybridisation?” *Review of Palaeobotany and Palynology* 117 (1-3): 139–152.

Coolen, J., and N. Mehler. 2015. “Surveying the Assembly Site and Churches of Þingeyrar.” *Archaeologia Islandica* 11: 11–32.

Cugny, C., F. Mazier, and D. Galop. 2010. “Modern and Fossil Non-Pollen Palynomorphs from the Basque Mountains (Western Pyrenees, France): The Use of Coprophilous Fungi to Reconstruct Pastoral Activity.” *Vegetation History and Archaeobotany* 19 (5-6): 391–408.

Dearing, J. 1994. *Environmental Magnetic Susceptibility, Using the Bartington MS2 System*. Kenilworth: Chi Publishing.

De Groot, W. J., P. A. Thomas, and R. W. Wein. 1997. “*Betula nana L.* and *Betula glandulosa Michx.*” *The Journal of Ecology* 85 (2): 241–264.

DI (Diplomatarium Islandicum). 1857–1986. *Íslenzkt fornbréfasafn I-XVI*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

DI (Diplomatarium Islandicum). 1857–1986. *Íslenzkt fornbréfasafn IX*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

DI (Diplomatarium Islandicum). 1857–1986. *Íslenzkt fornbréfasafn XII*. Kaupmannahöfn: Íslenzka bókmenntafélagið.

Dugmore, A. J., G. Gísladóttir, I. A. Simpson, and A. J. Newton. 2009. "Conceptual Models of 1200 Years of Icelandic Soil Erosion Reconstructed Using Tephrochronology." *Journal of the North Atlantic* 2 (1): 1–18.

Dugmore, A. J., G. Larsen, and A. J. Newton. 1995. "Seven Tephra Isochrones in Scotland." *The Holocene* 5 (3): 257–266.

Dumayne, L., R. Stoneman, K. Barber, and D. Harkness. 1995. "Problems Associated with Correlating Calibrated Radiocarbon-Dated Pollen Diagrams with Historical Events." *The Holocene* 5 (1): 118–123.

Eddudóttir, S. D. 2016. "Holocene environmental change in Northwest Iceland." PhD Thesis, University of Iceland.

Eddudóttir, S. D., E. Erlendsson, and G. Gísladóttir. 2015. "Life on the Periphery Is Tough: Vegetation in Northwest Iceland and Its Responses to Early-Holocene Warmth and Later Climate Fluctuations." *The Holocene* 25 (9): 1437–1453.

Eddudóttir, S. D., E. Erlendsson, and G. Gísladóttir. 2017. "Effects of the Hekla 4 Tephra on Vegetation in Northwest Iceland." *Vegetation History and Archaeobotany* 26 (4): 389–402.

Eddudóttir, S. D., E. Erlendsson, and G. Gísladóttir. 2018. "An Icelandic Terrestrial Record of North Atlantic Cooling c. 8800–8100 cal. yr BP." *Quaternary Science Reviews* 197: 246–256.

Eddudóttir, S. D., E. Erlendsson, L. Tinganelli, and G. Gísladóttir. 2016. "Climate Change and Human Impact in a Sensitive Ecosystem: The Holocene Environment of the Northwest Icelandic Highland Margin." *Boreas* 45 (4): 715–728.

Edwards, K. J., E. Erlendsson, and J. E. Schofield. 2011. "Is There a Norse 'Footprint.'" In *North Atlantic Pollen Records?" In Viking Settlements and Viking Society; Papers from the Proceedings of the 16th Viking Congress, Reykjavík and Reykholt, 16th–23rd August 2009*, edited by S. Sigmundsson, 65–82. Reykjavík: Hið íslenzka fornleifafélag and Háskóli Íslands.

Einarsson, Þ. 1962. "Vitnisburður frógreiningar um gróður, veðurfar og landnám á Íslandi." *Saga* 3: 442–469.

Eiríksson, J., K. L. Knudsen, H. Haflidason, and J. Heinemeier. 2000. "Chronology of Late Holocene Climatic Events in the Northern North Atlantic Based on AMS 14C Dates and Tephra Markers from the Volcano Hekla, Iceland." *Journal of Quaternary Science: Published for the Quaternary Research Association* 15 (6): 573–580.

Erlendsson, E. 2007. "Environmental Change Around the Time of the Norse Settlement of Iceland." PhD Thesis, University of Aberdeen.

Erlendsson, E., and K. J. Edwards. 2009. "The Timing and Causes of the Final Pre-Settlement Expansion of *Betula pubescens* in Iceland." *The Holocene* 19 (7): 1083–1091.

Erlendsson, E., K. J. Edwards, and P. C. Buckland. 2009. "Vegetational Response to Human Colonisation of the Coastal and Volcanic Environments of Ketilsstaðir, Southern Iceland." *Quaternary Research* 72 (2): 174–187.

Erlendsson, E., K. J. Edwards, and G. Gísladóttir. 2014. "Landscape Change, Land Use and Occupation Patterns Inferred from Two Palaeoenvironmental Datasets from the Mosfell Valley, SW Iceland." In *Viking Archaeology in Iceland: Mosfell Archaeological Project*, edited by J. Byock, and D. Zori, 181–192. Turnhout: Brepols.

Erlendsson, E., K. J. Edwards, I. Lawson, and O. Vésteinsson. 2006. "Can There Be a Correspondence between Icelandic Palynological and Settlement Evidence?" In *Dynamics of Northern Societies: Proceedings of the SILA/NABO Conference on Arctic and North Atlantic Archaeology*, edited by J. Arneborg, and B. Grønnow, 347–353. Copenhagen: P.N.M.

Erlendsson, E., K. J. Edwards, K. Vickers, G. Sveinbjarnardóttir, and G. Gísladóttir. 2018. "The Palaeoecology and Cultural Landscapes Associated with Reykholt." In *Snorri Sturluson and Reykholt. The Author and Magnate, His Life, Works and Environment at Reykholt in Iceland*, edited by H. Þorláksson, and G. Sveinbjarnardóttir, 161–203. Copenhagen: Museum Tusculanum Press.

Friðriksson, A., and O. Vésteinsson. 2003. "Creating a Past: A Historiography of the Settlement of Iceland." In *Contact, Continuity and Collapse: the Norse Colonisation of the North Atlantic*, edited by J. H. Bennett, 139–161. Turnhout: Brepols.

Gilchrist, R. 2014. "Monastic and Church Archaeology." *Annual Review of Anthropology* 43: 235–250.

Gísladóttir, G., E. Erlendsson, L. Rattan, and J. Bigham. 2010. "Erosional Effects on Terrestrial Resources Over the Last Millennium in Reykjanes, Southwest Iceland." *Quaternary Research* 73 (1): 20–23.

Grimm, E. C. 2011. *Tilia 1.7.16*. Springfield: Illinois State Museum.

Guðmundsson, A. T. 2007. *Living Earth: Outline of the Geology of Iceland*. Reykjavík: Mál og menning/Edda hf.

Hall, D. 2006. *Scottish Monastic Landscapes*. Stroud: Tempus.

Hallsdóttir, M. 1987. "Pollen Analytical Studies of Human Influence on Vegetation in Relation to the Landnám Tephra Layer in Southwest Iceland." PhD Thesis, University of Lund.

Hallsdóttir, M. 1993. *Frjórannsókn á mósniðum úr Viðey*. Reykjavík: Raunvísindastofnun Háskólans.

Hallsdóttir, M. 1995. "On the Pre-Settlement of Icelandic Vegetation." *Icelandic Agricultural Science (Búvísindi)* 9: 17–29.

Hallsdóttir, M., and C. J. Caseldine. 2005. "The Holocene Vegetation History of Iceland, State-of-the-Art and Future Research." In *In Iceland: Modern Processes and Past Environments*, edited by C. J. Caseldine, A. Russell, J. Harðardóttir, and O. Knudsen, 320–334. Amsterdam: Elsevier.

Hambrecht, G. 2009. "Zooarchaeology and the Archaeology of Early Modern Iceland." *Journal of the North Atlantic* 101 (Special Issue I): 3–22.

Hamilton-Dyer, S. 2010. *Skriðaklaustur Monastery, Iceland: Animal Bones 2003-2007*. Reykjavík: Skriðuklaustursrannsókna.

Heiri, O., A. F. Lotter, and G. Lemcke. 2001. "Loss on Ignition as a Method for Estimating Organic and Carbonate Content in Sediments: Reproducibility and Comparability of Results." *Journal of Paleolimnology* 25 (1): 101–110.

Hejcman, M., P. Hejcmanová, V. Pavlů, and A. G. Thorhallsdottir. 2016. "Forage Quality of Leaf Fodder from the Main Woody Species in Iceland and Its Potential Use for Livestock in the Past and Present." *Grass and Forage Science* 71: 649–658.

Hill, M. O., and H. G. Gauch. 1980. "Detrended Correspondence Analysis: An Improved Ordination Technique." In *Classification and Ordination. Advances in Vegetation Science (vol 2)*, edited by E. van der Maarl, 47–58. Dordrecht: Springer.

Hjartarson, H.J., S. Kristjánsdóttir, and J. Walser-Wallace III. 2017. *Kortlagning klaustra á Íslandi: Þingeyrar*. Reykjavík: Klaustur á Íslandi/Monasticism in Iceland.

Hjelle, K. L., L. S. Halvorsen, and A. Overland. 2010. “Heathland Development and Relationship between Humans and Environment Along the Coast of Western Norway through Time.” *Quaternary International* 220 (1): 133–146.

Hoffmann, R. 2014. *An Environmental History of Medieval Europe*. Cambridge: Cambridge University Press.

Icelandic Meteorological Office (Veðurstofa Íslands). 2018. *Mánaðarmeðaltöl*. Reykjavík. Accessed May 16, 2018. http://www.vedur.is/vedur/vedurfar/medaltalstoflur/.

Ísleifsdóttir, V.A. 2013. *Byltingin að ofan - stjórnskipunarsaga 16. aldar*. Reykjavík: Hið íslenska bókmenntafélag.

Jensson, G. 2016. “Íslenskar klausturreglur og libertas ecclesie á ofanverðri 12 öld.” In *Íslensk klausturmenning á miðöldum*, edited by H. Bernharðsson, 9–57. Reykjavík: Miðaldastofa Háskóla Íslands og Háskólaútgáfan.

Júlíusson, Á. D. 1997. “Bønder i prestens tid: landbrugg, godsdrift og social konflikt i semiddelalderens Islandske bondesamfund.” PhD Thesis, University of Copenhagen.

Júlíusson, Á. D. 2014. *Jarðeignir kirkjunnar og tekjur af þeim 1000-1550*. Reykjavík: Center for Agrarian Historical Dynamics.

Karlsdóttir, L. 2014. “Hybridisation of Icelandic Birch in the Holocene Reflected in Pollen.” PhD Thesis, University of Iceland.

Karlsson, G. 1996. “Plague without Rats: The Case of Fifteenth-Century Iceland.” *Journal of Medieval History* 22 (3): 263–284.

Karlsson, G. 2000. *Iceland’s 1100 Years: The History of a Marginal Society*. London: C. Hurst & Co. Publishers.

Knud, T., M. C. Nilsson, A. Michelsen, H. Lakkenborg-Kristensen, A. Shevtsova, M. T. Strandberg, M. Johansson, et al. 2000. “Nordic *Empetrum* Dominated Ecosystems: Function and Susceptibility to Environmental Changes.” *AMBIO: A Journal of the Human Environment* 29 (2): 90–97.

Kristinsson, H. 1986. *A Guide to Flowering Plants and Ferns of Iceland*. Reykjavík: Mál og Menning.

Kristjánsdóttir, S. 2008. “Skriðuklaustur Monastery: Medical Centre of Medieval East Iceland?” *Acta Archaeologica* 79 (1): 208–215.

Kristjánsdóttir, S. 2010a. “The Tip of the Iceberg: The Material of Skriðuklaustur Monastery and Hospital.” *Norwegian Archaeological Review* 43 (1): 44–62.

Kristjánsdóttir, S. 2010b. “Icelandic Evidence for a Late-Medieval Hospital: Excavations at Skriduklaustur.” *Medieval Archaeology* 54 (1): 371–381.

Kristjánsdóttir, S. 2017. *Leitin að klaustrunum – klausturhald á Íslandi í fimm aldir*. Reykjavík: Forlagið.

Kristjánsdóttir, S., and V. Gunnarsdóttir. 2014. *Kortlagning klaustra á Íslandi: Þingeyrar - Trumbsvalir*. Reykjavík: Klaustur á Íslandi/Monasticism in Iceland.

Kristjánsdóttir, S., V. Gunnarsdóttir, and H. Jónsdóttir. 2016. *Kortlagning klaustra á Íslandi: Þingeyrar*. Reykjavík: Klaustur á Íslandi/Monasticism in Iceland.

Kristjánsdóttir, S., I. Larsson, and P. A. Åsen. 2014. “The Icelandic Medieval Monastic Garden – Did It Exist?” *Scandinavian Journal of History* 39 (5): 560–579.

Larsen, D. J., G. H. Miller, Á Geirsdóttir, and S. Ólafsdóttir. 2012. “Non-Linear Holocene Climate Evolution in the North Atlantic: A High-Resolution, Multi-Proxy Record of Glacier Activity and Environmental Change from Hvítárvatn, Central Iceland.” *Quaternary Science Reviews* 39: 14–25.

Larsen, G., and S. Thorarinsson. 1977. “H4 and Other Acid Hekla Tephra Layers.” *Jokull* 27: 28–46.

Loftmyndir ehf. 2006. Aerial Photograph 347, Flight Line 15,3000 m., 9 August 2006, Reykjavík: Loftmyndir ehf.

Lomas-Clarke, S. H., and K. Barber. 2004. “Palaeoecology of Human Impact during the Historic Period: Palynology and Geochemistry of a Peat Deposit at Abbeyknockmoy, Co. Galway, Ireland.” *The Holocene* 14 (5): 721–731.

Lucas, G. 2012. “Later Historical Archaeology in Iceland: A Review.” *International Journal of Historical Archaeology* 16: 437–454.

Magnússon, Á, and P. Vídalín. 1926a. *Jarðabók I-XI*. Kaupmannahöfn: Hin íslensk fræðafelagið í Kaupmannahöfn & Möller, S.L.

Magnússon, Á, and P. Vídalín. 1926b. *Jarðabók VIII*. Kaupmannahöfn: Hin íslensk fræðafelagið í Kaupmannahöfn & Möller, S.L.

Mäkelä, E. 1996. “Size Distinctions between *Betula* Pollen Types — A Review.” *Grana* 35: 248–256.

Mann, M. E. 2002a. “Little Ice Age.” In *Encyclopedia of Global Environmental Change*, edited by T. Munn, 504–509. Chichester: John Wiley & Sons Ltd.

Mann, M. E. 2002b. “Medieval Climatic Optimum.” In *Encyclopedia of Global Environmental Change*, edited by T. Munn, 514–516. Chichester: John Wiley & Sons Ltd.

Möckel, S. C., E. Erlendsson, and G. Gísladóttir. 2017. “Holocene Environmental Change and Development of the Nutrient Budget of Histosols in North Iceland.” *Plant and Soil* 418 (1-2): 437–457.

Mooney, D. E. 2009. “Fuel Resources at Vatnsfjörður: An Archaeobotanical Perspective.” In *Vatnsfjörður 2008: Interim Report*, edited by K. Milek, 117–131. Reykjavík: Fornleifastofnun Íslands.

Moore, P. D., J. A. Webb, and M. E. Collison. 1991. *Pollen Analysis*. 2nd ed. Oxford: Blackwell Scientific Publications.

Nakagawa, T., E. Brugiapaglia, G. Digerfeldt, M. Reille, J. L. de Beaulieu, and Y. Yasuda. 1998. “Dense-Media Separation as a More Efficient Pollen Extraction Method for Use with Organic Sediment/Deposit Samples: Comparison with the Conventional Method.” *Boreas* 27 (1): 15–24.

Noël, H., E. Garbolino, A. Brauer, E. Lallier-Vergès, J. L. De Beaulieu, and J. R. Disnar. 2001. “Human Impact and Soil Erosion during the Last 5000 yrs as Recorded in Lacustrine Sedimentary Organic Matter at Lac d’Annecy, the French Alps.” *Journal of Paleolimnology* 25 (2): 229–244.

Ogilvie, A. E. J., and T. Jónsson. 2001. “‘Little Ice Age’ Research: A Perspective from Iceland.” *Climatic Change* 48 (1): 9–52.

Oksanen, J., F. G. Blanchet, R. Kindt, P. Legendre, P. R. Minchin, R. B. O’hara, G. L. Simpson, P. Solymos, M. H. H. Stevens, and H. Wagner. 2016. Vegan: Community Ecology Package. *R package version*: 2.3–3 ed.

Ólsen, B. M. 1910. “Um kornirkju á Íslandi að fornu.” *Búnaðaritt* 24: 81–168.

Ottósson, J. G., A. Sveinsdóttir, and M. Harðardóttir. 2016. *Vistgerðir á Íslandi*. Iceland: Oddi ehf.

Riddell, S., E. Erlendsson, G. Gísladóttir, K. J. Edwards, J. Byock, and D. Zori. 2018. “Cereal Cultivation as a Correlate of High Social Status in Medieval Iceland.” *Vegetation History and Archaeobotany* 27 (5): 679–696.

Schmid, M. M. E., A. J. Dugmore, O. Vésteinsson, and A. J. Newton. 2017. "Tephra Isochrons and Chronologies of Colonisation." *Quaternary Geochronology* 40: 56–66.

Smith, K. P. 1995. "*Landnám*: The Settlement of Iceland in Archaeological and Historical Perspective." *World Archaeology* 26 (3): 319–347.

Steinberg, J. M., D. J. Bolender, and B. N. Damiata. 2016. "The Viking Age Settlement Pattern of Langholt, North Iceland: Results of the Skagafjörður Archaeological Settlement Survey." *Journal of Field Archaeology* 41 (4): 389–412.

Stockmarr, J. 1971. "Tablets with Spores Used in Absolute Pollen Analysis." *Pollen et Spores* 13: 614–621.

Stolz, C., and J. Grunert. 2010. "Late Pleistocene and Holocene Landscape History of the Central Palatinate Forest (Pfälzerwald, South-Western Germany)." *Quaternary International* 222: 129–142.

Streeter, R., A. J. Dugmore, I. T. Lawson, E. Erlendsson, and K. J. Edwards. 2015. "The Onset of the Palaeoanthropocene in Iceland: Changes in Complex Natural Systems." *The Holocene* 25 (10): 1662–1675.

Streeter, R., A. J. Dugmore, and O. Vésteinsson. 2012. "Plague and Landscape Resilience in Premodern Iceland." *Proceedings of the National Academy of Sciences* 109 (10): 3664–3669.

Sverrisdottir, G. 2007. "Hybrid Magma Generation Preceding Plinian Silicic Eruptions at Hekla, Iceland: Evidence from Mineralogy and Chemistry of Two Zoned Deposits." *Geological Magazine* 144 (4): 643–659.

Thorarinsson, S. 1967. "The Eruptions of Hekla in Historical Times: A Tephrochronological Study." In *The Eruption of Hekla 1947-1948*, edited by S. Thorarinsson, 1–177. Reykjavík: Societas Scientiarum Islandica.

Thordarson, T., and A. Hoskuldsson. 2002. *Iceland, Classic Geology in Europe*. Harpenden: Terra.

Thórsson, Æ. Th., S. Pálsson, A. Sigurgeirsson, and K. Anamthawat-Jónsson. 2007. "Morphological Variation among *Betula nana* (diploid), *B. pubescens* (tetraploid) and Their Triploid Hybrids in Iceland." *Annals of Botany* 99: 1183–1193.

Tinganelli, L., E. Erlendsson, S. D. Eddudóttir, and G. Gísladóttir. 2018. "Impacts of Climate, Tephra and Land-Use upon Holocene Landscape Stability in Northwest Iceland." *Geomorphology*, in press.

Tipping, R. 1997. "Medieval Woodland History from the Scottish Southern Uplands: Fine Spatial-Scale Pollen Data from a Small Woodland Hollow." In *Scottish Woodland History*, edited by Christopher Smout, 51–74. Dalkeith: Scottish Cultural Press.

Tipping, R. 2004. "Palaeoecology and Political History: Evaluating Driving Forces in Historic Landscape Change in Southern Scotland." In *Society, Landscape, Environment in Upland Britain*, edited by I. Whyte, and A. J. L. Winchester, 11–21. UK: Society for Landscape Studies.

Tipping, R. 2010. *Bowmont: An Environmental History of the Bowmont Valley and the Northern Cheviot Hills, 10000 BC-AD 2000*. Edinburgh: Society of Antiquaries of Scotland.

Trbojevic, N., D. E. Mooney, and A. J. Bell. 2011. "A Firewood Experiment at Eiríksstaðir: A Step Towards Quantifying the Use of Firewood for Daily Household Needs in Viking Age Iceland." *Archaeologia Islandica* 9: 29–40.

Tweddle, J.C., K.J Edwards, and N.R.J. Fieller. 2005. "Multivariate Statistical and Other Approaches for the Separation of Cereal from Wild Poaceae Pollen Using a Large Holocene Dataset." *Vegetation History and Archaeobotany* 14: 15–30.

van Geel, B., J. Buurman, O. Brinkkemper, J. Schelvis, A. Aptroot, G. van Reenen, and T. Hakbijl. 2003. "Environmental Reconstruction of a Roman Period Settlement Site in Uitgeest (The Netherlands), with Special Reference to Coprophilous Fungi." *Journal of Archaeological Science* 30 (7): 873–883.

van Hoof, T. B., F. P. M. Bunnik, J. G. M. Waucomont, W. M. Kürschner, and H. Visscher. 2006. "Forest Re-Growth on Medieval Farmland After the Black Death Pandemic—Implications for Atmospheric CO_2 Levels." *Palaeogeography, Palaeoclimatology, Palaeoecology* 237: 396–409.

Vésteinsson, O. 1998. "Patterns of Settlement in Iceland." *Saga Book of the Viking Society* 25 (1): 1–29.

Vésteinsson, O. 2000. *The Christianization of Iceland: Priests, Power, and Social Change 1000-1300*. Oxford: Oxford University Press.

Vickers, K., E. Erlendsson, M. J. Church, K. J. Edwards, and J. Bending. 2011. "1000 Years of Environmental Change and Human Impact at Stóra-Mörk, Southern Iceland: A Multiproxy Study of a Dynamic and Vulnerable Landscape." *The Holocene* 21 (6): 979–995.

Vilmundardóttir, O. K., B. Magnússon, G. Gísladóttir, and S.H. Magnússon. 2009. "Áhrif sandfoks á mólendisgróður við Blöndulón." *Náttúrufræðingurinn* 78: 125–137.

Wimble, G., C. E. Wells, and D. Hodgkinson. 2000. "Human Impact on Mid-and Late Holocene Vegetation in South Cumbria, UK." *Vegetation History and Archaeobotany* 9 (1): 17–30.

Yeloff, D., and B. van Geel. 2007. "Abandonment of Farmland and Vegetation Succession Following the Eurasian Plague Pandemic of AD 1347–52." *Journal of Biogeography* 34: 575–582.

Paper II

A script born of sediment: vegetation and land use at the medieval monastery of Helgafell (Helgafellsklaustur) in western Iceland

Scott J. Riddell[a], Sigrún D. Eddudóttir[b], Egill Erlendsson[a,d], Wesley R. Farnsworth[c,d], Guðrún Gísladóttir[a,d], Steinunn Kristjánsdóttir[e]

[a]Faculty of Life and Environmental Sciences, University of Iceland, Sturlugata 7, 102 Reykjavík, Iceland, email: sjr3@hi.is
[b]Department of Archaeology & Ancient History, Uppsala University, Engelska Parken, Thunbergsvägen 3H, 752 38, Uppsala, Sweden
[c]Globe Institute, University of Copenhagen, Øster Volgarde 5-7, 1350 Copenhagen, Denmark
[d]Institute of Earth Sciences, University of Iceland, Sturlugata 7, 102 Reykjavík, Iceland
[e]Department of Archaeology, University of Iceland, Sæmundargata 12, 102 Reykjavík, Iceland

Keywords: palynology, tephrochronology, climate, Landnám, medicinal plants

Abstract

During the late 12th century, an Augustinian monastery (Helgafellsklaustur) was founded in AD 1184 somewhere within the immediate vicinity of the modern farm of Helgafell, western Iceland. Utilising sedimentary and palynological data derived from a core collected from Helgafellsvatn, it is the purpose of this study to evaluate the palaeoecological record of the Helgafell landholding. Data analysis seeks to understand land use associated with the Helgafellsklaustur e.g. livestock and cultivation, as well evidence for introduced plants. In order to establish a wider context, palaeoecological data from the pre-settlement and settlement (Landnám, c. AD 877) periods are also considered, in hand with reference to historical sources. This is enabled through the application of tephrochronology and Pu dating. The pre-settlement context is defined by *Betula* dominated habitats with developments in the terrestrial vegetation inferring a climate amelioration c. AD 500-900. This is followed by Landnám and a transition to a pastoral landscape and the introduction of medicinal and culinary herbs. The arrival of Helgafellsklaustur in the 12th century is equally visible in the landscape, with an expansion in grazing lands which is ongoing down to the early 16th century. A particularly striking feature of the palaeoecological record for Helgafell is the general stability in environmental conditions despite the presence of livestock and a cooling climate. This is attributed to the site being distal from windborne sources of minerogenic material i.e. erosion, volcanism, and glacier outwash plains.

Introduction

There is a growing body of interdisciplinary evidence to suggest that monasteries in Iceland (Fig. 1), while initially dependent upon episcopal and secular patronage, were embedded within a wider European monastic tradition (Clark, 2021; Kristjánsdóttir, 2023). For example, archaeological material from Skriðuklaustur has shown that medieval Icelandic monasticism mirrored that of Europe with regard to architecture and mission i.e. the provision of medical care to the lay population (Kristjánsdóttir, 2010a, 2010b, & 2012). A further manifestation of medieval health care is apparent via plant surveys of Icelandic monastic sites by Kristjánsdóttir et al. (2014) and Åsen (2021) where relict populations of herbs with medicinal properties survive, believed to have been introduced to Iceland via the cloister garden.

European monasticism was associated with a significant alteration to the medieval European landscape (Aston, 2000; Bond, 2004; Gilchrist, 2014). Palynologically, this is visible as woodland clearance (assarting), the development of pasture, expansion and intensification of cereal cultivation (Breitenlechner et al., 2010; Hjelle et al., 2010; Lomas-Clarke & Barber, 2004; Noël et al., 2001; Stolz & Grunert, 2010; Wimble et al., 2000), and technological innovation e.g. the introduction of nitrogen-fixing plant species (Tipping, 1997). Along with architecture, mission, and medicinal plants, it is reasonable to consider that Icelandic monasteries were also importing European ideas on agriculture. Indeed, there is some palynological evidence to support this premise e.g. the clearance of *Betula* (birch) scrub for fuel and pasture at Þingeyraklaustur (Riddell et al., 2022a), and similarly at Viðeyjarklaustur in hand with the introduction (or intensification) of cereal cultivation (Hallsdóttir, 1993).

In terms of the climatological context, the majority of Iceland's monasteries (including Helgafellsklaustur) were established during the 12th century, within the span of the Medieval Climatic Optimum (MCO, AD 900-1500) when mild conditions prevailed in the North Atlantic (Mann, 2002a). By the time of the Lutheran Reformation in the mid-16th century, Iceland was in the grip of the Little Ice Age (LIA), AD 1500-1900 (Mann, 2002b). However, within Iceland, the climate regime encompassed by the conventional framework of the MCO and LIA is far more complex (Mann, 2002b; Ogilvie & Jónsson, 2001). Marine sedimentary proxies from the Greenland Sea infer that the MCO in Iceland occurred AD 800-1350, followed by the LIA which lasted until AD 1900 (Eiríksson et al., 2000). Data from lacustrine sediments refine the MCO to AD 950-1150, with the LIA spanning AD 1250-1900 (Larsen et al., 2012). The latter is consistent with analysis of historical sources although these identify two distinct phases to the LIA (Ogilvie & Jónsson, 2001); a relatively mild early phase punctuated by brief periods of harsh climate c. AD 1250-1500 followed by an era where the incidence and severity of hostile conditions intensified c. AD 1500-1900.

Helgafell is a prominent hill (73 m a.s.l.) situated within the low lying landscape of Þórsnes on the north coast of Snæfellsnes in western Iceland, c. 4 km south of the harbour village of Stykkishólmur (Fig. 1). During the late 12th century, an Augustinian monastery (Helgafellsklaustur) was founded somewhere within the immediate vicinity of the modern farm, church, and lake (Helgafellsvatn), at the foot of the eponymous hill (Kristjánsdóttir, 2017). Utilising sedimentary and palynological data derived from a core collected from Helgafellsvatn, it is the purpose of this study to evaluate the palaeoecological record of the Helgafell landholding with the aim of understanding ecological and environmental change under the aegis of the monastery (AD 1184-1544). In particular, evidence for the introduction of plant species, of cultivation, and/or the intensification of grazing practices is sought. Analyses will also incorporate palaeoecological data from the pre-settlement and settlement (Landnám) periods as a means of providing some wider context for the environmental and ecological events associated with the monastic period. Historical sources are used to further elaborate upon findings (Haldon et al., 2018).

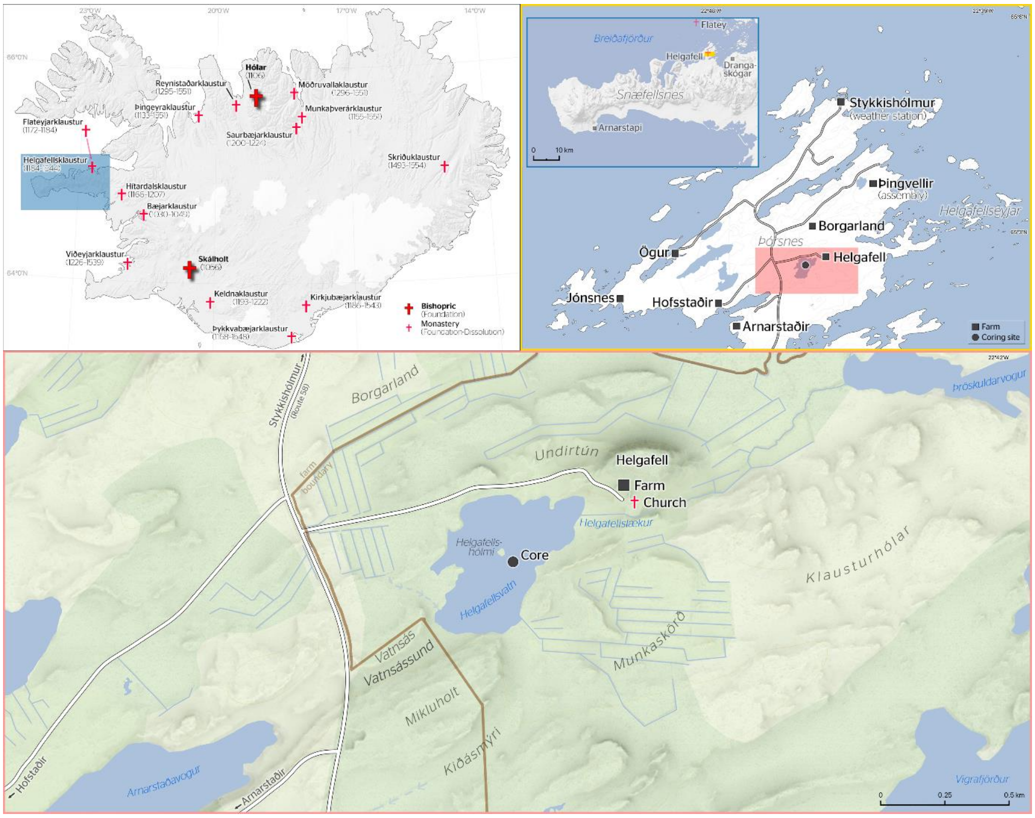


Fig 1. Iceland (monasteries and bishoprics), Helgafell and surrounding area.

Site description

Helgafell: Holy mountain, monastery, and farm

Helgafellsklaustur (Fig. 1) was established in AD 1184 when Abbot Ögmundur Kalfsson and three brethren relocated their nascent Augustinian institution (founded AD 1172) from the island of Flatey in Breiðafjörður to Þórsnes on the mainland (Drechsler, 2021; Kristjánsdóttir, 2017). Þórsnes and Helgafell (lit: holy mountain) feature in the Eyrbyggja Saga (Sveinsson & Þórðarson, 1985) in connection with pre-Christian religion (i.e. the Norse god Thor and ancestor worship) and the establishment of a "þing" (a law court) to its north (Fig. 1). To the south, the farm of Helgafell is a focal point of the Laxdæla Saga (Sveinsson, 1934), particularly with regard to its main protagonist Guðrún Ósvífursdóttir. Guðrún is credited to be among the first of Iceland's Christian anchoresses and was buried at Helgafell, her supposed grave marked there to this day. It is possible that the monastery's move to Helgafell sought to capitalise upon all of the above associations but the simple fact that the farm of Helgafell was vacant at this time is hard to ignore (Kristjánsdóttir 2017).

The newly acquired landholding of Helgafell and its associated assets were extensive. Marine resources (fish, seals, whale wrecks, seabirds, eggs, eiderdown and driftwood) were near at hand with direct access to the coast, and through the ownership of numerous islands (DI-II, 1857-1986) i.e. the Helgafellseyjar (Fig. 1). The names of some of these islands intimate their importance with regard to resources e.g. meat and eggs from Álku hólmar (literally, auk isles), while Akurey (figuratively, island of the cultivated field) may imply crops were grown there. There are references to the consumption of beer at Helgafellsklaustur (Kristjánsdóttir, 2017) and it is possible that cereals were grown there as they were in many places in Iceland during the medieval period (Mooney & Guðmundsdóttir, 2020; Ólsen, 1910; Riddell et al., 2018). Wood for rafters was sourced from Drangaskógur (DI-I, 1857-1986), east of Þórsnes (Fig 1).

The brethren brought a small number of domestic animals with them from Flateyjarklaustur to Helgafell; 30 cattle and c. 20 horses (DI-I, 1857-1986). Inventories for AD 1377/78 and AD 1397 show that livestock numbers grew considerably (Fig. 2; 548 and 711 animals respectively; DI-III & DI-IV 1857-1986). Livestock were an important source of meat, dairy, vellum, hides and wool, as well as beasts of burden. Given the number of cattle at Helgafell, animal husbandry may have been particularly linked to manuscript production (Kristjánsdóttir, 2023). A number of dairy cows were also leased by the monastery to its tenants (separate from tenancy rental, the fee paid to the monastery in dairy produce, the remainder kept by the lessee). The acquisition of tenant farms in the surrounding area began with the monastery's foundation in the 12th century (DI-I, 1857-1986) although most were acquired during the 14th century (DI-III, 1857-1986). Rent was paid in fish, dairy, and woollen goods. By the time of the Lutheran Reformation in the 16th century, Helgafellsklaustur owned c. 95 farms across Snæfellsnes (Júlíusson, 2014). To date, little is understood of the impact that monastic oversight had upon tenants with regard to land use (Riddell et al., 2022b). Upon dissolution c. AD 1544, Helgafellsklaustur and its assets became the property of the Danish crown (Kristjánsdóttir, 2017), with the *caput* of the estate soon moving to Arnarstapi (Fig. 1) on the south coast of Snæfellsnes (AD 1550).

Of the monastery itself, historical sources describe it as comprised of a number of buildings forming a cloister about a herb garden. Here, scribes were trained, manuscripts produced, rents and tithes administered, pensioners cared for, and the monastic garden tended, all alongside daily liturgical practice. Unfortunately, the exact location of the cloister at Helgafell remains elusive (Kristjánsdóttir, 2017). Archaeologists suspect that it was situated where the church and cemetery of Helgafell now stand (Fig. 1). Furthermore, there are few artefacts that can confidently be associated directly with the monastery (Kristjánsdóttir, 2016 & 2017; Kristjánsdóttir & Gunnarsdóttir, 2014). To date, the only tangible part of the monastery's legacy is a corpus of manuscripts written there in the 14th century (Drechsler, 2021; Kristjánsdóttir, 2023).

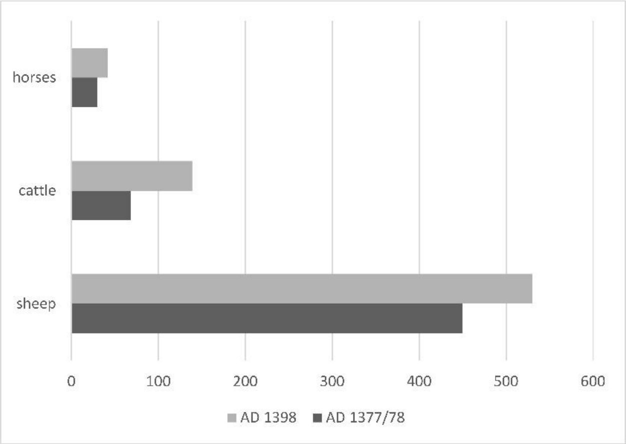


Fig. 2 Livestock numbers at Helgafell in the 14th century (DI-III & DI-IV 1857-1986)

Helgafell: the land and lake

Climate data for Helgafell (Table 1) are derived from the weather station (65°04.442'N, 22°44.033'W) at Stykkishólmur (Fig. 1). The prevailing winds are from the east and southeast. Geologically, the Helgafell area is comprised entirely of c. 16-3 million-year-old Tertiary basalts (Jóhannesson & Sæmundsson, 1998) underlying a pedology of Histosols and Histic Andosols (Arnalds, 2004). The area is fortunate compared with other parts of Iceland in that it experiences little or no soil erosion (Arnalds et al., 2001), incidence restricted to glacial deposits (gravel) and rock outcrops. Vegetation comprises of a matrix of semi-improved grassland, fen, and *Vaccinium uliginosum/Empetrum nigrum* (blueberry/crowberry) heath, grazed by sheep (Ottósson et al., 2016). Plants found close to the farmstead are as would be expected in Iceland (Kristinsson (1986) and include Poaceae (grasses; dominant), *Achillea millefolium* (yarrow), *Alchemilla vulgaris* (lady's mantle), *Cardamine pratensis* (cuckoo flower), *Lathyrus japonicas* (sea pea), *Ranunculus acris* (meadow buttercup), *Rumex acetosa* (common sorrel), *Rumex acetosella* (sheep's sorrel) and *Taraxacum* spp. (dandelions), with rock outcrops and thinner soils supporting *Alchemilla alpine* (Alpine lady's mantle), *Galium boreale* (northern bedstraw), *Rhinanthus minor* (yellow rattle), *Sedum annuum* (annual stonecrop), *Selaginella selaginoides* (lesser clubmoss), *Thymus praecox* (wild thyme) and *Viola canina* (dog violet).

Table 1. Meteorological data for Stykkishólmur, Þórsnes. Snæfelsnes (Fig. 1)

Recording period	1961-1990
Elevation (m a.s.l)	10
Avg. temp. °C tritherm	8.1
Avg. temp. °C July	9.2
Avg. temp. °C January	-1.3
Avg. pptn. mm yr.-1	704.6

Helgafellsvatn (Fig. 1) is c. 0.2 km^2 in size and situated at c. 17 m a.s.l., separated from the sea (Arnarstaðavogur) to the south west by a low ridge (c. 20 m a.s.l.). There is no evidence of any natural watercourses having ever flowed into the lake, its basin relatively contained. It is nominally oligotrophic (Langdon et al., 2008) but has probably experienced some degree of eutrophication since Iceland's settlement in the late 9th century (Lawson et al., 2007; Richter et al., 2021); especially following agricultural intensification in the 20th century. Aquatic plants typical of Helgafellsvatn include *Equisetum fluviatile* (water horsetail), *Menyanthes trifoliata* (bogbean) and *Myriophyllum alterniflorum* (alternate water milfoil), species commonly found in lakes in Iceland (Kristinsson (1986) The lake has been cored previously, first with regard to chironomids and their potential to shed light upon Holocene climate regimes (Langdon et al., 2008), and secondly, concerning late glacial sea level changes (Brader et al., 2015).

An area (c. 0.2 km^2) of semi-improved grassland (formerly wetland) east of the lake (Fig. 1, Munkaskörð) is fertilised annually and maintained by a modern network of drainage ditches that feed into Helgafellsvatn from the south east. Another network of ditches feeds Helgafellsvatn from the west, although the main ditch here is overgrown, almost imperceptible on the ground. The same applies to the drains associated with the wetlands that transition into the lake to the south i.e. Vatnsássund and Kiðásamýri (Fig. 1), although a ditch on the land of Arnastaðir actively drains Kiðásamýri toward the sea. These wetlands are dominated by Cyperaceae (sedges) including *Eriophorum angustifolium* (common cottongrass), *Carex nigra* (black sedge) and *Carex rostrata* (bottle sedge), along with *Betula nana* (dwarf birch), *Salix phylicifolia* (tea-leaved willow), and *Sphagnum* spp. while the surrounding rocky and eroded heights (c. 40 m a.s.l.) support *Arctostaphylos uva-ursi* (bearberry), *Armeria maritima* (thrift), *Dryas octopetala* (mountain avens), *E. nigrum*, *Salix lanata* (woolly willow), *Silene acaulis* (moss campion), *T. praecox*, and *V. uliginosum*. Stands of polycormic *Betula pubescens* (downy birch), ≤1.5 m in height, are also present on free draining slopes, possibly triploid-hybrids (Thórsson et al., 2007).

The outlet at the north eastern end of the lake (Fig. 1, Helgafellslækur), now a modified watercourse, flows eastward and empties into the sea at Þröskuldarvogur c. 1 km distant. A build-up of sediments around the outflow has inundated this portion of the lake basin (c. 0.02 km^2) and supports a wetland vegetation community dominated by Cyperaceae (including *E. angustifolium*, *C. nigra* and *C. rostrata*) with *A. vulgaris*, *Caltha palustris* (marsh marigold), *C. pratensis*, *Equisetum* spp. (horsetails), *Hippuris vulgaris* (common mare's-tail), *Potentilla palustris* (marsh cinquefoil) and *Sphagnum* spp. Ongoing maintenance of Helgafellslækur inhibits the flooding of this area by the lake. This wetland and the linear ditch section of Helgafellslækur that cuts through it both feature in a late 19th century landscape painting of Helgafell by Collingwood (1899).

Methods

Lacustrine coring

In February 2020, a sediment core (HFK8) was taken from Helgafellsvatn (water depth 125 cm from ice), just east of Helgafellshólmi (Fig. 1; 65º02.442'N, 22º44.168'W), using a Livingstone piston corer with a Bolivia adapter and a 75 mm diameter polycarbonate tube. Helgafellsvatn was selected for its contained basin and close proximity to the site of Helgafellsklaustur. Furthermore, the lake's watershed is almost entirely encapsulated by the modern land boundary of the Helgafell landholding (a portion lies within the neighbouring farm of Arnastaðir, a former tenancy of Helgafelsklaustur; Júlíusson 2014), and even though ownership has changed over time, the boundaries of landholdings in Iceland usually remain stable (Vésteinsson et al., 2002). Moreover, the watershed encompasses a toponymy that directly references the historical ownership of the land by the monastery e.g. Klausturhólar and Munkaskörð (Fig. 1). Therefore, for the most part, palaeoecological data accrued from Helgafellsvatn should reflect the ecological and environmental conditions of the monastic landholding for the period we are concerned with and earlier; especially as the present drainage network at Helgafell is post-medieval and will not have influenced sediments deposited in Helgafellsvatn from earlier periods.

Sedimentology

Troels-Smith (1955) was used to describe the strata of HFK8, modified according to Aaby & Berglund (1986), supplemented by Munsell Soil Color Charts (2009). HFK8 was measured every 1 cm (between 110-1 cm) for magnetic susceptibility (MS; SI) with a Bartington MS2 meter and MS2E probe (Dearing, 1994). Measures of dry bulk density (DBD; g/m^3) and organic matter (OM %) were also taken for every 1 cm (110-0 cm). Samples were heated at 105 ºC for 24 hours and the DBD calculated by dividing the dry weight of each sample by sample volume (1.2 cm^3), consistent with Brady and Weil (1996). OM was measured by combusting the remaining material of each sample at 550 ºC for 4 hours (Heiri et al., 2001). Sediment accumulation rates (SAR) are derived from the HFK8 chronology.

Age determination

The chronological framework for HFK8 is founded upon identifiable volcanic ash layers (tephra) and plutonium (Pu) isotope analysis i.e. the Pu peak associated with nuclear testing in 1963/64 (Kelley et al., 1999; Ketterer et al., 2002).

Tephra samples were extracted from specific horizons identified within HFK8 (visually or via MS). In order to discern the origin of the tephra samples, each was cleaned of humic material, sieved (63 µm), mounted, polished and carbon-coated for geochemical analysis. Tephra geochemistry was analysed at the University of Iceland using a JEOL JXA-8230 electron probe micro-analyser (EPMA). The acceleration voltage was 15 kV, the beam current 10 nA, with a beam diameter of 10 µm, except for intermediate or rhyolitic tephra which were set at 5 µm (due to crystallization and thin walls). The standards A99 (for basaltic tephra), ATHO and Lipari Obsidian (both for silicic and intermediate tephra), were measured prior to, and after, the analyses in order to verify consistency in analytical conditions. Data were then inspected for, and cleaned of, anomalies and analyses with sums < 96% and > 101%.

While the uppermost sedimentary layers of HFK8 are ostensibly recent (2019/2020), the interface with the water column is ambiguous (Moore et al., 1991). Therefore, in order to secure a more reliable date, the top ten centimetres (0-10 cm) of the core were sampled for plutonium ($^{239+240}$Pu) as derived from nuclear weapons testing in 1963/1964 (Ketterer et al., 2002). These samples were subjected to Inductively Coupled Plasma Mass Spectrometry (ICPMS) analysis performed using a Thermo X2 quadrupole ICPMS system at the Northern Arizona University, procedures adapted from Ketterer et al. (2004).

The HFK8 age/depth model was developed with the Bacon package (v. 2.5.0; Blaauw & Christen, 2011) using the IntCal20 dataset (Reimer et al., 2020). The plot was created in RStudio (R version 3.3.3; R Core Team 2021). The age-depth model was constructed using the mean accumulation rates (acc. mean) of 20 yr/cm and thick-value of 3.

Palynology

A total of 40 samples were extracted between the depths of 103.5 cm and 35.5 cm with sample resolution concentrated at depths thought to encapsulate the monastic period (c. 63.5-35.5 cm). The volumes of the HFK8 samples (2 cm^3 per sample) were determined by displacement in 10% HCL (Bonny, 1972) with one *Lycopodium clavatum* tablet (Batch nos. 124961 and 50220211) added per sample (Stockmarr, 1971) to determine pollen concentration (grains 1 cm^{-3}). Samples were rinsed in 10% HCL to remove residual glue from the control tablet, 10% NaOH to break down humic material, and sieved (through a 150 µm mesh) to remove coarse material (Moore et al., 1991). Minerogenic material was removed by dense media separation using LST Fastfloat, density 1.9-1.915 g/ml (Björck et al., 1978; Nakagawa et al., 1998). Pollen grains were separated from other organic material via acetolysis before being slide-mounted with silicone oil (viscosity of 12,500 cSt.) and counted with a microscope at 400× to 1,000× magnification (Moore et al., 1991).

Pollen identification relied upon Moore et al. (1991) with pollen and spore taxonomy adapted to the Icelandic context (Erlendsson, 2007). Plant nomenclature follows Kristinsson (1986). Three hundred native land pollen grains were counted per sample (total land pollen; TLP) with high chronological resolution favoured over large counts per sample. The determination of the relative proportions of pollen and spore taxa within the sample is based upon pollen percentage data, TLP underpinning the base sum (Birks & Birks, 1980). As a result, the percentages for some aquatics and non-pollen palynomorphs (NPP) can exceed 100%. Therefore, concentration data are used to supplement interpretation. Recorded NPP comprise of microscopic charcoal (Patterson III et al., 1987), and coprophilous fungal spores

(CFS). Charcoal and CFS (e.g. *Podaspora HdV-368, Sordaria HdV 55A* and *Sporormiella HDV-113*) are considered environmental proxies for human activity in Iceland, the latter, indicative of livestock (Edwards et al., 2011). CFS identification follows Cugny et al. (2010) and van Geel et al. (2003). All Poaceae pollen grains were evaluated as potential cereal-type pollen i.e. mean grain diameter ≥37 µm, annulus diameter ≥8 µm (Andersen, 1979). All *Betula* (birch) pollen grains were measured in order to distinguish between *B. nana* and *B. pubescens*. Following Karlsdóttir (2014), the mean size of *B. nana* pollen grains is 20.4 µm while that of *B. pubescens* is 24.2 µm. This differentiation can be used to separate dwarf birch heathland from birch woodland (Caseldine, 2001; Erlendsson & Edwards, 2009; Mäkelä, 1996). Non-triporate *Betula* pollen is separated from *Betula* as an indicator of hybridisation between *B. nana* and *B. pubescens* (Karlsdóttir, 2014).

Pollen data and NPP count data were entered into TILIA (version 2.0.41) and subjected to a total sum of squares analysis (CONISS), producing a stratigraphically constrained dendrogram (Grimm, 2011). Visual evaluation of the dendrograms allowed data to be divided into Pollen Zones (PZ). In order to better understand the nature of the relationship between PZ's, ordination analysis was applied to HFK8 via the package vegan in R (Oksanen et al., 2016). Detrended Correspondence Analysis (DCA) revealed a linear response of 0.78 on the first axis (Hill & Gauch, 1980). Therefore, Principal Component Analysis (PCA) was performed on Hellinger-transformed data incorporating terrestrial pollen and spore taxa with abundances ≥1%.

Results

Sedimentology

The sediments of Helgafellsvatn HFK8 (Table 2) comprise of a pseudo-fibrous or amorphous, silty gyttja, unless interrupted by a specific influx of material e.g. tephra, wood. SAR prior to the deposition of the LTL is 0.04 cm per annum, 0.7 cm per annum afterwards. With regard to the physical properties of the sediments (Fig. 3), the following interpretation utilises the same zonation as that identified via CONISS for the pollen data (HFK8-I to HFK8-V).

Table 2. Sediment description for HFK8.

Depth (cm)	Troels-Smith	Munsell	Note
0-33	Sh^3 Th$^+$ Ag$^+$	10YR 4/3 (brown)	Live roots present
33-33.5	Sh^4 Ag$^+$	10YR 4/3 (brown)	Tephra (unknown)
33.5-50	Sh^4 Ag$^+$	10YR 4/3 (brown)	Tephra (unknown)
50-77.5	Sh^4 Ag$^+$	10YR 4/4 (dark yellowish brown)	
77.5-78.5	Tl^{3}Ga^1	10YR 5/4 (yellowish brown)	Veiðivötn/Torfajökull (LTL) AD 877 & wood fragments.
78.5-79.5	Tl^3 Sh^1 Ag$^+$	10YR 2/1 (black)	Wood fragments.
79.5-105.5	Sh^4 Ag$^+$	10YR 4/4 (dark yellowish brown)	
105.5-106.3	Gs	2.5Y 7.4 (pale brown)	Snæfellsjökull (Sn-1) AD 170
106.3-110	Sh^4 Ag$^+$	10YR 4/3 (brown)	

For HFK8-I (104.5-93.5 cm), OM (≤ 35%) increases following the deposition of the Sn-1 tephra with a corresponding decline in DBD (≤0.18 g/m^3). MS follows DBD but suggests that there may have been some disruption. Within HFK8-II (93.5-76 cm), there is an increase in OM (37.6% on average) between 88.5 cm until 80.5 cm with a peak of 39.4% at 82.5 cm. In contrast, DBD is relatively stable (≤0.10 g/m^3), while MS declines to become negligible. Of further note are wood fragments (up to 2.5 cm long and 8 mm broad) and bark flakes (≤8 mm) found in sediments within and just below the LTL (between 79.5-77.5 cm) raising the OM to

62.6% at 79.5 cm; the OM signal of the wood within the LTL itself (7.4%, 78.5 cm) is suppressed due to the overriding minerogenic content of the tephra deposit.

After the deposition of the LTL, OM falls to below half that of the earlier sediments (on average 14%), associated with influxes of minerogenic material which persist into HFK8-III (76-61 cm). These might account for an increase in SAR, but OM recovers from 71 cm (on average 22.3%). The increasing trend in OM is sustained into HFK8-IV (27.1% on average), MS values are erratic, and DBD (range 0.22 to 0.09 g/m^3) is in decline. The only interruption to this trend arises at 46.5 cm with a possible eruption/erosion event (only detectable via the sediment properties in Fig. 3 rather than being visible to the naked eye; Table 2). The period that follows (HFK8-V, 61-44.5 cm) is stable with regard to MS and DBD with OM 40.4% on average and peaking at 44.6% at 36.5 cm (greater than for HFK8-I and II). HFK8-V (44.5-35.5 cm) terminates upon the deposition of minerogenic material at 35.5cm derived either from an eruption or erosion.

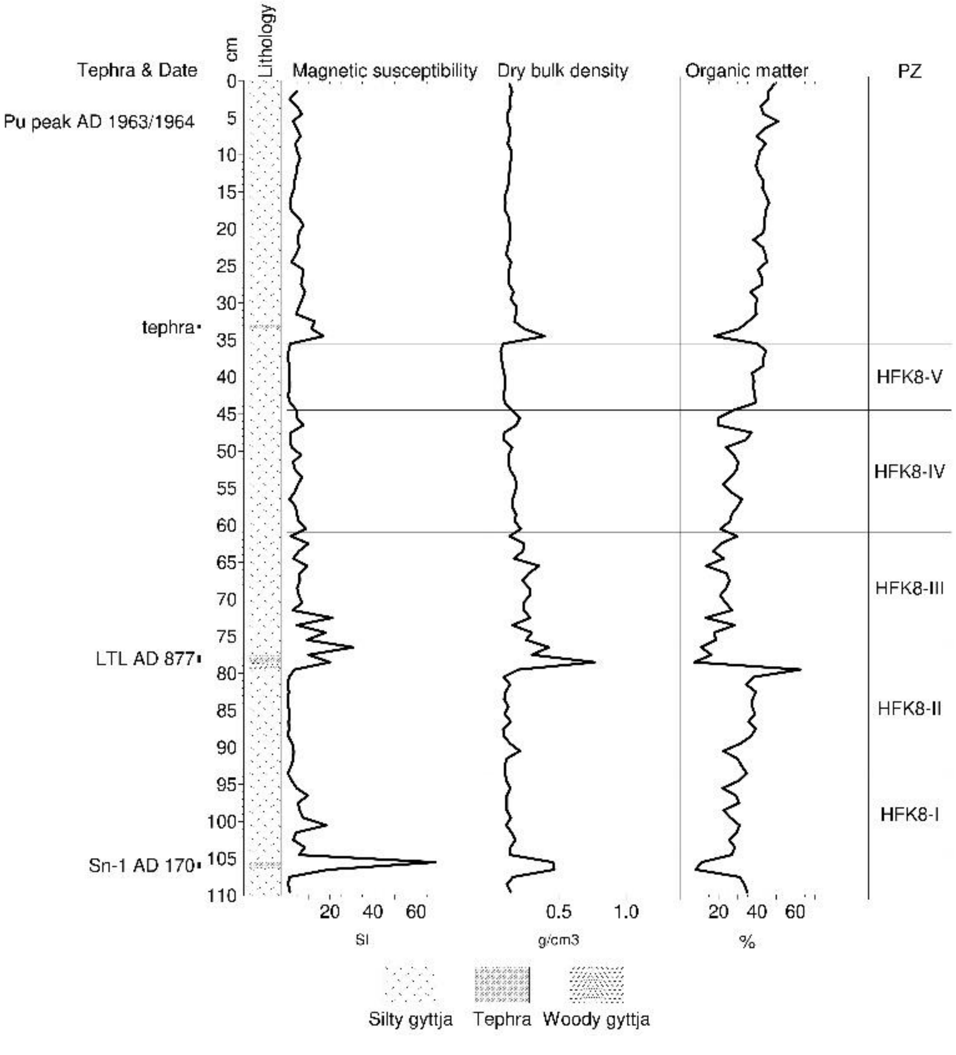


Fig. 3 Sedimentary properties for HFK8.

Age determination

The age/depth model for HFK8 (Fig. 4) was constructed with reference to known tephra layers and Pu isotopes. Two visible horizons containing a high concentration of tephra were identified and sampled for HFK8 at 105-106 cm and 77.5-78.5 cm (Table 2). Their presence is further reflected in corresponding peaks in MS and DBD (Fig. 3). These two tephra horizons geochemically correlate with the Snæfellsjökull (Sn-1) AD 170$^{+/-45}$ (based upon ^{14}C; Kristjánsdóttir et al., 2007; Larsen et al., 2002) and the Veiðivötn/Torfajökull (LTL) AD 877 (Larsen et al., 1999; Meara et al., 2020; Schmid et al., 2017) eruptions respectively (Table 3). An additional sample at 33-34 cm was analysed based upon sediment properties (Fig. 3; MS, DBD and OM). The analysis of this concentration of minerogenic material resulted in a heterogeneous mix of geochemistry that was impossible to attribute to any known eruption. Bulk density Pu concentrations suggest that the upper 5.5 cm represent the post peak fall out from nuclear weapons testing and confirm the assumption that the they are post 1950 (Ketterer et al. 2004). The absence of an intermediary date between the LTL AD 877 and the Pu concentrations limits the refinement of the chronological sequence for HFK8 III, IV and V.

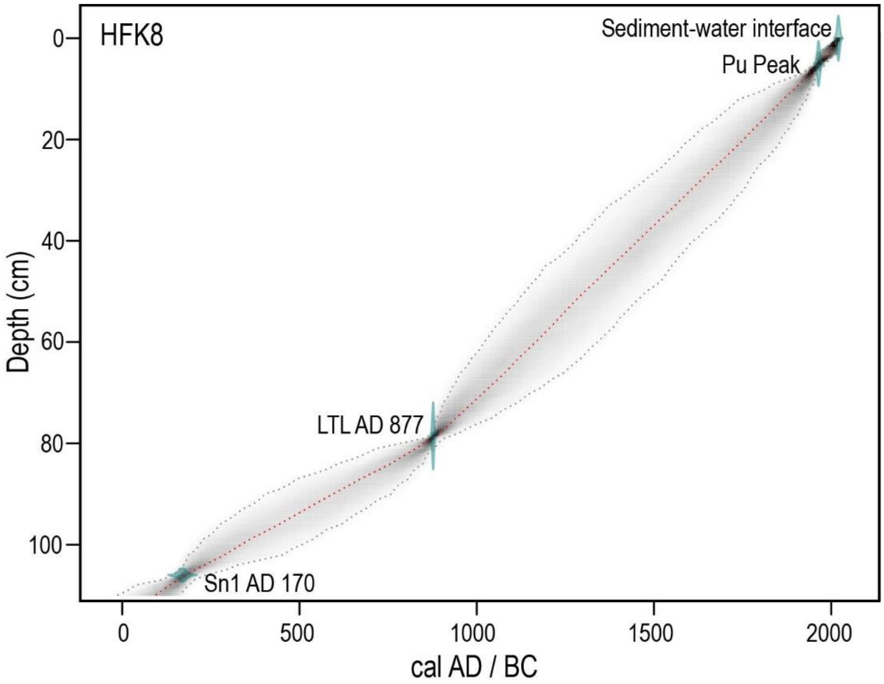


Fig. 4 Age-depth model for HFK8

Table 3. Non-normalized mean major element values for HFK8 tephra samples. The number of analyzed shards shown in parentheses. M refers to mean while SD refers to standard deviation. All analysis was conducted at the Institute of Earth Science, University of Iceland. Superscripts refer to reference data in lower section of table.

SAMPLE		**SiO_2**	**TiO_2**	**Al_2O_3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**	**Total**
HFK8_77b (18)	M	48,89	2,54	13,47	13,30	0,23	6,02	10,82	2,66	0,38	0,28	98,59
	SD	1,13	1,21	0,40	0,82	0,02	0,78	0,88	0,36	0,27	0,18	0,55
HFK8_77r (10)	M	70,02	0,27	14,75	2,51	0,08	0,23	0,93	5,38	4,48	0,04	98,70
	SD	1,54	0,08	0,42	0,74	0,05	0,05	0,38	0,26	0,25	0,02	0,47
HFK8_105 (13)	M	66,10	0,45	16,05	4,51	0,19	0,35	1,97	5,67	4,01	0,06	99,35
	SD	0,74	0,04	0,20	0,28	0,02	0,07	0,17	0,20	0,14	0,03	0,44
HFK8_141 (13)	M	48,15	2,76	14,35	11,13	0,20	6,00	11,61	2,93	1,19	0,47	98,79
	SD	0,28	0,22	0,30	0,63	0,02	0,37	0,50	0,21	0,13	0,04	0,46
Ldm 877b (7) [1]	M	49,27	1,83	13,73	12,19	0,23	6,85	11,55	2,36	0,21	-	98,22
	SD	0,62	0,11	0,12	0,53	0,02	0,42	0,40	0,09	0,05	-	0,52
Ldm 877r (12) [1]	M	70,97	0,24	14,43	2,31	0,09	0,24	0,89	4,83	4,66	-	98,66
	SD	0,80	0,05	0,32	0,11	0,04	0,03	0,06	0,25	0,13	-	1,06
Ldm 877b (7) [2]	M	46,65	2,61	15,79	13,03	0,21	7,45	10,95	2,65	0,41	0,24	97,60
	SD	0,40	0,10	0,25	0,27	0,01	0,09	0,08	0,06	0,03	0,01	0,50
Ldm 877r (10) [2]	M	71,78	0,26	14,35	2,36	0,07	0,24	0,87	5,28	4,75	0,03	98,39
	SD	0,25	0,02	0,20	0,15	0,01	0,02	0,04	0,12	0,13	0,01	0,62
Sn1 170 (6) [3]	M	67.27	0.38	15.69	4.08	-	0.33	1.72	5.07	4.36	-	98.96
	SD	1.21	0.04	0.37	0.40	-	0.12	0.35	0.19	0.23	-	0.67
Sn1 170 (8) [4]	M	71.1	0.25	14.5	3.12	-	0.09	1.16	5.14	4.54	-	97.16
	SD	1.20	0.03	0.36	0.17	-	0.01	0.05	1.13	0.21	-	0.66

[1] Larsen et al. 1999; [2] Meara et al. 2020; [3] Larsen et al. 2002; [4] Kristjánsdóttir et al. 2007

Palynology

Pollen diagrams (Figs. 5, 6, 7 & 8) are divided into five PZ's based on CONISS (HFK8-I to HFK8-V) with the following interpretation based upon TLP, pollen percentages, and pollen concentration. The main characteristics of each pollen zone are summarised in Table 4. *Betula* pollen grains sizes are given in Fig. 9.

HFK8-I (104.5-93.5 cm, c. AD 212-507)

In reference to Fig. 5, from 103.5 cm *Betula* is ≤49.2% TLP, primarily *B. nana* according to pollen grain size (Fig. 8; $21^{+/-2}$ µm). *Salix* (willow; ≤5% TLP), *Juniperus* (juniper; ≤1% TLP), *Vaccinium*-type (blueberry; ≤2% TLP) and *E. nigrum* (≤1.7% TLP) are present, with *Salix* decreasing. Both Cyperaceae and Poaceae are present (≤21% and ≤18.5% TLP respectively). Other taxa include *Angelica archangelica* (garden angelica; ≤1% TLP), *Angelica sylvestris* (wild angelica; ≤1.7% TLP), *R. acris*-type (≤0.3% TLP), *C. palustris* (≤1% TLP), *Geum rivale* (water avens; ≤3% TLP), *H. vulgaris* (≤2.7% TLP), *R. acetosa* (≤1.7% TLP), *Thalictrum alpinum* (alpine meadow rue; ≤2% TLP) and *Oxyria*-type (e.g. mountain sorrel; ≤0.7% TLP). *Sordaria* HdV 55A and *Sporormiella* HDV-113 are present (Fig. 7; ≤124 grains 1 cm^{-3}).

HFK8-II (93.5-76 cm, c. AD 507-920)

With reference to Fig. 5, from 93.5 cm, *Betula* values are consistently above 50% TLP with a peak of 57.4% (79.5 cm). *Betula* pollen grain size is $23^{+/-2}$ µm (Fig. 9) inferring *B. pubescens*. Non-triporate *Betula* are 1.1% TLP on average. *Betula* pollen concentration doubles (Fig. 7; ≤11100 grains 1 cm^{-3}) with a similar increase in non-triporate *Betula* pollen (Fig. 6; ≤335 grains 1 cm^{-3}). A slight increase can be seen for *Juniperus* (Fig. 4; ≤1.8% TLP), more visible with regard to pollen concentration (Fig. 7; ≤343 grains 1 cm^{-3}). *E. nigrum* is stable (Fig. 5; ≤1.7% TLP) while *Vaccinium*-type (Fig. 5; ≤2.3% TLP) and Ericales (Fig. 5; ≤1.6% TLP) are slightly raised. Overall, *Vaccinium*-type is dominant among these shrub taxa. Cyperaceae and Poaceae are lower (Fig. 5; 18.6% TLP on average and ≤14% TLP respectively). *Salix* (Fig. 5; 1.6% TLP on average) is also reduced. Pollen concentration (Figs. 7 & 8) is raised for all species and taxa (including aquatics, and especially *Isoëtes*) from 87.5 to 79.5 cm. The CFS (Fig. 6) *Podaspora* HdV-368, *Sordaria* HdV 55A and *Sporormiella* HDV-113 are present. Traces of charcoal are present (Fig. 8; ≤56 grains 1 cm^{-3}) prior to a substantial change in presence from 76.5 cm (Fig. 8; ≤4675 grains 1 cm^{-3}).

HFK8-III (76-61 cm, c. AD 920-1144)

With reference to Fig. 5, *Betula* drops to 43.3% TLP (on average, recovering to ≤56.7% TLP) with *Betula* pollen grain size reduced to 21$^{+/-1}$ µm (Fig. 9). *Juniperus* (≤0.3 % TLP), *Salix* (1.3% TLP on average), and *Vaccinium*-type (1.7% TLP on average) are in decline. *E. nigrum* remains constant (1.7% TLP on average). Cyperaceae (23.8% TLP on average) and Poaceae (18.8% TLP on average) increase. A number of taxa also appear in the pollen record for the first time e.g. *Anthemis*-type (e.g. yarrow/sneezewort; 75.5 cm), *Artemisia*-type (mugwort/wormwood; 75.5 cm), *Carum carvi* (caraway; 62.5 cm), *Chelidonium majus* (greater celandine; 69.5 cm), *Plantago lanceolata* (ribwort plantain; 62.5 cm), *Polygonum aviculare* (common knotgrass; 62.5 cm) and *R. acetosella* (75.5 cm, ≤2% TLP). Increased values and/or greater consistency regarding presence applies to Lactuceae (≤2.6% TLP), *Plantago maritima* (sea plantain; ≤0.6% TLP), and *T. alpinum* (≤2.7% TLP). In the aquatic environment, following a previous collapse in concentration values, *M. alterniflorum* recovers to 12899 grains 1 cm^{-3} (Fig. 7; 62.5 cm). *Isoëtes* (quillwort) experiences a declining trend from 71.5 cm (Figs. 6 & 8). Of the cryptograms (Figs. 6 & 8), the occurrence of both *Sphagnum* and Pteropsida (mono) indet. (ferns) is stronger. CFS (*Podaspora* HdV-368, *Sordaria* HdV 55A and *Sporormiella* HDV-113) values rise (Fig. 8; ≤583 grains 1 cm^{-3}) and are more consistent. Charcoal is present (Fig. 8; ≤6261 grains 1 cm^{-3}).

HFK8-IV (61-44.5 cm, c. AD 1144-1407)

With reference to Fig. 5, *Betula* rises to ≤55.3% TLP (51.5 cm), with a decreasing trend toward 44.5 cm. *Betula* pollen grain size is 22$^{+/-1}$ µm (Fig. 9). *Vaccinium*-type continues to decline (1.3% TLP on average) while *E. nigrum* increases (2.7% TLP on average). Similarly, Cyperaceae (20% TLP on average) has declined while Poaceae (19.4% TLP on average) has increased marginally. *Hordeum*-type (barley) arises at 55.5 cm and 49.5 cm. *Anthemis*-type and *Artemisia*-type (57.5 cm) recur. *R. acetosella* (≤2.9% TLP) increases while *P. maritima* (≤0.9% TLP) values can be more than double than previously. In the aquatic environment, there is an increase in pollen concentration for both *M. alterniflorum* (Fig. 7; ≤21099 grains 1 cm^{-3}, 50.5 cm) and *Myriophyllum spicatum* (spiked water-milfoil; Fig. 7; ≤341 grains 1 cm^{-3}, 57.5 cm). CFS persist (*Sordaria* HdV 55A and *Sporormiella* HDV-113) and the signal for *Podaspora* HdV-368 is stronger (Fig. 8; ≤135 grains 1 cm^{-3}). Charcoal is present, on average 1487 grains 1 cm^{-3} (Fig. 8).

HFK8-V (44.5-35.5 cm, c. AD 1407-1524)

With reference to Fig. 5, *Betula* drops to below 40% TLP (33.2% on average), *Betula* pollen grain size is 22$^{+/-2}$ µm (Fig. 9). *E. nigrum* remains relatively stable (2.6% TLP on average) with a slight increase in *Vaccinium*-type (1.7% TLP on average). Values for Poaceae (≤28.1% TLP) and Cyperaceae (≤29% TLP) increase, with the former more dominant overall (26.7% TLP on average compared with 22.2% TLP). New herbaceous taxa include *Gentianella*-type (Gentian), *Montia fontana* (water blinks), *Rhinanthus*-type (e.g yellow rattle) and *Sinapis*-type (mustard). The values for *R. acetosella* (≤2.6% TLP) and *T. alpinum* (≤3.9% TLP) decrease slightly while Caryophyllaceae (pinks family; ≤1.3% TLP) flourishes. Similarly, with regard to the wetland context, the signal of *G. rivale* appears more regularly (≤1.3% TLP). In the lake, *M. alterniflorum* pollen concentration is reduced (Fig. 7; ≤10116 grains 1 cm^{-3}). CFS (*Podaspora* HdV-368, *Sordaria* HdV 55A and *Sporormiella* HDV-113) are more consistently represented, with an all-time peak (Fig. 8; ≤545 grains 1 cm^{-3}) at 40.5 cm. Charcoal is present, on average 1259 grains 1 cm^{-3} (Fig. 8).

Table 4. The main characteristics of the pollen zones for HFK8.

HFK8	**Depth (cm)**	**Age* (AD)**	**Characteristic and advancing taxa from the previous zone.**	**Main retreating taxa from the previous zone.**
V	44.5-35.5	1407-1524	Poaceae, Cyperaceae, Caryophyllaceae, *G. rivale*, CFS	*Betula, M. alterniflorum*
IV	61-44.5	1144-1407	Poaceae, *P. maritima, R. acetosella, E. nigrum, M. alterniflorum, M. spicatum,*	*Betula, Vaccinium*-type
III	76-61	920-1144	Cyperaceae, Poaceae, Lactuceae, *P. lanceolata, P. maritima, P. aviculare, R. acetosella, T. alpinum,* Pteropsida (mono) indet., *M. alterniflorum,* CFS, Charcoal	*Betula, Juniperus, Salix, Vaccinium, Isoëtes*
II	93.5-76	507-920	*Betula, Juniperus, Vaccinium*	*Salix*, Poaceae
I	104-93.5	212-507	*Betula*, Cyperaceae	N/a

* approximate dates

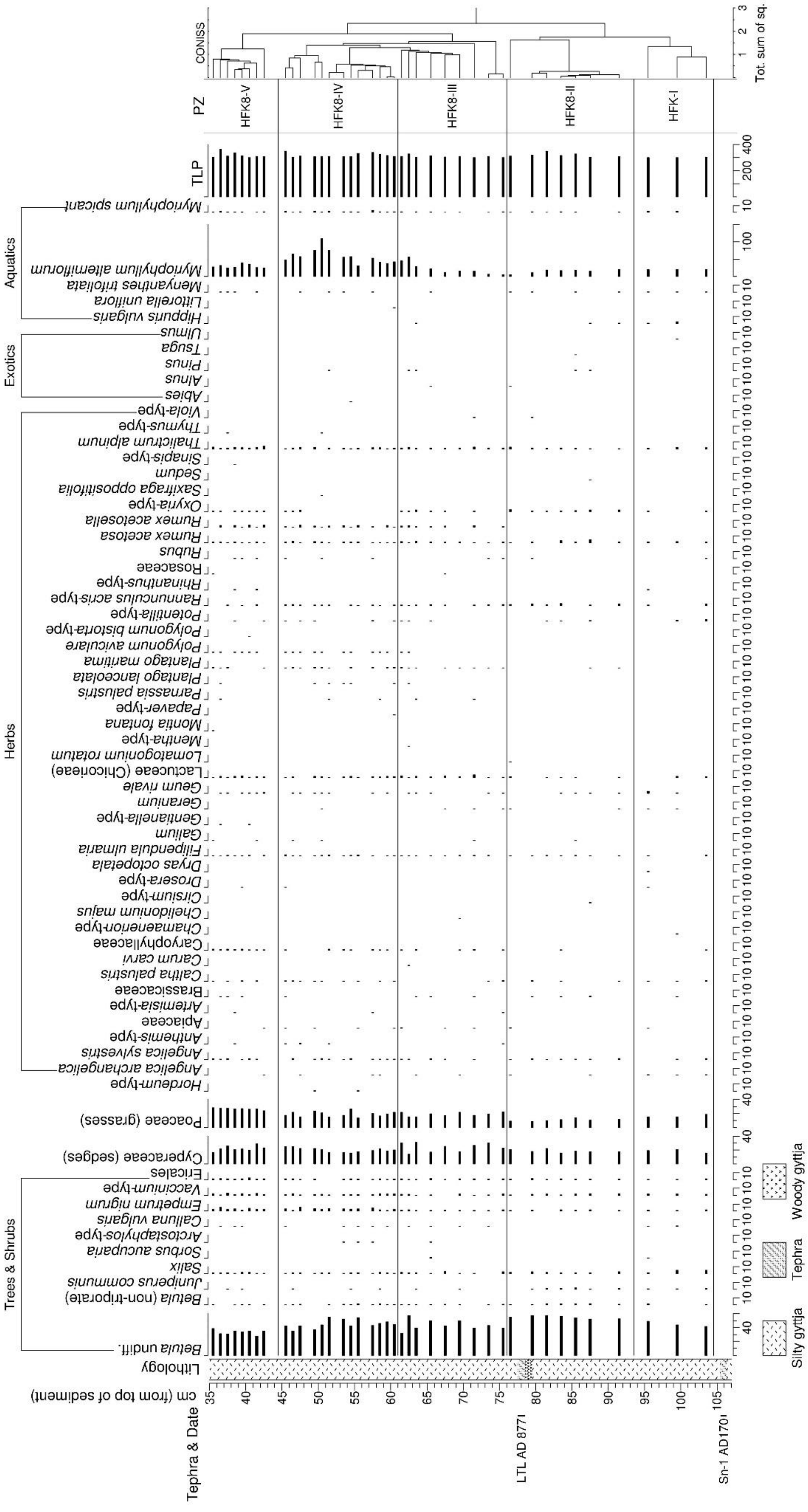


Fig. 5 Pollen percentage diagram for HFK8

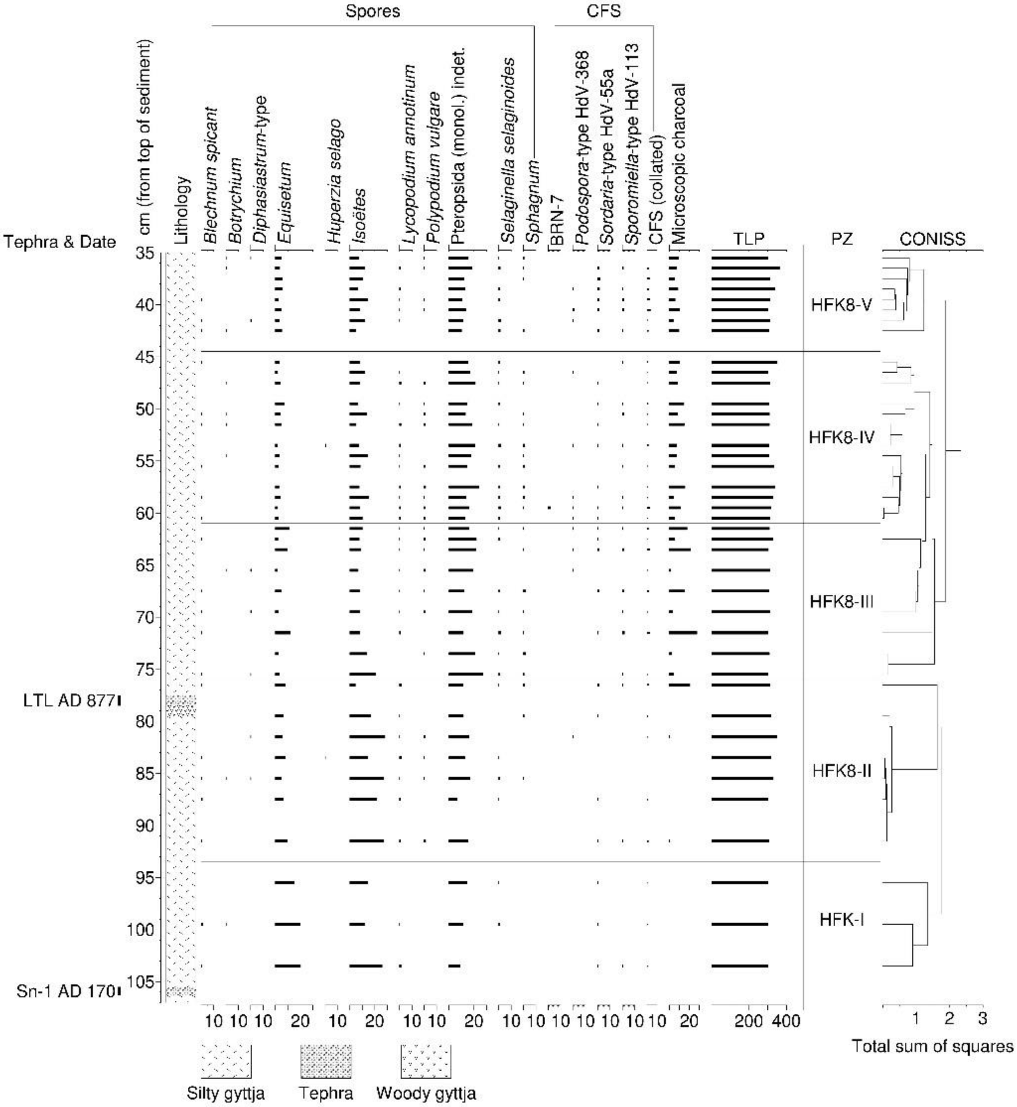


Fig. 6 Spore and NPP percentage diagram for HFK8.

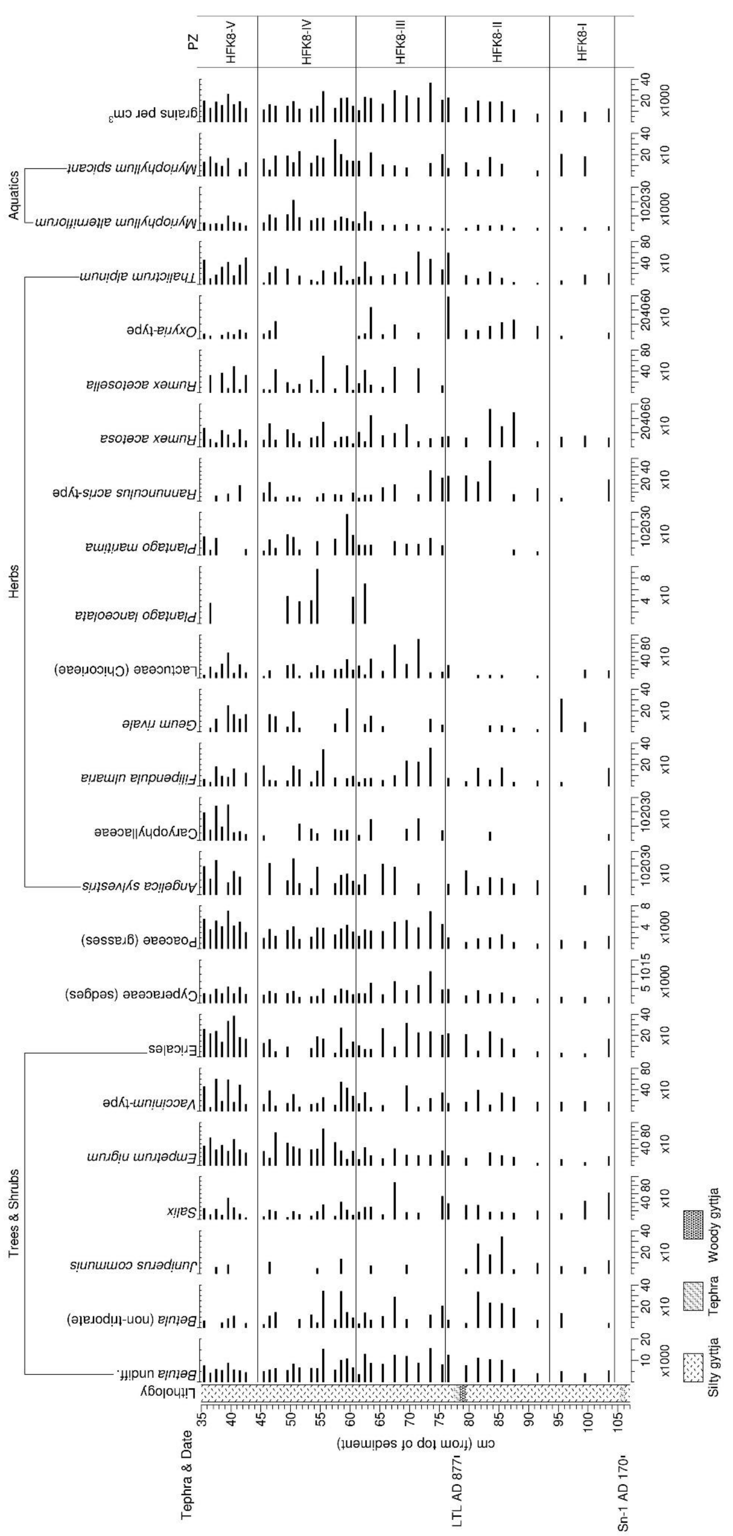


Fig. 7 Pollen concentration diagram for HFK8, taxa and species ≥10% TLP.

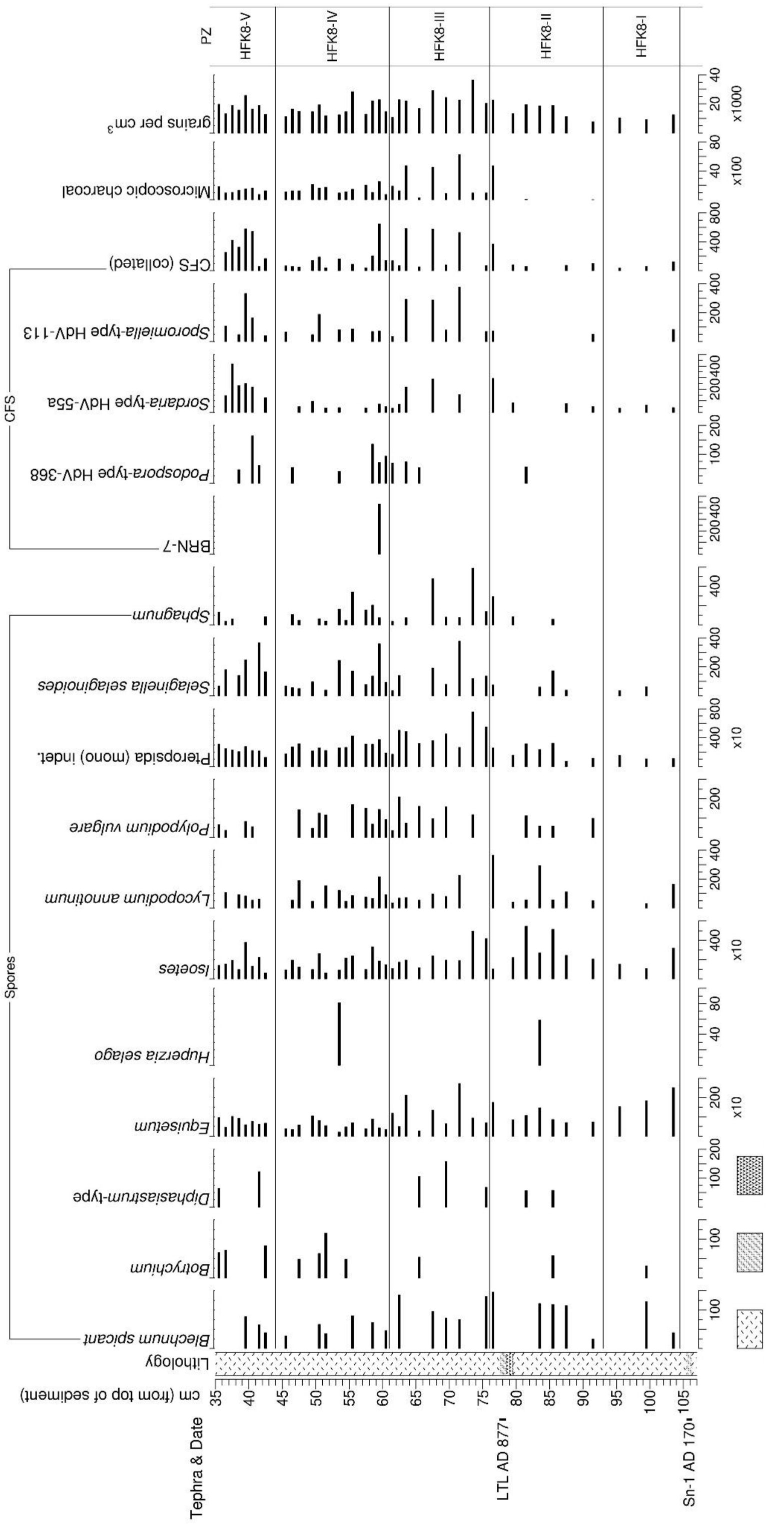


Fig. 8 Spore and NPP concentration diagram for HFK8

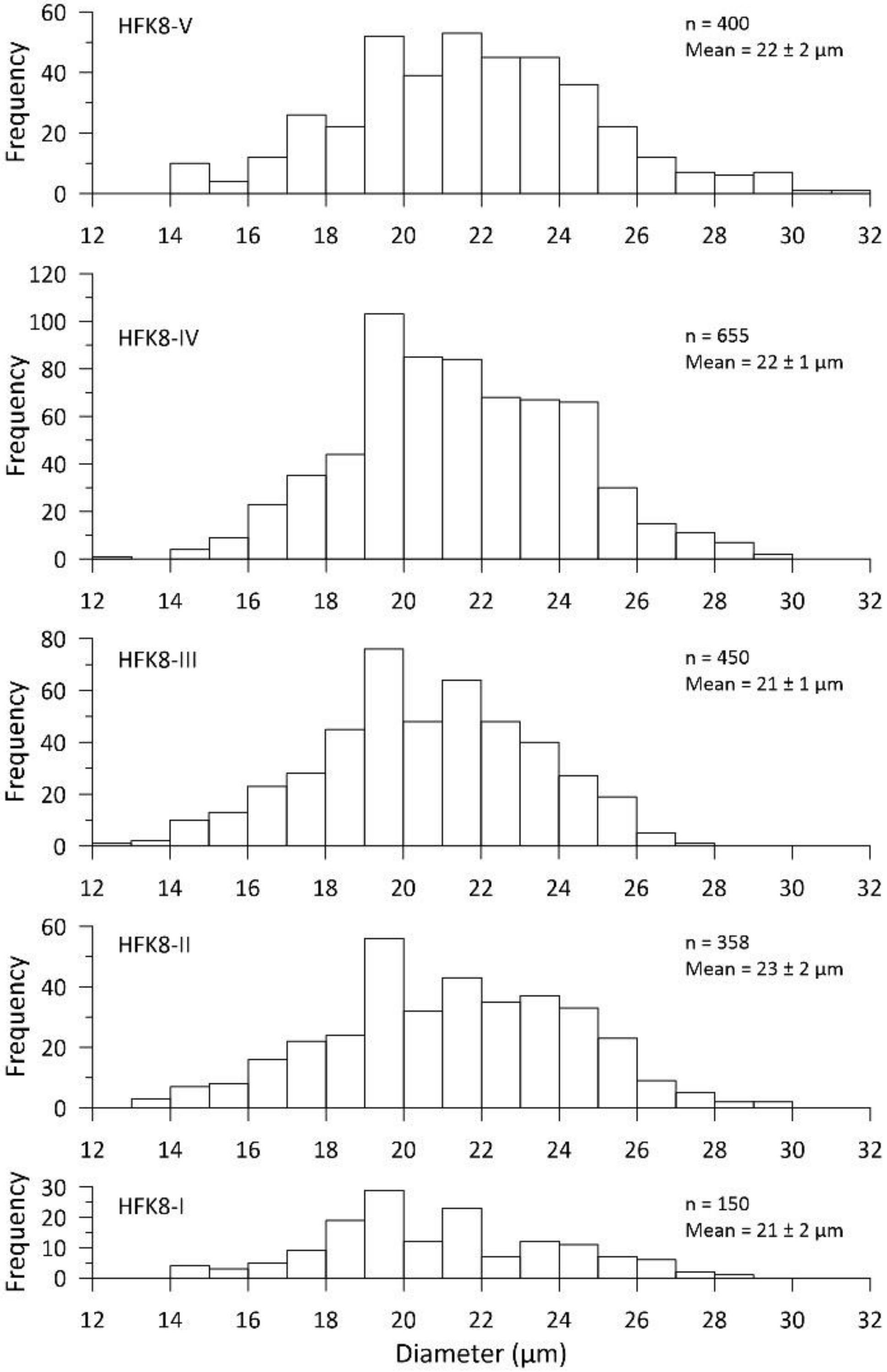


Fig. 9 Measured diameters (µm) of *Betula* pollen grains for HFK8-I to HFK8-V.

Ordination analysis

With reference to Fig. 10, the first axis accounts for 34.85% of variance while the second axis accounts for 11.43%. With regard to the pre-Landnám context, the expansion of *Betula* is quite clear between HFK8-I and HFK8-II. Similarly, there is an obvious division between the pre-Landnám (HFK8-I and HFK8-II) and post-Landnám (HFK8-III to HFK8-V) PZ's with the former comprised of grazing sensitive taxa e.g. *A. sylvestris*, *F. ulmaria*, *Juniperus*, *Salix*, *Vaccinium*-type etc. The post-Landnám vegetation embodies the progressive evolution of a more open landscape at Helgafell and HFK-III harbours characteristics that span both the later PZ's of HFK8-IV and HFK8-V, probably because the expansion in Poaceae and Cyperaceae generally keep apace post-Landnám. The evolution of HFK8-III into HFK8-IV is driven by the increasing presence of apophytes such as *P. maritima*, *P. aviculare*, *R. acetosella* and *S. selaginoides* with *E. nigrum*. The pastoral landscape culminates in HFK8-V with Poaceae, Cyperaceae, Caryophyllaceae and Lactuceae (dandelions and hawkweeds) in association with CFS.

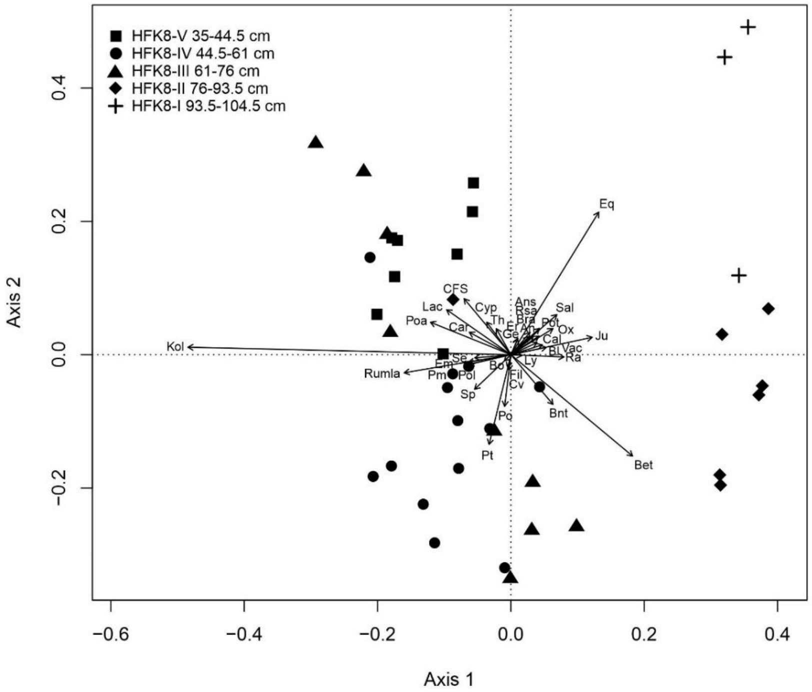


Fig. 10 Principal Component Analysis for HFK8. Note that only taxa with a TLP ≥1% are represented; An (*A. archangelica*), Ans (*A. sylvestris*), Bet (*Betula*), Bnt (non-triporate *Betula*), Bl (*Blechnum spicant;* hard fern), Bo (*Botrychium*; moonwort), Bra (*Brassicaceae*; crucifers), Cal (*C. palustris*), Car (Caryophyllaceae), CFS (coprophilous fungal spores), Cyp (Cyperaceae), Cv (*Calluna vulgaris*), Em (*E. nigrum*), Eq (*Equisetum*), Er (Ericales), Fil (*F. ulmaria*), Ge (*G. rivale*), Ju (*Juniperus*), Kol (microscopic charcoal), Lac (Lactuceae), Ly (*Lycopodium annotinum*), Ox (*Oxyria*-type), Pm (*P. maritima*), Po (*Polypodium vulgare*; common polypody), Poa (Poaceae), Pol (*P. aviculare*), Pot (*Potentilla*-type e.g. *P. palustris*), Pt (Pteropsida (monol.) indet.), Ra (*Ranunculus acris*-type), Rsa (*R. Acetosa*), Rumla (*R. acetosella*), Sal (*Salix*), Se (*S. selaginoides*), Sp (*Sphagnum*), Th (*T. alpinum*), Vac (*Vaccinium*-type).

Discussion

The pre-Landnám vegetation of Helgafell (HFK8-I, 104.5-93.5 cm, c. AD 212-507)

For HFK8-I, outwith the residual impact of the Sn-1 tephra, OM within the lake increased (Fig. 3; ≤35%). *Betula* is prominent in the pollen assemblage (Fig. 5; 40-50% TLP) and as evidence of hybridisation, non-triporate *Betula* (Fig. 5; ≤1% TLP) pollen asserts that both *B. pubescens* and *B. nana* were present at Helgafell (Karlsdóttir et al., 2007). With an average *Betula* pollen grain size of $21^{+/-2}$ µm (Fig. 9), *B. nana* is more prominent although this lies on the cusp of the size distinction between the two *Betula* species (Karlsdóttir, 2014). Cyperaceae (Fig. 5; ≤21% TLP) in association with, *C. palustris*, *G. rivale*, *M. trifoliata* and *H. vulgaris* suggest wetland was also present, while Poaceae (Fig. 5; ≤18.5% TLP) with *R. acetosa* and *T. alpinum* identify grassland (Kristinsson, 1986). Heathland shrubs e.g. *Vaccinium*-type and *E. nigrum*, as well as *Juniperus* are poorly represented, perhaps due to competition from *Betula*.

The incidence of CFS (Fig. 8; ≤124 grains 1 cm^{-3}) in the pre-Landnám (AD 877) sediments of Helgafellsvatn could be associated with wild birds (Eddudóttir et al., 2015). Both *Sordaria HdV 55A* and *Sporormiella HDV-113* have been identified as present in the dung of Ptarmigan (*Lagopus muta*) in Iceland while *Sporormiella HDV-113* has been identified in the faeces of a number of other bird species (Hallgrímsson & Eyjólfsdóttir, 2004); in this case perhaps wildfowl roosting and feeding on Helgafellsvatn.

A climate amelioration (HFK8-II, 93.5-79.5 cm, c. AD 507-873)

From c. AD 560 (91.5 cm), *Betula* became even more prominant (Fig. 5; ≥50%) with a peak of 57.4% c. AD 873 (79.5 cm). Note that the timing of the rise in *Betula* is nuanced; *Betula* pollen concentration from 85.5 cm (Fig. 7; 10118 grains 1 cm^{-3}) is almost double that of what came before. On the face of it, there is little change in values for non-triporate *Betula* (Fig. 5; ≤1.1% TLP on average), however it also experiences an increase in pollen concentration values (Fig. 7; ≤335 grains 1 cm^{-3}). *Betula* pollen grain size ($23^{+/-2}$ µm) indicates that *B. pubescens* is now present (Fig. 9). Increased pollen concentration of non-triporate *Betula*, accompanied by the altered values for *Betula* grain size, infer increased hybridisation between *B. pubescens* and *B. nana* and an expansion in *B. pubescens* (Karlsdóttir, 2014).

This *Betula* expansion occurred mostly at the expense of Poaceae (Fig. 5; ≤14% TLP) but also Cyperaceae (Fig. 5; ≤18.6% TLP), the former possibly reflecting the preference of *B. pubescens* for dry ground conditions (Kristinsson, 1986). This is a proclivity shared with *Juniperus* (Thomas et al., 2007) for which values also increase during this period (Fig. 5; ≤1.8% TLP), especially with regard to pollen concentration (Fig. 7; ≤343 grains 1 cm^{-3}). Aside from Poaceae, *Salix* is the only taxon to have declined (Fig. 5; from ≤5% TLP to 1.6% TLP on average), perhaps shaded out by *B. pubescens* and *Juniperus*. Overall, there is a notable increase in pollen concentration (Fig. 7) across almost all pre-settlement terrestrial taxa between c. AD 667 (87.5 cm) and AD 873 (79.5 cm).

Change in the terrestrial vegetation between c. AD 560 and c. AD 873 is paralleled in the aquatic environment of Helgafellsvatn. Pollen concentration (Fig. 8) for the macrophyte *Isoëtes* go from ≤1500 grains 1 cm^{-3} (HFK8-I) to ≤5466 grains 1 cm^{-3} (HFK8-II). These spores can be derived from one of two species (Kristinsson, 1986), either *Isoëtes echinospora* (spring quillwort) or *Isoëtes lacustris* (lake quillwort); most probably the former assuming that Helgafellsvatn was oligotrophic (Langdon et al., 2008). As a species that demands an undisturbed lakebed (Arts, 2002), raised amounts would suggest a degree of environmental stability both within the lake and in its surroundings, perhaps intimating mild temperatures (Mørk et al., 2018; Rundgren, 1995). The increase in biological productivity in aquatic and terrestrial contexts explain the increase in OM in the lake sediments (Fig. 3; 34.8% on average between 93.5 cm and 80.5 cm). As there are no increases in DBD, and as MS is barely registering, the sense of environmental stability is borne out further.

The timing of these changes (c. AD 560-873) i.e. *Betula* expansion, a slight shift toward *B. pubescens* and more hybridisation, increased flowering across taxa (pollen concentration), raised *Isoëtes* values, limited mineral input, and higher organic content, are all consistent with a period of climate amelioration in Iceland c. AD 600-800 (Erlendsson & Edwards, 2009). This interpretation is upheld if we accept that *Betula* hybridisation is a direct consequence of *B. pubescens* displacing *B. nana* during warm periods (Karlsdottir et al., 2009). As a note of caution, *Betula* can be overrepresented in pollen assemblages (Rymer, 1973; Schofield et al., 2007). However, the increased presence with regard to *Juniperus*, a species that is likely underrepresented in the pollen assemblage (Eddudóttir et al., 2015; Schofield et al., 2007), further bears out the assertion that climate conditions at Helgafell were clement at this time.

The Landnám transition and Medieval Helgafell (HFK8-II & III, 79.5-61 cm, c. AD 877-1144)

Archaeological and palaeoecological studies (as well as saga narratives) all suggest that Iceland was initially settled by humankind during the late 9th century (Erlendsson, 2007; Karlsson, 2019; Schmid et al., 2021). At Helgafell, the sudden appearance of high microscopic charcoal values in the sedimentary record from 76.5 cm (Fig. 8; c. AD 913; 4675 grains 1 cm^{-3}) implies a human presence in the landscape (Edwards et al., 2021; Erlendsson, 2007; Riddell et al., 2022b). The manifestation of the charcoal is suggestive of traces of domestic fires rather than conflagrations aimed at land clearance (Church et al., 2007; Smith, 1995) i.e. there are no macrofossil scale charcoal flecks or charcoal layers visible in the strata (Table 2). Traces of microscopic charcoal (Fig. 6) in the pre-settlement context are attributed to windborne material from Europe (Duncan & Bey, 2004), or from vegetation burnt as a consequence of volcanism (Buckland et al., 1995).

OM also falls (10.9%) in association with influxes of minerogenic material (MS $\leq$30.9 SI, DBD $\leq$0.4 gm/^{3}) at 76.5 cm (Fig. 3). However, an interesting feature of the sedimentary record from Helgafellsvatn (Table 2) is the occurrence of macrofossils in the form of twigs and bark concentrated within and just below the LTL (78.5-77.5 cm and 79.5.5-78.5 cm respectively). The latter is associated with a sudden peak in OM at 79.5 cm (Fig. 3; 62%). This (unprecedented) influx of woody detritus into the lake might intimate active land clearance of trees and shrubs by humans c. AD 877. Unfortunately, it is difficult to elucidate this further as there is only a slight downturn in *Betula* values afterwards, CFS values are inconclusive, while the LTL overrides evidence of anything other than its own contribution to the sediments of Helgafellsvatn.

Isoëtes and *M. alterniflorum* values are lower following the deposition of the LTL (Figs. 7 & 8; 76.5 cm, both 1023 grains 1 cm^{-3}). Tephra deposition can inhibit the redistribution of sediments and nutrients within lacustrine environments in Iceland, thereby stymying productivity (Hiles et al., 2021; Lawson et al., 2007). Acknowledging that there were some decades since the Veiðivötn/Torfajökull eruption, the low *Isoëtes* and *M. alterniflorum* values at 76.5 cm could be representative of an initial recovery from the deposition of the LTL. This perhaps emphasises the sensitivity of aquatic vegetation in Iceland to environmental change, and volcanism in particular (Eddudóttir et al., 2015; Eddudóttir et al., 2016; Hiles et al., 2021; Lind et al., 2022).

However, minerogenic influxes (most apparent in the MS, Fig. 3, 76-71 cm) may suggest other vectors of environmental disturbance i.e. introduced livestock. Further evidence of such disturbance might be represented by increased Pteropsida (monol.) indet. values (Fig. 8; $\leq$7552 grains 1 cm^{-3}) from 75.5 cm to 61.5 cm, fossil cryptogram spores released into the lake catchment by the trampling and erosion of terrestrial sediments (Gathorne-Hardy et al., 2009). Increasing OM (Fig. 3; 21.2 % on average from 76 cm) might be the result of the same grazing beasts unlocking nutrients (via dung) into the watershed that were hitherto stored within the vegetation surrounding the lake (Lawson et al. 2006; Lawson et al. 2007; Spierenburg et al. 2009). This release of nutrients into the lake would benefit *M. alterniflorum* (Roelofs et al., 1984), the values of which reach more than double than what was previously recorded from 65.5 cm (Fig. 7; ≥6344 grains 1 cm^{-3}). Conversely, increased nutrient levels are detrimental to *Isoëtes* (Arts, 2002; Hiles et al., 2021; Lawson et al., 2007; Spierenburg et al., 2009) which, despite a recovery after Landnám (Fig. 8; ≤4956 grains 1 cm^{-3}), declines to levels lower than those prior to Landnám (Fig. 8; ≤1068 grains 1 cm^{-3}).

One would expect an increase in the presence of CFS, but values are only marginally greater than those of the pre-Landnám context (Fig. 8; ≤583 grains 1 cm^{-3}). Such limited alteration suggests that there were no domestic animals at Helgafell or that there was a low density of livestock distributed over a large area (Davies, 2019). However, in low energy lacustrine systems such as that of Helgafellsvatn, CFS tend to accumulate within sediments on lake margins (Lee et al., 2022); the HFK8 core was extracted from near the middle of Helgafellsvatn.

With regard to the terrestrial vegetation (Fig. 5), a move toward a pastoral landscape is quite clear in HFK8-III (76-61 cm). *Betula* values are generally lower, 43.3% TLP on average although are able to reach values of 56.7% TLP (Fig. 5: 62.5 cm). Average pollen grain size is reduced to $21^{+/-2}$ µm (Fig. 9), implying that it is *B. nana* rather than *B. pubescens* that is sustained, perhaps a consequence of selective grazing by domestic animals to which *B. nana* is generally unpalatable (Hejcman et al., 2016). This development leaves room for Cyperaceae and Poaceae dominated habitats to expand (Fig. 5; ≤31% TLP and ≤22.3% TLP respectively). Apophytic taxa, i.e. native Icelandic plants that benefit from human activity and the presence of grazing animals (Lactuceae, *P. maritima* and *T. alpinum*), can be seen to have a more consistent presence and/or higher values (Edwards et al., 2021; Erlendsson, 2007; Hallsdóttir, 1987). *Anthemis*-type, *Artemisia*-type and *R. acetosella*, all appear in the pollen record for the first time, all three considered archaeophytes, i.e. plants introduced to Iceland through human agency (Edwards et al., 2021; Erlendsson, 2007; Hallsdóttir, 1987).

The occurrence of single pollen grains of *Artemisia*-type (75.5 cm), *C. majus* (69.5 cm) and *C. carvi* (62.5 cm) are of particular interest given their medicinal and/or culinary applications (Edwards et al., 2011; Zielińska et al., 2018). *Artemisia vulgaris* (mugwort) is also used for dyeing wool (Guinot et al., 2006; Pluenneke, 2017). In terms of context, with reference to Laxdæla Saga, (Sveinsson, 1934; Ch. 60, p. 179):

“Fám nóttum síðar en Guðrún hafði heim komit heimti hún sonu sína til máls við sik í laukagarð sinn”

“A few nights after Guðrún had returned home, she called her sons to speak with her in her kitchen garden” (author translation).

Likely nothing more than a narrative foil, that there was a “laukagarður” (literally onion/leek garden, figuratively a kitchen garden or vegetable plot) at Helgafell was plausible to the medieval Icelandic audience for whom the saga was written. There are also references to laukagarður in the Icelandic historical record e.g. the Bishop of Hólar is said to have died in a laukagarður in AD 1457 (Kristjánsdóttir et al. 2014). Furthermore, there is evidence from southern Scandinavia to show that medicinal plants were grown alongside culinary herbs in medieval kitchen gardens outwith ecclesiastical institutions (Helweg, 2020). Overall, there is no reason to preclude lay folk from the cultivation of medicinal herbs (Gilchrist, 2020), and there are certainly historical accounts of secular healers in Iceland in the medieval period e.g. Hrafn Sveinbjarnarson (Kristjánsdóttir 2023).

The occurrence of exotic tree pollen from Europe and North America (Fig. 5) i.e. *Abies* (fir), *Alnus* (alder), *Pinus* (pine), *Tsuga* (hemlock) and *Ulmus* (elm), in the sediments of Helgafellsvatn is testament to the potential of pollen to reach Iceland from any quarter. This undermines the suggestion that exotic plant species were deliberately introduced to Helgafell, particularly where the utilitarian plants are represented by a single pollen grain. Nonetheless, collectively, it is hard to imagine that the manifestation of these taxa and species at Helgafell is down to mere coincidence. Moreover, *C. majus* and *C. carvi* are entomophilous, i.e. they depend upon insects rather than wind (anemophilous) with regard to pollen dispersal. Plants that rely upon insects for pollen dispersal tend to produce less pollen than those that count upon the wind (Bakels, 2020; Moore et al., 1991) and in general, do not circulate their pollen as far afield due to large pollen grain size (Hjelle, 1997). Such factors therefore, reduce the chance that entomophilous pollen grains arrived in Iceland by accident.

In AD 1181 the church of Helgafell burned to the ground and the farm was abandoned. With reference to microscopic charcoal (Figs. 6 & 8), there are no exceptional peaks in the data that might be indicative of this event and nor are there any visible charcoal macrofossils in the core (Table 2).

Helgafellsklaustur (HFK8-IV, 61-44.5 cm, c. AD 1144-1407)

HFK8-IV encompasses the first 250 years of Helgafellsklaustur (late 12th century to the early 15th century) and within it, a further transition in environmental and ecological conditions. The sediments of Helgafellsvatn (Fig. 3) suggest ongoing stability in the surrounding environment as OM continues to rise (27.1% on average) while DBD returns to pre-Landnám levels (range 0.22 to 0.09 g/m^3). Even so, MS is higher than pre-Landnám levels, a hint that reworked sediments might occasionally wash into the lake e.g. at 53. 5 cm and 50.5 cm.

Increased OM may be a consequence of developments in the aquatic environment as amounts for *M. alterniflorum* (and to a lesser degree *M. spicatum*) also increase from 61 cm (Fig. 7; 9211 grains 1 cm^{-3} on average) and reach a peak at 50.5 cm (21099 grains 1 cm^{-3}) in the late 13th century. This might be due to ongoing nutrient enrichment which can result in a luxuriant growth of species such as *M. alterniflorum* in oligotrophic systems (Roelofs et al., 1984).

The most obvious source of nutrients would be domestic livestock (Lawson et al., 2006; Lawson et al., 2007). A stronger and more consistent CFS signal verifies their presence (Fig. 7; 139.9 grains 1 cm^{-3} on average), with *Podaspora HdV-368* flourishing (in relative terms; ≤135 grains 1 cm^{-3}) and BRN-7 cf. *Schizothecium conicum* (Feeser & O'Connell, 2010) appearing briefly (Fig. 7; 59.5 cm; 431 grains 1 cm^{-3}), an ascomycete with a strong association with domestic mammals (Richardson, 2011). Nonetheless, greater values for CFS in HFK8-IV would be expected and if it were not for thriving *M. alterniflorum* and the historical record (Fig. 2), the presence of livestock at Helgafell would be understated. Indeed, the available historical data undermine any prospect that low amounts of CFS are a consequence of low livestock density. This therefore probably pertains to patterns of CFS deposition in lacustrine environments as discussed with regard to HFK8-III (Lee et al., 2022).

A further step in the development of an agricultural landscape is obvious with regard to terrestrial vegetation communities (Fig. 5). The archaeophytes *Hordeum*-type (barley), and *P. aviculare* arrive at Helgafell and the incidence of the apophytes *P. lanceolata* and *P. maritima* (≤2.9% and ≤0.9% TLP respectively) is stronger than previously (particularly the latter), while archaeophytes *Anthemis*-type, *Artemisia*-type and *R. acetosella* recur. Recurring *Artemisia*-type is a common feature of medieval Icelandic pollen assemblages e.g. Einarsson

(1962) and Hallsdóttir (1987). It has been associated with beer production in lieu of *Humulus lupulus* (hops; Edwards et al. 2021), but has further applications with regard to medicine and dyeing as discussed for the previous HFK8-III). Acknowledging that there are limits with regard to the number of pollen grains involved, it is interesting to see that *Artemisia*-type (57.5 cm) is populating the same PZ as *Hordeum*-type (55.5 cm and 49.5 cm), while *Hordeum*-type may actually be under-represented due to the poor dispersal of its large pollen grains (Vuorela, 1973). Both the high social status attached to Helgafellsklaustur and its lowland coastal context favour cereal cultivation (Riddell et al. 2018), while beer production is a feature of the historical record attached to the institution (Kristjánsdóttir, 2017). The possibility that *Hordeum*-type pollen might represent the native wild grass *Leymus arenaria* (lyme grass) is negated due to the absence of suitable habitat (Erlendsson, 2007; Mooney & Guðmundsdóttir, 2020; Riddell et al., 2018). Helgafell does lie in close proximity to the coast but the sand dune systems that *L. arenaria* thrives upon are absent within the immediate locale (Guðmundsson, 1996). Indications of long term erosion and the redeposition of terrestrial sediments, which might create conditions suitable for *L. arenaria*, are generally absent from the sedimentary record i.e. DBD and MS are declining while OM increases (Fig. 3).

The occurrence of archaeophytes and apophytes (Fig. 5) seems bound to a slight expansion in grassland (Poaceae), while wetland (Cyperaceae) and habitats associated with *Betula* are sustained (≤26.7%, ≤24.9% and ≤55.3% respectively). The average pollen grain size of *Betula* (Fig. 9; $22^{+/-1}$ µm) remains closer to *B. nana* (despite a slight increase in size) and infers heath. That Helgafellsklaustur was acquiring wood from beyond its immediate landholding from its foundation in AD 1184 also suggests *B. pubescens* was absent and lends strength to this interpretation (DI-I, 1857-1986). The predominance of *B. nana* intimates selective grazing by livestock as discussed for the previous HFK8-III (Hejcman et al., 2016). Selective grazing may also apply in relation to the dominance of *E. nigrum* (Fig. 5; 2.7% TLP on average) over *Vaccinium*-type (1.3% TLP on average), the former also generally avoided by grazing animals (Knud et al., 2000).

HFK8-IV effectively terminates in the late 14th century with a minor influx of minerogenic material at 46.5 cm (Fig. 3; OM 20%; DBD 0.27 g/m^3; MS 7.6 SI units, c. AD 1360) derived either from a volcanic or erosion event. If the latter, given what we understand with regard to livestock at Helgafell in the late 14th century (Fig. 2), some disruption to terrestrial sediments is perhaps unsurprising (but remains minimal). It is interesting to note that the number of cattle in particular doubles between AD 1377 and AD 1398 when manuscript production was at its peak at Helgafell (Drechsler, 2021; Kristjánsdóttir, 2023).

Helgafellsklaustur and environmental stability (HFK8-V, 44.5-35.5 cm, c. AD 1407-1524)

HFK8-V incorporates the last 150 years of Helgafellsklaustur, the 15th century into the early 16th century, encompassing two plague epidemics in Iceland (AD 1402 and AD 1495). Evidence of the recovery of woodland and scrub as a consequence of plague human populations has been observed in Europe (van Hoof et al., 2006; Yeloff & van Geel, 2007) and at Þingeyraklaustur in northern Iceland (Riddell et al., 2022a). At Helgafell, *Betula* is reduced (Fig. 5; ≤38.4% TLP), suggesting that there was no such recovery. This is consistent with the historical view that neither of the plague epidemics in Iceland are believed to have had a significant impact at Helgafellsklaustur (Drechsler, 2021; Júlíusson, 1997; Karlsson, 1996; Kristjánsdóttir, 2017; Riddell et al., 2022a).

Indeed, in fear for their souls, the local laity bestowed substantial gifts of land upon the monastery and it prospered (Kristjánsdóttir, 2017). That it was business as usual at Helgafell is borne out by the terrestrial palynological record where Poaceae (Fig. 5; ≤28.1% TLP) and Cyperaceae (Fig. 5; ≤29% TLP) dominated habitats continued to expand at the expense of *B.*

nana scrub (Fig. 9; $22^{+/-1}$ µm). This is accompanied by yet another (albeit discrete) set of apophytes (Fig. 5; *Gentianella*-type, *M. fontana*, *Rhinanthus*-type and *Sinapis*-type) while CFS (as an indication of livestock) reach their highest amount for HFK8 overall (Fig. 8; ≤545 grains 1 cm^{-3}). On the presumption that it is livestock that are the source of the nutrients upon which *M. alterniflorum* depends (Lawson et al., 2006; Lawson et al., 2007; Roelofs et al., 1984), why have values fallen (Fig. 7; ≤10116 grains 1 cm^{-3})? This might be a consequence of a deteriorating climate, the onset of the harshest phase of the LIA c. AD 1500 (Eddudóttir et al., 2015; Eddudóttir et al., 2016; Hiles et al., 2021).

OM rapidly recovered from the minor erosion/eruption event of HFK8-IV (46.5 cm) in the late 14th century. In fact, OM is higher than ever before (discounting the influx of woody material at 78.5-79.5 cm) i.e. 40.4% on average and peaking at 44.6% at 36.5 cm (Fig. 3). Strikingly, there is virtually no minerogenic input into Helgafellsvatn for this PZ below the minerogenic influx at 35.5 cm i.e. average for DBD and MS are ≤0.1 g/m^3 and 1.7 SI units respectively (Fig. 3). Indeed, between the deposition of the LTL c. AD 877 (Fig. 3; 77.5-78.5 cm) and 35.5 cm, the growth in OM has been persistent throughout. This is despite the presence of livestock (apparent via CFS, the changes in the terrestrial vegetation and historical record; Fig. 2) and a progressively deteriorating climate from c. AD 1250 (Ogilvie & Jónsson, 2001). These relatively stable conditions in the environment surrounding Helgafellsvatn are in stark contrast with environmental change recorded elsewhere for Medieval Iceland e.g. Dugmore et al. (2009); Gísladóttir et al. (2011); Gísladóttir et al. (2010). In order to reconcile this stability in the terrestrial environment with changes in the terrestrial vegetation, it is assumed that land use practices associated with Helgafellsklaustur were operating within the carrying capacity of the land (Hallsdóttir, 1987). However, this might simply be down to chance as we know that there were relatively large numbers of domestic animals present, at least in the 14th century (Kristjánsdóttir, 2023). Therefore, the impact of grazing animals may have been offset by two factors: 1) Helgafell is situated within a lowland coastal area where weather and temperatures are milder than further inland, which may have helped sustain vegetation cover in the face of grazing; 2) Helgafell is distal to eroding uplands, active volcanism, and the *sandur* derived of glacial floods. Any windborne minerogenic material originating from such sources might be substantially dispersed by the time it reaches Helgafell (Arnalds, 2004; Dugmore et al., 2009; Gísladóttir et al., 2011; Gísladóttir et al., 2010; Möckel et al., 2017).

Conclusions

The sediments of HFK8-I (c. AD 212-507) identify an environment dominated by *Betula*, most likely *B. nana* (perhaps with some *B. pubescens*), within a wider matrix of wetland and grassland. HFK8-II (c. AD 507-920) is subject to significant changes to terrestrial and aquatic plant communities (AD 560-873). *Betula* values, including non-triporate *Betula* pollen, increase which might infer increased hybridisation between *B. nana* and *B. pubescens* (Karlsdóttir, 2007 & 2014), perhaps corroborated by a shift in pollen grain size (from $21^{+/-2}$ µm to $23^{+/-2}$ µm). Furthermore, pollen concentration values increase for almost all pollen taxa, as do those of the aquatic lycopod *Isoëtes*. These changes arise in conjunction with a period of environmental stability i.e. high OM and low MS and DBD. The sum of this is consistent with data from other pollen assemblages in Iceland e.g. Erlendsson & Edwards (2009), that have been linked to a climate amelioration c. AD 600-800.

At the transition between HFK8-II and III, there are indications of the arrival of humankind at Helgafell i.e. an unprecedented influx of woody debris into the lake sediments just below (79.5-78.5 cm) and within the LTL (78.5-77.5 cm). Firmer evidence of human settlement arises at 76.5 cm with an influx of microscopic charcoal (Edwards et al., 2021). For HFK-III (c. AD 920-1144), the expansion of open habitat types (Poaceae, Cyperaceae), the arrival of archaeophytes and an increase in apophytes, in hand with raised CFS and charcoal values, all suggest a human presence in the landscape (Edwards et al., 2021; Einarsson, 1963; Erlendsson, 2007; Hallsdóttir, 1987; Lawson et al., 2007). This is contemporaneous with disturbance to lake sediments and eutrophication of Helgafellsvatn (increased *M. alterniflorum*, decreased *Isoëtes*). There is also evidence that medicinal and culinary plants were being cultivated i.e. *Artemisia*-type, *C. carvi* and *C. majus*. Notably, these occur prior to the foundation of Helgafellsklaustur and emphasise that the cultivation of such need not be the preserve of ecclesiastical institutions (Gilchrist, 2020).

As has been observed with regard to Þingeyraklaustur (Riddell et al., 2022a) and at Viðeyjarklaustur (Hallsdóttir, 1993) the data reveal the arrival of Helgafellsklaustur in the landscape (HFK8-IV, c. AD 1144-1407). The presence of the monastery accompanies another expansion of open habitats (particularly grassland), increases in associated apophytes and the arrival of a new archaeophytes, with evidence of selective grazing by livestock i.e. increased values for *B. nana* and *E. nigrum*. Livestock are implicated in the eutrophication of Helgafellsvatn, apparent through increased *M. alterniflorum* values (Lawson et al., 2006; Lawson et al., 2007; Roelofs et al., 1984). The presence of *Hordeum*-type might infer cereal cultivation, and in association with *Artemisia*-type, beer production (Edwards et al., 2011). Whether or not the land use practices associated with Helgafellsklaustur can be directly attributed to the influence of European monasticism remains open to question. There are limits to the range of options available with regard to agriculture in Iceland and the expansion in grazing area at Helgafell conforms with such developments at non-monastic sites e.g. Erlendsson (2007); Erlendsson et al. (2018); Lawson et al. (2007) and Riddell et al. (2022b). This trajectory is maintained for HFK8-V (c. AD 1407-1524) with yet further expansion in Poaceae and Cyperaceae habitat types at the expense of *Betula* (although the latter retains a strong presence), alongside the (subtle) arrival of another suite of apophytes, and the highest values for CFS yet (i.e. livestock presence). Such changes to the terrestrial vegetation are significant in their own right in terms of land use i.e. ongoing development of a pastoral economy, but it also asserts the continuity of a human presence during the plague epidemics of the 15th century. There is some intimation of change in the aquatic environment for HFK8-V i.e. a decline in *M. alterniflorum* values. If we accept that *M. alterniflorum* is a proxy for nutrient enrichment (Roelofs et al., 1984), a decline would suggest a change in the source of nutrients i.e. land use (Gauthier et al., 2010; Lawson et al., 2007). As the pollen assemblage conveys continuity in pastoralism at Helgafell, it is possible that the decline in *M. alterniflorum* is due to climate cooling as the later phase of the LIA ensues (c. AD 1500).

Throughout the sedimentary sequence, environmental conditions at Helgafell are remarkably resilient despite a cooling climate and a land use strategy geared toward raising livestock. Declines in OM and increases in DBD and MS are generally associated with eruptions, with further disturbance low key (Fig. 3). Furthermore, OM has always recovered rapidly and has shown persistent growth to ultimately exceed pre-Landnám values. In fact, OM appears to be responsible for increased SAR post-Landnám (from 0.04 to 0.07 cm per annum). This stability is attributed to it geographical location, relatively mild climate, and distance from sources of minerogenic material dispersed by wind.

Acknowledgements

First and foremost, we would like to thank Hjörtur Helgasson of Helgafell for access to his land for the purposes of this study. We'd also like to thank Prof. Benjamin Hennig, University of Iceland, for the production of the maps, Dr Emily Lethbridge, Örnefnastofnun Íslands, Stofnun Árna Magnússonar, for supplying information on the place names of Helgafell, and Glóey Helgudóttir Finnsdóttir for assistance with translating Icelandic text.

REFERENCES

Aaby, B. & Berglund, B. E. (1986) Characterisation of lake and peat deposits. In: Berglund B.E. (ed) Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley & Sons Ltd., Chichester, pp. 231-246

Andersen, S. T. (1979) Identification of wild grass and cereal pollen. Danmarks Geologiske Undersøgelse Årbog, 25:491-518

Arnalds, Ó. (2004) Volcanic soils of Iceland. Catena, 56(1-3):3-20

Arnalds, Ó., Þorarinsdóttir, E. F., Metúsalemsson, S., Jónsson, Á., Grétarsson, E., & Árnason, Á. (2001) Soil erosion in Iceland. Iceland: Soil Conservation Service and the Agricultural Research Institute, Iceland

Arts, G. H. (2002) Deterioration of Atlantic soft water macrophyte communities by acidification, eutrophication and alkalinisation. Aquatic Botany, 73(4):373-393

Åsen, P. A. (2021) Medieval Monastery Gardens in Iceland and Norway. Religions, 12(5):317

Aston, M. (2000) Monasteries in the Landscape. Tempus, Stroud

Bakels, C. (2020) Pollen and Archaeology. In: Henry A. (ed.) Handbook for the Analysis of Micro-Particles in Archaeological Samples. Springer, Switzerland, pp. 203-224

Birks, H. J. B., & Birks, H. H. (1980) Quaternary palaeoecology. Edward Arnold, London

Björck S., Persson, T., & Kristersson, I. (1978) Comparison of two concentration methods for pollen in minerogenic sediments. Geologiska Föreningen i Stockholm Förhandlingar, 100(1):107-111

Blaauw, M., & Christen, J. A. (2011) Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian analysis, 6(3):457-474

Bond, J. (2004) Monastic Landscapes. Tempus, Stroud

Bonny, A. P. (1972) A method for determing absolute pollen frequencies in lake sediments. New Phytol, 71:393-405

Brader, M. D., Lloyd, J. M., Bentley, M. J., & Newton, A. J. (2015) Lateglacial to Holocene relative sea-level changes in the Stykkishólmur area, northern Snæfellsnes, Iceland. Journal of Quaternary Science, 30(5):497-507

Brady, N. C., & Weil, R. R. (1996) Elements of the nature and properties of soils. Pearson Prentice-Hall, Upper Saddle River

Breitenlechner, E., Hilber, M., Lutz, J., Kathrein, Y., Unterkircher, A., & Oeggl, K. (2010) The impact of mining activities on the environment reflected by pollen, charcoal and geochemical analyses. J Archaeol Sci, 37(7):1458-1467

Buckland, P., Edwards, K., Blackford, J., Dugmore, A., Sadler, J., & Sveinbjarnardóttir, G. (1995) A question of Landnám: pollen, charcoal and insect studies on Papey, eastern Iceland. In: Butlin R. & Roberts N. (eds.) Ecological relations in historical times: Human impact and adaption. Blackwell, Oxford, pp. 245-264

Caseldine, C. (2001). Changes in Betula in the Holocene record from Iceland - a palaeoclimatic record or evidence for early Holocene hybridisation? Review of Palaeobotany and Palynology, 117(1-3):139-152

Church, M., Dugmore, A., Mairs, K., Millard, A., Cook, G., Sveinbjarnardóttir, G., Ascough & Roucoux, K.H. (2007) Charcoal production during the Norse and Early Medieval periods in Eyjafjallahreppur, southern Iceland. Radiocarbon, 49(2):659-672

Clark, J. G. (2021) The Making of Nordic Monasticism, c. 1076 - c. 1350. Religions, 12(8):581

Collingwood, W. G. (1899) A Pilgrimage to the Saga-steads of Iceland. Рипол Классик

Cugny, C., Mazier, F., & Galop, D. (2010) Modern and fossil non-pollen palynomorphs from the Basque mountains (western Pyrenees, France): the use of coprophilous fungi to reconstruct pastoral activity. Veget Hist Archaeobot, 19(5-6):391-408

Davies, A. L. (2019) Dung fungi as an indicator of large herbivore dynamics in peatlands. Rev Palaeobot Palynol, 271:104-108

Dearing, J. (1994) Environmental Magnetic Susceptibility. Chi Publishing, Kenilworth

DI-I. (1857-1986) Diplomatarium Íslandicum: Íslenzkt fornbréfasafn (Vol. I). Íslenzka bókmenntafélagið, Kaupmannahöfn

DI-II. (1857-1986) Diplomatarium Íslandicum: Íslenzkt fornbréfasafn (Vol. II). Íslenzka bókmenntafélagið, Kaupmannahöfn

DI-III. (1857-1986) Diplomatarium Íslandicum: Íslenzkt fornbréfasafn (Vol. III). Íslenzka bókmenntafélagið, Kaupmannahöfn

Drechsler, S. (2021) Illuminated manuscript productionin Medieval Iceland: literary and artistic activities of the monastery at Helgafell in the fourteenth century. Brepols, Turnhout

Dugmore, A. J., Gísladóttir, G., Simpson, I. A., & Newton, A. (2009) Conceptual models of 1200 years of Icelandic soil erosion reconstructed using tephrochronology. J North Atlantic, 2(1):1-18

Duncan, B., & Bey, I. (2004) A modeling study of the export pathways of pollution from Europe: Seasonal and interannual variations (1987–1997). Journal of Geophysical Research: Atmospheres, 109(D8):1-19

Eddudóttir, S. D., Erlendsson, E., & Gísladóttir, G. (2015) Life on the periphery is tough: Vegetation in Northwest Iceland and its responses to early-Holocene warmth and later climate fluctuations. Holocene, 25(9):1437-1453

Eddudóttir, S. D., Erlendsson, E., Tinganelli, L., & Gísladóttir, G. (2016) Climate change and human impact in a sensitive ecosystem: the Holocene environment of the Northwest Icelandic highland margin. Boreas, 45(4):715-728

Edwards, K. J., Erlendsson, E., & Schofield, J. E. (2011) Is there a Norse 'footprint' in North Atlantic pollen records? In: Sigmundsson S. (ed), Viking settlements and Viking society; papers from Proceedings of the 16th Viking Congress, Reykjavík and Reykholt, 16th-23rd August 2009. Hið íslenzka fornleifafélag and Háskóli Íslands, Reykjavík, pp. 65-82

Edwards, K. J., Erlendsson, E., & Schofield, J. E. (2021) Landnám and the North Atlantic flora. In: Panagiotakopulu, E. & Saler, J.P. (eds) Biogeography in the Sub-Arctic: The Past and Future of North Atlantic Biota. Jon Wiley & Sons, Oxford, pp. 185-214

Einarsson, Þ. (1963). Pollen-analytical studies on the vegetation and climate history of Iceland in late and post-glacial times. In: Löve Á. & Löve D. (eds), North Atlantic Biota and their History. Pergamon, Oxford, pp. 255-365

Erlendsson, E. (2007) Environmental change around the time of the Norse settlement of Iceland. PhD, University of Aberdeen

Erlendsson, E., & Edwards, K. J. (2009) The timing and causes of the final pre-settlement expansion of *Betula pubescens* in Iceland. Holocene, 19(7):1083-1091

Erlendsson, E., Edwards, K. J., Vickers, K., Sveinbjarnardóttir, G., & Gísladóttir, G. (2018) The palaeoecology and cultural landscapes associated with Reykholt. In: Sveinbjarnardóttir, G. & Þorláksson, H. (eds) Snorri Sturluson and Reykholt: The Author and Magnate, his life, works and environment at Reykholt in Iceland.Museum Tusculanum Press, Copenhagen, pp. 161-203

Feeser, I., & O'Connell, M. (2010) Late Holocene land-use and vegetation dynamics in an upland karst region based on pollen and coprophilous fungal spore analyses: an example from the Burren, western Ireland. Veget Hist Archaeobot, 19(5):409-426

Gathorne-Hardy, F. J., Erlendsson, E., Langdon, P. G., & Edwards, K. J. (2009) Lake sediment evidence for late Holocene climate change and landscape erosion in western Iceland. Journal of Paleolimnology, 42(3):413-426

Gauthier, E., Bichet, V., Massa, C., Petit, C., Vannière, B., & Richard, H. (2010) Pollen and non-pollen palynomorph evidence of medieval farming activities in southwestern Greenland. Veget Hist Archaeobot, 19(5):427-438

Gilchrist, R. (2014) Monastic and church archaeology. Annu Rev Anthropol, 43:235-250

Gilchrist, R. (2020) The materiality of magic: the ritual lives of people and things. In: Gilchrist R. (ed.), Spirit, mind and body: the archaeology of monastic healing. Cambridge University Press, Cambridge, pp. 110-144

Gísladóttir, G., Erlendsson, E., & Lal, R. (2011) Soil evidence for historical human-induced land degradation in West Iceland. Applied Geochemistry, 26:S28-S31

Gísladóttir, G., Erlendsson, E., Lal, R., & Bigham, J. (2010) Erosional effects on terrestrial resources over the last millennium in Reykjanes, southwest Iceland. Quat Res, 73(1):20-32

Guðmundsson, G. (1996) Gathering and processing of lyme-grass (*Elymus arenarius L.*) in Iceland: an ethnohistorical account. Veget Hist Archaeobot, 5(1):13-23

Guinot, P., Rogé, A., Gargadennec, A., Garcia, M., Dupont, D., Lecoeur, E., Candelier, L. & Andary, C. (2006) Dyeing plants screening: an approach to combine past heritage and present development. Coloration Technology, 122(2):93-101

Haldon, J., Mordechai, L., Newfield, T. P., Chase, A. F., Izdebski, A., Guzowski, P., Labuhn, I. & Roberts, N. (2018) History meets palaeoscience: Consilience and collaboration in studying past societal responses to environmental change. Proceedings of the National Academy of Sciences, 115(13):3210-3218

Hallgrímsson, H., & Eyjólfsdóttir, G. G. (2004). Íslenskt sveppatal I smásveppir. Fjölrit Náttúrufræðistofnunar, 45:1-194

Hallsdóttir, M. (1987) Pollen analytical studies of human influence on vegetation in relation to the Landnám tephra layer in southwest Iceland. PhD, University of Lund

Hallsdóttir, M. (1993) Frjórannsókn á mósniðum úr Viðey. Raunvísindastofnun Háskólans, Reykjavík

Heiri, O., Lotter, A. F., & Lemcke, G. (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. J Paleolimnol, 25(1):101-110

Hejcman, M., Hejcmanová, P., Pavlů, V., & Thorhallsdottir, A. G. (2016) Forage quality of leaf fodder from the main woody species in Iceland and its potential use for livestock in the past and present. Grass Forage Sci, 71:649-658

Helweg, K. K. (2020) Gardening at medieval farmsteads: Archaeobotanical indications of horticulture in Denmark and southern Sweden, AD 1000–500. Archaeobotanical studies of past plant cultivation in northern Europe, 5:119-130

Hiles, W., Lawson, I. T., Roucoux, K. H., & Streeter, R. T. (2021) Late survival of woodland contrasts with rapid limnological changes following settlement at Kalmanstjörn, Mývatnssveit, northeast Iceland. Boreas, 50(4):1209-1227

Hill, M. O., & Gauch, H. G. (1980) Detrended correspondence analysis: an improved ordination technique. In: Classification and ordination: Symposium on advances in vegetation science, Nijmegen, The Netherlands, May 1979. Springer, Netherlands, pp. 47-58

Hjelle, K. L. (1997) Relationships between pollen and plants in human-influenced vegetation types using presence-absence data in western Norway. Review of Palaeobotany and Palynology, 99(1):1-16

Hjelle, K. L., Halvorsen, L. S., & Overland, A. (2010) Heathland development and relationship between humans and environment along the coast of western Norway through time. Quat Int, 220(1):133-146

Jóhannesson, H., & Sæmundsson, K. (1998). Geological map of Iceland, 1: 500,000

Júlíusson, Á. D. (1997) Bønder i prestens tid: landbrugg, godsdrift og social konflikt i semiddelalderens Islandske bondesamfund. PhD, University of Copenhagen

Júlíusson, Á. D. (2014) Jarðeignir kirkjunnar og tekjur af þeim 1000-1550. Center for Agrarian Historical Dynamics, Reykjavík

Karlsdóttir, L. (2014) Hybridisation of Icelandic birch in the Holocene reflected in pollen. PhD, University of Iceland

Karlsdottir, L., Hallsdottir, M., Thorsson, A. T., & Anamthawat-Jonsson, K. (2009) Evidence of hybridisation between *Betula pubescens* and *B. nana* in Iceland during the early Holocene. Review of Palaeobotany and Palynology, 156(3-4):350-357

Karlsdóttir, L., Thórsson, Æ. T., Hallsdóttir, M., Sigurgeirsson, A., Eysteinsson, T., & Anamthawat-Jónsson, K. (2007) Differentiating pollen of Betula species from Iceland. Grana, 46(2):78-84

Karlsson, G. (1996) Plague without rats: the case of fifteenth-century Iceland. J Mediev Hist, 22(3):263-284

Karlsson, G. (2019) The settlement of Iceland: a story from the ninth and tenth centuries. Mal og menning, Reykjavík

Kelley, J., Bond, L., & Beasley, T. (1999) Global distribution of Pu isotopes and 237Np. Science of the Total Environment, 237:483-500

Ketterer, M. E., Hafer, K. M., Jones, V. J., & Appleby, P. G. (2004) Rapid dating of recent sediments in Loch Ness: inductively coupled plasma mass spectrometric measurements of global fallout plutonium. Science of the Total Environment, 322(1-3):221-229

Ketterer, M. E., Watson, B. R., Matisoff, G., & Wilson, C. G. (2002) Rapid dating of recent aquatic sediments using Pu activities and 240Pu/239Pu as determined by quadrupole inductively coupled plasma mass spectrometry. Environmental science & technology, 36(6):1307-1311

Knud, T., Nilsson, M.-C., Michelsen, A., Lakkenborg Kristensen, H., Shevtsova, A., Strandberg, M. T., Johansson, M., Nielsen, K.E., Riis-Nielsen, T., Strandberg, B., & Johnsen, I. (2000) Nordic *Empetrum* Dominated Ecosystems: Function and Susceptibility to Environmental Changes. AMBIO: A Journal of the Human Environment, 29(2):90-97

Kristinsson, H. (1986) A guide to flowering plants and ferns of Iceland. Mál og Menning, Reykjavík

Kristjánsdóttir, G. B., Stoner, J. S., Jennings, A. E., Andrews, J. T., & Grönvold, K. (2007) Geochemistry of Holocene cryptotephras from the North Iceland Shelf (MD99-2269): intercalibration with radiocarbon and palaeomagnetic chronostratigraphies. The Holocene, 17(2):155-176

Kristjánsdóttir, S. (2010a) Icelandic Evidence for a Late-medieval Hospital: Excavations at Skriduklaustur. Mediev Archaeol, 54(1):371-381

Kristjánsdóttir, S. (2010b) The Tip of the Iceberg: The Material of Skriðuklaustur Monastery and Hospital. Norwegian Archaeological Review, 43(1):44-62

Kristjánsdóttir, S. (2012) Sagan af klaustrinu á Skriðu. Sögufélag, Reykjavík

Kristjánsdóttir, S. (2017) Leitin að klaustrunum – klausturhald á Íslandi í fimm aldir. Forlagið, Reykjavík

Kristjánsdóttir, S. (2023) Monastic Iceland. Routledge, Abingdon

Kristjánsdóttir, S., & Gunnarsdóttir, V. (2014) Kortlagning klaustra á Íslandi: Helgafell. University of Iceland, Reykjavík

Kristjánsdóttir, S., Larsson, I., & Åsen, P. A. (2014) The Icelandic medieval monastic garden-did it exist? Scandinavian Journal of History, 39(5), 560-579

Kristjánsdóttir, S., Vala, G., & Helga, J. (2016) Kortlagning klaustra á Íslandi: Helgafell. University of Iceland, Reykjavík

Langdon, P. G., Holmes, N., & Caseldine, C. J. (2008) Environmental controls on modern chironomid faunas from NW Iceland and implications for reconstructing climate change. Journal of paleolimnology, 40(1):273-293

Larsen, D. J., Miller, G. H., Geirsdóttir, Á., & Ólafsdóttir, S. (2012) Non-linear Holocene climate evolution in the North Atlantic: a high-resolution, multi-proxy record of glacier activity and environmental change from Hvítárvatn, central Iceland. Quat Sci Rev, 39:14-25

Larsen, G., Dugmore, A., & Newton, A. (1999) Geochemistry of historical-age silicic tephras in Iceland. The Holocene, 9(4):463-471

Larsen, G., Eiríksson, J., Knudsen, K. L., & Heinemeier, J. (2002) Correlation of late Holocene terrestrial and marine tephra markers, north Iceland: implications for reservoir age changes. Polar Research, 21(2):283-290

Lawson, I. T., Gathorne-Hardy, F. J., Church, M. J., Einarsson, A., Edwards, K. J., Perdikaris, S., McGovern, T.H., Amundsen, C & Sveinbjarnardottir, G. (2006) Human impact on freshwater environments in Norse and early medieval Iceland. In: Dynamics of northern societies: proceedings of the SILA/NABO Conference on Arctic and North Atlantic Archaeology, May 10th-14th, 2004. Aarhus University Press, Copenhagen, pp. 375-382

Lawson, I. T., Gathorne-Hardy, F. J., Church, M. J., Newton, A. J., Edwards, K. J., Dugmore, A. J., & Einarsson, A. (2007) Environmental impacts of the Norse settlement: palaeoenvironmental data from Myvatnssveit, northern Iceland. Boreas, 36(1):1-19

Lee, C. M., van Geel, B., & Gosling, W. D. (2022) On the Use of Spores of Coprophilous Fungi Preserved in Sediments to Indicate Past Herbivore Presence. Quaternary, 5(3):1-23

Lind, L., Eckstein, R. L., & Relyea, R. A. (2022) Direct and indirect effects of climate change on distribution and community composition of macrophytes in lentic systems. Biological Reviews, 97(4):1677-1690

Lomas-Clarke, S. H., & Barber, K. E. (2004) Palaeoecology of human impact during the historic period: palynology and geochemistry of a peat deposit at Abbeyknockmoy, Co. Galway, Ireland. Holocene, 14(5):721-731

Mäkelä, E. (1996) 1996: Size distinctions between *Betula* pollen types–a review. Grana 35:248-256

Mann, M. E. (2002a) Medieval Climatic Optimum. In: Munn T. (ed.), Encyclopedia of Global Environmental Change (Vol. 1). John Wiley & Sons Ltd., Chichester, pp. 514-516

Mann, M. E. (2002b) Little Ice Age. In: Munn T. (ed.), Encyclopedia of Global Environmental Change (Vol. 1). John Wiley & Sons Ltd., Chichester, pp. 504-509

Meara, R. H., Thordarson, T., Pearce, N., Hayward, C., & Larsen, G. (2020) A catalogue of major and trace element data for Icelandic Holocene silicic tephra layers. Journal of Quaternary Science, 35(1-2):122-142

Möckel, S. C., Erlendsson, E., & Gísladóttir, G. (2017) Holocene environmental change and development of the nutrient budget of histosols in North Iceland. Plant and Soil, 418(1-2):437-457

Mooney, D. E., & Guðmundsdóttir, L. (2020) Barley cultivation in Viking Age Iceland in light of evidence from Lækjargata 10–12, Reykjavík. In: Vanhanen, S. & Lagerås, P. (eds) Archaeobotanical studies of past plant cultivation in northern Europe, Barkhuis, Netherlands, pp. 5-19

Moore, P. D., Webb, J. A., & Collison, M. E. (1991) Pollen Analysis. Blackwell, Oxford

Mørk, O., Kragh, T., Kristensen, E., & Sand-Jensen, K. (2018) Adaptation and growth performance of four endangered amphibious freshwater species. Aquatic Botany, 150:16-22

Munsell Soil Color Charts. (2009) Munsell Soil Color Charts. Xrite, Grand Rapids

Nakagawa, T., Brugiapaglia, E., Digerfeldt, G., Reille, M., Beaulieu, J. L. d., & Yasuda, Y. (1998) Dense-media separation as a more efficient pollen extraction method for use with organic sediment/deposit samples: comparison with the conventional method. Boreas, 27(1):15-24

Noël, H., Garbolino, E., Brauer, A., Lallier-Vergès, E., De Beaulieu, J.-L., & Disnar, J.-R. (2001) Human impact and soil erosion during the last 5000 yrs as recorded in lacustrine sedimentary organic matter at Lac d'Annecy, the French Alps. J Paleolimnol, 25(2):229-244

Ogilvie, A. E. J., & Jónsson, T. (2001) "Little Ice Age" research: A perspective from Iceland. Clim Change, 48(1):9-52

Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L. & Solymos, P. (2016) vegan: Community Ecology Package. R package version 2.4-3

Ólsen, B. M. (1910) Um kornirkju á Íslandi að fornu. Búnaðaritt, 24:81-168

Ottósson, J. G., Sveinsdóttir, A., & Harðardóttir, M. (2016) Vistgerðir á Íslandi. Icelandic Institute of Natural History. http://vistgerdakort.ni.is/. Accessed 17 Februray 2023

Patterson III, W. A., Edwards, K. J., & Maguire, D. J. (1987) Microscopic charcoal as a fossil indicator of fire. Quat Sci Rev, 6(1):3-23

Pluenneke, M. (2017) Shift in Icelandic Plant Populations Due to Climate Change: Through the Lens of Natural Dyes. Independent Study Project (ISP) Collection, 2751

Reimer, P. J. et al. (2020) The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon, 62(4):725-757

Richardson, M. J. (2011) Additions to the coprophilous Mycota of Iceland. *Acta Botanica Islandica*, 15:23-49

Richter, N., Russell, J. M., Garfinkel, J., & Huang, Y. (2021) Impacts of Norse settlement on terrestrial and aquatic ecosystems in Southwest Iceland. Journal of paleolimnology, 65(2):255-269

Riddell, S., Erlendsson, E., Gísladóttir, G., Edwards, K. J., Byock, J., & Zori, D. (2018) Cereal cultivation as a correlate of high social status in medieval Iceland. Veget Hist Archaeobot, 27(5):679-696

Riddell, S. J., Erlendsson, E., Eddudóttir, S. D., Gísladóttir, G., & Kristjánsdóttir, S. (2022a). Pollen, Plague & Protestants: The Medieval Monastery of Þingeyrar (Þingeyraklaustur) in Northern Iceland. Environ Archaeol, 27(2):193-210

Riddell, S. J., Erlendsson, E., Eddudóttir, S. D., Gísladóttir, G., & Kristjánsdóttir, S. (2022b) The vegetation and land use histories of two farms in Iceland: settlement, monasticism, and tenancy. Veget Hist Archaeobot, 31(4):395-414

Roelofs, J., Schuurkes, J., & Smits, A. (1984) Impact of acidification and eutrophication on macrophyte communities in soft waters. II. Experimental studies. Aquatic Botany, 18(4):389-411

Rundgren, M. (1995) Biostratigraphic evidence of the Allerød-Younger Dryas-Preboreal oscillation in northern Iceland. Quaternary Research, 44(3):405-416

Rymer, L. (1973) Modern pollen rain studies in Iceland. New Phytologist, 72(6):1367-1373

Schmid, M. M., Zori, D., Erlendsson, E., Batt, C., Damiata, B. N., & Byock, J. (2017) A Bayesian approach to linking archaeological, paleoenvironmental and documentary datasets relating to the settlement of Iceland (Landnám). Holocene, 28(1):19-33

Schmid, M. M. E., Dugmore, A. J., Newton, A. j., & Vésteinsson, O. (2021) Multidisciplinary chronological data from Iceland indicate a Viking Age settlement flood, rather than a flow or trickle. In: Napolitano, M.F., Stone, J.H. & DiNapoli, R.J. (eds) The Archaeology of Island Colonisation: global approaches to initial human settlement. University Press, Florida, pp. 132-179

Schofield, E. J., Edwards, K. J., & Andy McMullen, J. (2007) Modern pollen-vegetation relationships in subarctic southern Greenland and the interpretation of fossil pollen data from the Norse landnám. Journal of Biogeography, 34(3):473-488

Smith, K. P. (1995) Landnám: the settlement of Iceland in archaeological and historical perspective. World Archaeol, 26(3):319-347

Spierenburg, P., Lucassen, E., Lotter, A., & Roelofs, J. (2009) Could rising aquatic carbon dioxide concentrations favour the invasion of elodeids in isoetid-dominated softwater lakes? Freshwater Biology, 54(9):1819-1831

Stockmarr, J. (1971) Tablets with spores used in absolute pollen analysis. Pollen et Spores, 13:614-621

Stolz, C., & Grunert, J. (2010) Late Pleistocene and Holocene landscape history of the central Palatinate forest (Pfälzerwald, south-western Germany). Quat. Int, 222(1-2):129-142

Sveinsson, E. (1934) Laxdœla Saga. Hið íslenzka fornritafélag, Reykjavík

Sveinsson, E., & Þórðarson, M. (1985) Eyrbyggja Saga. Hið Íslenzka Fornritafélag, Reykjavík

Thomas, P., El-Barghathi, M., & Polwart, A. (2007) Biological flora of the British Isles: *Juniperus communis L.* Journal of Ecology, 95(6):1404-1440

Thórsson, Æ. T., Pálsson, S., Sigurgeirsson, A., & Anamthawat-Jónsson, K. (2007) Morphological variation among *Betula nana* (diploid), *B. pubescens* (tetraploid) and their triploid hybrids in Iceland. Annals of Botany, 99(6):1183-1193

Tipping, R. (1997) Medieval woodland history from the Scottish Southern Uplands: fine spatial-scale pollen data from a small woodland hollow. In: Smout C. (ed), Scottish Woodland History. Scottish Cultural Press, Dalkeith, pp. 51-74

Troels-Smith, J. (1955) Karakterisering af lose jordarter. Characterization of unconsolidated sediments. Danmarks Geologiske Undersøgelse Årbog, 3(10)

van Geel, B., Buurman, J., Brinkkemper, O., Schelvis, J., Aptroot, A., van Reenen, G., & Hakbijl, T. (2003) Environmental reconstruction of a Roman Period settlement site in Uitgeest (The Netherlands), with special reference to coprophilous fungi. J Archaeol Sci, 30(7):873-883

van Hoof, T. B., Bunnik, F. P. M., Waucomont, J. G. M., Kürschner, W. M., & Visscher, H. (2006) Forest re-growth on medieval farmland after the Black Death pandemic - implications for atmospheric CO_2 levels. Palaeogeogr Palaeoclimatol Palaeoecol, 237:396-411

Vésteinsson, O., McGovern, T. H., & Keller, C. (2002) Enduring impacts: social and environmental aspects of Viking Age settlement in Iceland and Greenland.

Vuorela, I. (1973) Relative pollen rain around cultivated fields. Acta Botanica Fennica, 102

Wimble, G., Wells, C. E., & Hodgkinson, D. (2000) Human impact on mid-and late Holocene vegetation in south Cumbria, UK. Vegetat Hist Archaeobot, 9(1):17-30

Yeloff, D., & van Geel, B. (2007) Abandonment of farmland and vegetation succession following the Eurasian plague pandemic of AD 1347-52. J Biogeogr, 34:575-582.

Zielińska, S., Jezierska-Domaradzka, A., Wójciak-Kosior, M., Sowa, I., Junka, A., & Matkowski, A. M. (2018) Greater Celandine's Ups and Downs-21 Centuries of Medicinal Uses of *Chelidonium majus* From the Viewpoint of Today's Pharmacology. Frontiers in Pharmacology, 9:299

Paper III

Vegetation History and Archaeobotany (2022) 31:395–414
https://doi.org/10.1007/s00334-021-00861-y

ORIGINAL ARTICLE

The vegetation and land use histories of two farms in Iceland: settlement, monasticism, and tenancy

Scott J. Riddell[1] · Egill Erlendsson[1] · Sigrún Dögg Eddudóttir[3] · Guðrún Gísladóttir[1,2] · Steinunn Kristjánsdóttir[4]

Received: 14 April 2021 / Accepted: 3 September 2021 / Published online: 25 October 2021

Abstract
Palaeoecological research in Iceland has rarely considered the environmental consequences of landlord-tenant relations and has only recently begun to investigate the impact of medieval monasticism on Icelandic environment and society. Through the medium of two tenant farm sites, this investigation seeks to discern whether or not monastic landlords were influencing resource exploitation and the land management practices of their tenants. In particular, sedimentary and phyto-social contexts were examined and set within a chronological and palaeoecological framework from the late 9th century down to the 16th century. How this relates to medieval European monasticism is also considered while the prevailing influences of climate and volcanism are acknowledged. Palaeoecological data shed light upon the process of occupation at the two farms during the settlement period, with resources and land use trajectories already well-established by the time they were acquired by monastic institutions. This suggests that the tenant farms investigated were largely unaffected ecologically by absorption into a manorial system overseen by monasticism. This could be a consequence of prevailing environmental contexts that inhibited the development of alternative agricultural strategies, or simply that a different emphasis with regard to resource exploitation was paramount.

Keywords Pollen · Iceland · Medieval · Monasteries · Tenancy · Land use

Introduction

Here, through the application of palaeoecological methods (sedimentology and palynology), the vegetation and land use histories of the farms of Helgadalur and Ásbjarnarnes in Iceland (Fig. 1) are examined. Seeking to expand upon ongoing investigations regarding the impact of medieval monasteries on Icelandic society and the environment (Kristjánsdóttir 2017; Riddell et al. 2018b), the aim is to discern how much influence Icelandic monasteries exerted over their tenants with regard to resource exploitation and land management practices. This may be expressed as an alteration in otherwise prevailing trends in sediments and vegetation and/or the appearance of plants that were hitherto absent from within the vegetation communities. This is considered within the wider context of medieval European monasticism (Kristjánsdóttir 2017; Riddell et al. 2018b), as well as a desire to appreciate better the relationship between tenants and their landlords more generally in medieval Iceland (Júlíusson et al. 2020). Palaeoecological material is derived from two wetland sites from within the landholdings of the respective tenant farms, its interpretation enhanced through the use of tephrochronology (Thorarinsson 1967) and reference to Icelandic historical sources (Haldon et al. 2018).

Communicated by M.-J. Gaillard.

✉ Scott J. Riddell
sjr3@hi.is

[1] Institute of Life and Environmental Sciences, University of Iceland, Sturlugata 7, 102 Reykjavík, Iceland

[2] Institute of Earth Sciences, University of Iceland, Sturlugata 7, 102 Reykjavík, Iceland

[3] Department of Archaeology and Ancient History, Uppsala University, Engelska Parken, Thunbergsvägen 3H, 752 38 Uppsala, Sweden

[4] Department of Archaeology, University of Iceland, Sæmundargata 12, 102 Reykjavík, Iceland

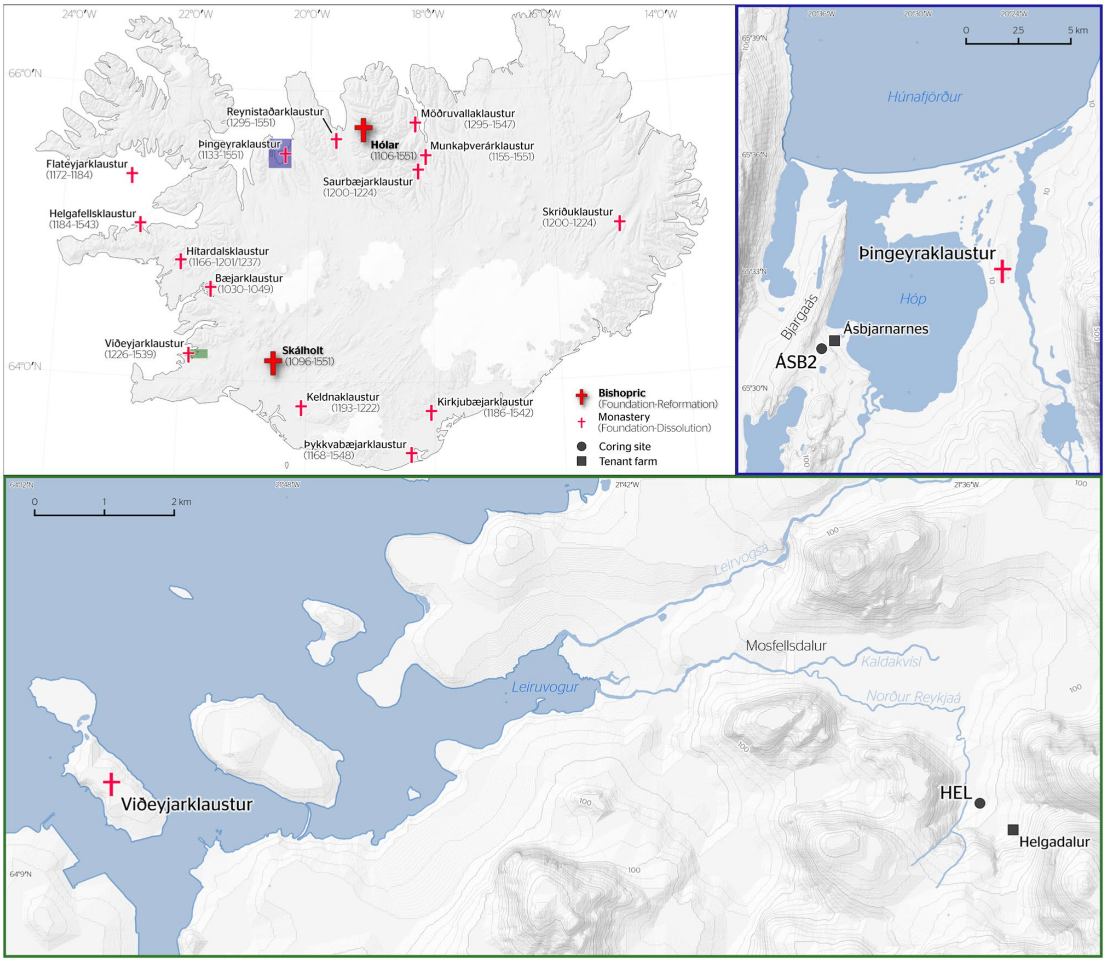


Fig. 1 Map of Iceland indicating the distribution of monasteries and the location of coring sites, tenant farms, and landlords, as discussed in text (map courtesy of Benjamin D. Hennig, University of Iceland)

Medieval monasticism, tenancy and environment in Iceland

Recent archaeological studies have sought to improve the understanding of Icelandic monasteries in the Middle Ages, particularly concerning their relationship with wider Icelandic society (Kristjánsdóttir 2017). Archaeological evidence demonstrates a clear link between the medieval Icelandic monastic tradition and that of Europe; architecturally and with regard to mission i.e. the provision of medical care to the lay population (Kristjánsdóttir 2010). On the continent, medieval European monasticism is strongly associated with altered landscapes (Aston 2000; Bond 2004; Gilchrist 2014) including woodland clearance (assarting), pasture development, cultivation (Wimble et al. 2000; Noël et al. 2001; Lomas-Clarke and Barber 2004; Breitenlechner et al. 2010; Hjelle et al. 2010; Stolz and Grunert 2010) and technological innovation e.g. nitrogen-fixing plant species (Tipping 1997) and hemp-retting (Laine et al. 2010). There is similar palaeoecological evidence to show that this may also have been the case with regard to monasticism in Iceland (Fig. 1) e.g. the clearance of birch scrub for fuel and pasture at the monastery of Þingeyrar (Riddell et al. 2018b) and the introduction (or intensification) of cereal cultivation at the monastery of Viðey (Hallsdóttir 1993). Notably, the scale of landscape change associated with continental monasteries could extend beyond the immediate cloister, monastic reach influencing tenancies subject to their estate (Wimble et al. 2000; Tipping 2010).

The majority of Icelandic monasteries were founded in the 12th century (Fig. 1). Contemporaneously, many formerly independent landholdings were transitioning into tenancies subject to a manor-type farm (Júlíusson 2010; Jakobsson 2013) and a peasant society evolved (Júlíusson 2007; Vésteinsson 2007). As landownership became increasingly centralised, outwith niche markets and marine commodities, subsistence shifted toward cultivating a surplus in woollen goods for export, the latter evident in altered bovine/caprine bone ratios from medieval farm middens (McGovern et al. 2017). It was under such a regime that by the 14th century, the monasteries of Iceland had amassed a large number of landholdings, tenancies submitting rental payments in the form of fish, dairy, meat, woollens, charcoal etc. (Jakobsson 2013; Júlíusson 2014). Indeed, zooarchaeological evidence from medieval tenant farms in Hörgárdalur (northern Iceland) suggests that the monastery of Möðruvellir (Fig. 1) may have been exerting significant control in relation to the production of woollens and beef there (Harrison 2014).

However, from both an archaeological and historical perspective, although considerable effort has been given to investigating the household economics of individual farms in Iceland on the one hand, and the macro-economics of international trade on the other, there remains a gap in understanding as to how this may apply to farms which were, for the most part, tenanted (Lucas 2012; Pálsson 2018; Bolender et al. 2020; Júlíusson et al. 2020). This certainly holds true for palaeoecology too, with associated methodologies only recently being deployed to consider questions pertaining to socio-economic circumstances in Iceland's past, e.g. social status (Riddell et al. 2018a) and the management of commons (Sigurmundsson et al. 2014). Therefore, any appreciation of landlord-tenant relations in Iceland through palaeoecology can only enhance our understanding of natural resource utilisation in the past (Vésteinsson 1998–2001; Erlendsson et al. 2006) and the manner in which the ecosystems that underpin it are to be sustained into the future (Edwards et al. 2019).

It is important to acknowledge that human influence upon the environment of Iceland does not operate in isolation (Dugmore et al. 2009) and that climate and volcanism (Eddudóttir et al. 2015, 2017, 2020; Tinganelli et al. 2018) represent significant agents with regard to modelling the Icelandic landscape. The climate regime in the North Atlantic at this time spans both the Medieval Climatic Optimum (MCO) AD 900–1500 (Mann 2002a) and the Little Ice Age (LIA) AD 1500–1900 (Mann 2002b). With regard to Iceland, both marine (Eiríksson et al. 2000) and lacustrine cores (Larsen et al. 2012) suggest that the MCO occurred AD 800–1350 followed by the LIA which persisted until AD 1900. Such regional variation forms the basis of arguments that criticise the concept of an LIA (Ogilvie and Jónsson 2001; Mann 2002b). Indeed, within Iceland, reference to Icelandic historical material suggests that the LIA is comprised of two distinct phases (Ogilvie and Jónsson 2001). Between AD 1250 and AD 1500 (the period that encompasses this study), the prevailing conditions in Iceland were relatively mild but punctuated by short periods of harsh climate. From AD 1500 until AD 1900, the incidence and severity of conditions became far more exacting in terms of cooler temperatures, glacier advance, sea ice, and storminess.

Study sites

Helgadalur

Helgadalur (97 m a.s.l.) is situated in southwest Iceland, ca. 25 km east of Reykjavík (Fig. 1). The valley is bounded to the west, south and east by upland, culminating in Grímannsfell (482 m a.s.l.), with a basic/intermediate, Upper Pliocene and Lower Pleistocene (0.8–3.3 my) geology. The drift geology is of rock exposure, glacial till and Holocene histosols and andosols of volcanic origin (Arnalds et al. 2001). Pasture, hayfields, and mixed-broadleaved/conifer plantations (Ottósson et al. 2016) are maintained through a 20th century drainage system that feeds into the Norður-Reykjaá. The valley basin of Helgadalur is categorised as experiencing "none" or "little" erosion (Arnalds et al. 2001). In contrast, the surrounding uplands are subject to "considerable" erosion. Where upland vegetation persists, it is comprised of a matrix of moss, grassland and heath (Ottósson et al. 2016). Regional mean annual temperature and precipitation data are derived from Reykjavík (Table 1) but as seasonal and daily insolation are limited by the surrounding uplands (Pétursdóttir 2014), temperatures are likely to be lower at Helgadalur. Similarly, precipitation is probably higher at Helgadalur due to its altitude. The prevailing wind is from the east.

Charcoal, burnt bone and compacted soil, revealed during archaeological survey (Zori and Byock 2014), testify that Helgadalur has been occupied since the deposition of the AD 877 Landnám Tephra Layer (LTL). This is also apparent palaeoecologically with land use focussed upon the development of a pastoral regime between AD 877 and AD 1226 (Riddell et al. 2018a). The earliest historical reference to Helgadalur comes from AD 1395 (DI-III 1857–1986). Here it is said that Helgadalur came into the ownership of the Augustinian monastery of Viðeyjarklaustur (Fig. 1) during the rule of Abbot Páll Magnússon (AD 1379–1403), i.e. within the 16 years between the Abbot's ordination in AD 1379 and the compilation of the inventory of AD 1395 (Kristjánsdóttir 2017). A relatively low value of 12 hundreds is given for the tenancy at Helgadalur. Representatives of the Danish Crown attacked Viðeyjarklaustur in the name of Reformation on Whitsun AD 1539. Following dissolution, Viðeyjarklaustur

Table 1 Climatological data for the study sites (Icelandic Meteorological Office (Veðurstofa Íslands) 2007)

Data/weather station	Reykjavík	Blönduós/Hjaltabakki[a]
Location	N 65° 36′ 54″ W 19° 57′ 15″	N 65° 42′ 10″ W 20° 10′ 24″/N 65° 39′ 42″ W 20° 15′ 1″
Recording period	1961–1990	1961–1999[a]
Elevation (m a.s.l.)	52	8/~23
Avg. temp °C tritherm (June–August)	10.0	8.7
Avg. temp °C July	10.6	9.4
Avg. temp °C January	− 0.5	− 2.5
Avg. precipitation mm $year^{-1}$	799	458

[a] Blönduós 1961–1965 and 1981–1999, Hjaltabakki 1967–1981

and approximately 60 tenancies (Júlíusson 2014), including Helgadalur, effectively became a royal fiefdom (Karlsson 2000), remaining so into the 18th century (Magnússon and Vídalín 1926).

Ásbjarnarnes

The farm of Ásbjarnarnes is situated by a peninsula on the western shore of Hóp, a semi-saline, coastal lagoon in Vestur-Húnavatnssýsla, northwest Iceland (Fig. 1). The ridge of Bjargaás (95 m a.s.l., northeast-southwest axis), a dominant landscape feature within the landholding, is formed of Upper Pleistocene basalts and is situated within a geological landscape largely defined by Tertiary basalts (Jóhannesson and Sæmundsson 1998). The drift geology is comprised of rock exposure, glacial till, coastal and riverine deposits, and Holocene histosols and andosols of volcanic origin (Moriwaki 1990; Arnalds et al. 2001; Thordarson and Hoskuldsson 2002). Much of the landholding is subject to "considerable" erosion (Arnalds et al. 2001). Vegetated areas comprise a matrix of heath and fen, grassland, and modified pasture (Ottósson et al. 2016). Land is still grazed but no one resides at Ásbjarnarnes permanently today. Temperature and precipitation data are derived from Blönduós/Hjaltabakki (Table 1). The prevailing wind is from the southwest.

Reference to Ásbjarnarnes in historical sources (also known as *Nes í Víðidalur*, *Nes í Vestur Hóp*, *Ásbjarnarnes í Þverárhreppi*) begins in the early 14th century in association with the Benedictine monastery of Þingeyraklaustur. This material is concerned with shore rights such as sealing and beached whales (*Diplomatarium Islandicum*: DI-II 1857–1986). However, in AD 1361, half of the Ásbjarnarnes landholding, including the home farm and an extensive area of woodland, is bequeathed to Þingeyraklaustur by the farmer Árni Bárðarsson (DI-III 1857–1986). Subsequent inventories show that this portion of Ásbjarnarnes remained a tenancy of Þingeyraklaustur, along with around 62 other tenancies (Júlíusson 2014), until the Reformation (DI-IX 1857–1986; DI-VIII 1857–1986; DI-XII 1857–1986).

Methodology

Site selection and fieldwork

Both historical and geographical factors influenced the selection of the coring sites. Confirmation that a farm site was formerly a tenancy of a monastery (in association with a date of acquisition) was required and effected via the *Diplomatarium Islandicum* (DI-I-XVI 1857–1986), a collection of medieval letters, inventories, and deeds, originating from ca. AD 1150 to ca. 1550. Moreover, an association with an Icelandic monastery for which there is some indication of the modification of ecological conditions in their immediate environs at the time of foundation was also preferred; in this instance Viðeyjarklaustur (Hallsdóttir 1993) and Þingeyraklaustur (Riddell et al. 2018b).

The presence of a wetland within the landholding of the selected tenant farm was necessary. The identification of suitable wetlands was achieved via a consideration of aerial photographs and site visits. Pollen profiles derived from cores from such contexts are considered to be representative of past plant communities within and around wetlands (Rymer 1973; Moore et al. 1991; Caseldine and Hatton 1994). Therefore, as a central area for human activity, close proximity to the farmstead was desirable regarding the detection of land use practices. However, this also depends upon the presence (determined through the sampling of selected wetlands with a JMC "Backsaver") of a relatively intact sedimentary sequence that contains dateable tephra layers. In Iceland, sediments can often be damaged or interrupted by peat (fuel) and turf (construction) cutting, and modern agricultural practices (drainage, levelling of pasture, etc.), especially in the immediate vicinity of farmsteads. Hence, any wetland with an intact sedimentary sequence within the landholding was deemed suitable on the premise that it will capture some degree of human activity.

Helgadalur was chosen as it complied with the historical requirements of the selection criteria, and because there was already a core to hand from the landholding that had been previously processed for pollen for an earlier period of the sites history (Riddell et al. 2018a). This 1 m core (HEL) was extracted from a modified wetland, ca. 600 m northwest (64° 9′ 49.19″ N, 21° 35′ 38.65″ W) of the modern farmstead of Helgadalur (Fig. 1). The exact extent of the original mire at Helgadalur is unclear given its conversion to pasture, but it is at least 0.27 km^2 and situated at the head of a relatively enclosed valley. Poaceae (grass) is dominant within the current vegetation community with Cyperaceae (sedge) sub-dominant.

Ásbjarnarnes was selected as it complied with all criteria (although upper strata subsequently proved to be devoid of identifiable tephra layers and ^{14}C dates were necessary). The 75 cm core (ÁSB2) was extracted from Sund (65° 31′ 8.44″ N, 20° 35′ 32.48″ W), a relatively intact wetland (ca. 0.4 km^2) situated between Bjargaás and some small, eroded hillocks ca. 90 m southwest of the remains of Ásbjarnarnes farm (Fig. 1). Regarding the present vegetation community, *Eriophorum angustifolium* is dominant with *Betula nana*, *Salix callicarpaea* and *Vaccinium uliginosum* also present.

Sedimentology

Strata for both sites were described according to Troels-Smith (1955) as modified by Aaby and Berglund (1986), supplemented by Munsell soil color charts (2009). Each column was measured every 0.5 cm for magnetic susceptibility (MS) with a Bartington MS2 meter and MS2E probe (Dearing 1994), before being processed for soil properties. Measures of dry bulk density (DBD; g/m^3) and organic matter (OM; %) were acquired for every 1 cm. The dry weight was obtained by heating samples at 105 °C for 24 h. DBD was calculated by dividing the dry weight of the sample by sample volume (1.2 cm^3) (Brady and Weil 1996). OM was calculated by combusting 1.2 cm^3 of sediment at 550 ºC for 4 h (Heiri et al. 2001).

Age determination

Tephra samples were extracted from distinct horizons identified within the sediment profiles (visually or via MS). In order to discern the origin of the tephra samples, each was cleaned of humic material, sieved (63 µm), mounted, polished and carbon-coated for geochemical analysis. Tephra geochemistry was analysed at the University of Iceland using a JEOL JXA-8230 electron probe micro-analyser (EPMA). The acceleration voltage was 15 kV, the beam current 10 nA, with a beam diameter of 10 µm, except for intermediate or rhyolitic tephra which were set at 5 µm (due to crystallisation and thin walls). The standards A99 (for basaltic tephra), ATHO and Lipari Obsidian (both for silicic and intermediate tephra), were measured prior to, and after, the analyses in order to verify consistency in analytical conditions. Data were then inspected for, and cleaned of, anomalies and analyses with sums < 96% and > 101%. Sometimes it is necessary to seek ^{14}C dates in Icelandic contexts if there is a shortfall in the presence of tephra layers i.e. where sites lie beyond isopach range. Therefore, three ^{14}C dates were acquired to supplement the tephra sequence for ÁSB2 by sieving (< 250 µm) sediment samples and selecting suitable material for analyses, in this instance, wood and bark. This material was analysed by ETH Zurich, Switzerland, and the results were calibrated using IntCal20 (Reimer et al 2020). Smooth-spline age-depth models were derived from tephra and ^{14}C data and constructed using the clam package in R (Blaauw 2010).

Palynology

A total of 45 samples were prepared for HEL and 39 samples for ÁSB2. HEL samples for depths 6.75 to 28.25 cm were taken at 0.5 and 1 cm intervals with a volume of 2 cm^3 per sample. The greater resolution (0.5 cm intervals) applies to HEL samples situated between the Katla AD 1500 (20 cm) and Medieval AD 1226 (28.25 cm) tephra layers as there was confidence in capturing the period of monastic oversight associated with the tenancy (AD 1379–1539). The processing of HEL samples for the depths 29.50–43.25 cm (volume of 1 cm^3 per sample) is described in Riddell et al. (2018a), with these samples only revisited in order to acquire microscopic charcoal data. ÁSB2 was sampled at 1 cm intervals with a volume of 2 or 3 cm^3 per sample, with greater sample size used where low pollen concentration was anticipated.

The volumes of HEL and ÁSB2 samples were determined by displacement in 10% HCL (Bonny 1972). One *Lycopodium clavatum* tablet (Batch no. 124961 for ÁSB2 and HEL 6.75–28.25 cm, Batch no. 1031 for HEL 29.5–43.25) was added to each sample in order to determine pollen concentration (Stockmarr 1971). Samples were rinsed in 10% HCL to remove residual glue from the control tablet, 10% NaOH to break down humic material, and sieved (through a 150 µm mesh) to remove coarse material (Moore et al. 1991). Minerogenic material was removed by dense media separation utilising LST Fastfloat, density 1.9 g/ml (Björck et al. 1978; Nakagawa et al. 1998). Acetolysis allowed for the separation of pollen grains from other organic material (Moore et al. 1991). Pollen grains were slide-mounted with silicone oil of 12,500 cSt. viscosity and counted by using a microscope at ×400 to ×1,000 magnification (Moore et al. 1991).

Moore et al. (1991) was used as the primary pollen key, with pollen and spore taxonomy adapted according to the Icelandic context (Erlendsson 2007), as was plant nomenclature (Kristinsson 1986). Total land pollen (TLP) values per sample for HEL range between 210 and 640 while that for ÁSB2 is 299 to 933. Preferably, these numbers would be higher given the low pollen productivity of Icelandic vegetation (Caseldine and Hatton 1994) but in this instance, high chronological resolution has been favoured over large counts per sample. A minimum of 100 non-Cyperaceae pollen grains were counted for each sample in order to overcome the dominance of Cyperaceae in Icelandic pollen profiles (Caseldine and Hatton 1994). In order to determine the relative proportions of pollen and spore taxa within the sample, palynological interpretation is based primarily upon pollen percentage data (Birks and Birks 1980). The TLP for each sample underpins the base sum on which the percentages for all taxa are calculated. As a result, percentages for some non-pollen palynomorphs (NPP) can exceed 100%. Furthermore, as these values are co-dependent, Cyperaceae values will suppress the values of other taxa (Moore et al. 1991). Therefore, palynomorph concentration data are used to supplement the interpretation.

Recorded NPP's are comprised of cryptogram spores (Moore et al. 1991), microscopic charcoal (Patterson III et al. 1987), and coprophilous fungal spores (CFS) (van Geel et al. 2003; Cugny et al. 2010). Charcoal and CFS are considered part of a suite of environmental proxies indicative of human activity and the presence of livestock in Iceland (Edwards et al. 2011). All Poaceae pollen grains were evaluated as potential cereal-type pollen i.e. a mean grain diameter > 37 µm and an annulus diameter > 8 µm (Andersen 1979). Pollen data and NPP count data were entered into TILIA (version 2.0.41) and subjected to a total sum of squares analysis (CONISS), producing a stratigraphically constrained dendrogram (Grimm 2011). Visual evaluation of the dendrograms allowed data to be divided into Local Pollen Assemblage Zones (LPAZ). In order to better understand the nature of the relationship between LPAZ, ordination analyses were applied to the HEL and ÁSB2 datasets via the package vegan in R (Oksanen et al. 2016). Principal Component Analysis (PCA) was performed on Hellinger-transformed data incorporating terrestrial pollen and spore taxa as well as coprophilous fungal spores with abundances ≥ 1%.

Results

Age determination

Age/depth models for the HEL and ÁSB2 (Fig. 2a, b) cores provide the chronological framework required to interpret palynological and sedimentary data and were constructed with reference to known tephra layers and ^{14}C dates. Tephra layers (Tables 2 and 3) were identified for HEL and ÁSB2 based upon their geochemical composition (ESM1 Tables 1 and 2) in comparison with other published material pertaining to tephra and palaeoecological studies in southwest and northern Iceland (Tables 2 and 3).

A cryptic tephra at HEL 7.5 cm was identified by MS and is thought to originate from Katla (Table 2 and ESM1 Table 2). However, it is impossible to narrow this down to any specific eruption and this tephra is excluded from the age/depth model. Similarly, although the HEL tephra layer situated at 37 cm does share characteristics with tephra from the Katla AD 920 eruption (Hafliðason et al. 1992;

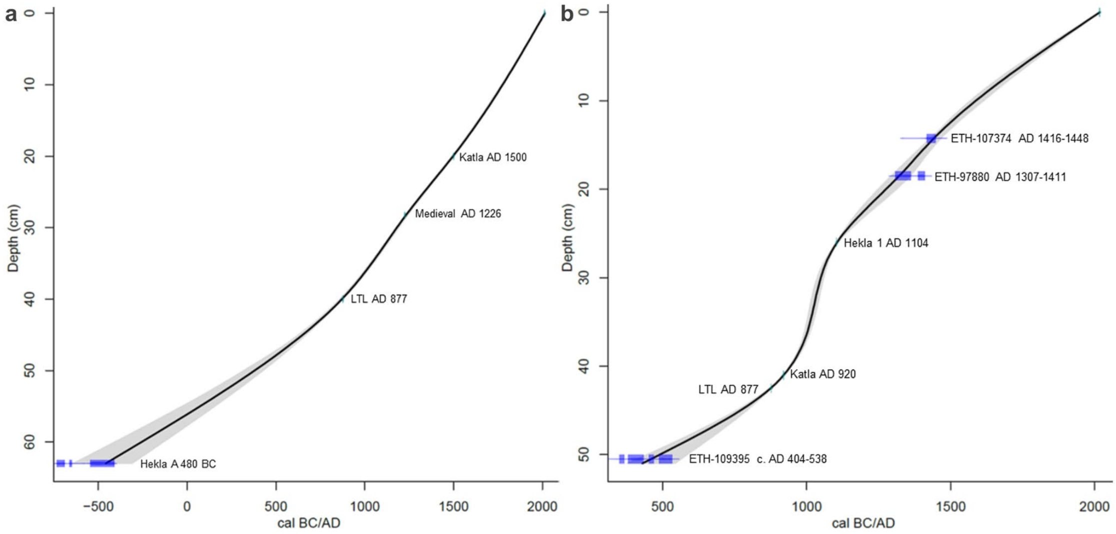


Fig. 2 Age-depth model for HEL (**a**) and ÁSB2 (**b**)

Erlendsson et al. 2014; Riddell et al. 2018a), its geochemical signal is obscured by tephra shards of Vatnaöldur origin (perhaps reworked fragments from the LTL at 38–40 cm) and is also excluded (Table 2 and ESM1 Table 2). Radiocarbon data for ÁSB2 are presented in Table 4.

Palynology and sedimentology

All HEL and ÁSB2 pollen (Figs. 3, 4, 5 and 6) and sediment (Fig. 7a, b: MS, DBD and OM) charts include a chronology, LPAZ, and a simplified sediment stratigraphy (for detail see ESM2 Table 3). Supplementary material pertaining to pollen percentage values (≥ 1% TLP) that exclude Cyperaceae are given in ESM2 Figs. 1 and 2 (respectively). Ordination data is featured in Fig. 8a and 8b.

LPAZ and sediment properties for HEL I-IV

HEL I (Fig. 3, 43.50–37.75 cm, ca. AD 711–885)

Woody peats define sediments until they are truncated by the AD 877 LTL (40 cm) with OM values (Fig. 7a) as high as 84.5% (64.5–40 cm). DBD and MS (Fig. 7a) are low (< 0.5 g/cm^3 and 10 SI respectively) with increases only associated with the AD 877 LTL. Cyperaceae (40.9% to 61.7%) is increasingly dominant while *Betula* and *Empetrum nigrum* initially vie for sub-dominance before *Betula* (38%) ultimately replaces *E. nigrum* (5%) at 38.25 cm (ca. AD 864), the initial shift arising at 41.25 cm (ca. AD 819). This change also sees values for Ericales (3.9% to 0%), *Filipendula ulmaria* (8.3% to < 3%) and *Angelica* indet. (1.7% to < 1%) fall, as do those of *Sphagnum* (182.5% to 28%). These alterations in the ratios between species and taxa are also apparent with regard to pollen concentrations (Fig. 4). PCA (Fig. 8a) clearly distinguishes HEL I from the later LPAZ with taxa characteristic of natural vegetation where grazing is absent, e.g. *Betula*, Ericales, *Angelica* indet. and *F. ulmaria*. Traces of microscopic charcoal are present (≤ 5%).

HEL II (Fig. 3, 37.75–28 cm, ca. AD 885–1235)

The sedimentary context is now defined by a silty peat and is truncated by tephra deposits at 37 cm (ca. AD 917) and 28.50 cm (ca. AD 1219). Both tephra deposits have a negative impact upon OM values (Fig. 7a) with the interim period characterised by a peak OM of 60.2% (34.50 cm) and OM does not recover to the level of HEL I. Cyperaceae is

Table 2 Interpretation of tephra layers for HEL

Depth (cm)	Origin	Name	Cal BP (1950)	BC/AD	References
7.5	Katla	n/a	n/a	n/a	n/a
18–20	Katla	n/a	450	AD 1500	Hafliðason et al. (1992) and Eiríksson et al. (2000)
28–28.5	Reykjanes (marine)	Medieval	724	AD 1226	Jóhannesson and Einarsson (1988)
37	Katla?	n/a	1030?	AD 920?	Hafliðason et al. (1992)
38–40	Veiðivötn/Torfajökull	LTL	1073	AD 877	Schmid et al. (2017)
54.5–55	Katla	n/a	n/a	n/a	n/a
63–64	Hekla	A	2430	480 BC	Larsen et al. (2020)

Table 3 Tephra layers and dates for ÁSB2

Depth (cm)	Origin	Name	Cal BP (1950)	Cal. AD	Reference
25.5–26	Hekla	H1	846	1104	Eiríksson et al. (2000)
40.5–41	Katla	n/a	1030	920	Hafliðason et al. (1992)
42–42.5	Veiðivötn	LTL	1073	877	Schmid et al. (2017)

Table 4 Radiocarbon dates for ÁSB2

Code	Depth (cm)	^{14}C date (BP)	Error 1σ	δ ^{13}C (‰)	Cal. age (AD) 2σ	Weight (mg)	Material
ETH-107374	14–14.5	476	21	– 29.9	1416–1448	1.5	Wood and bark
ETH-97880	18–19	584	20	– 29.7	1307–1411	1.5	Wood
ETH-109395	50–51	1630	23	29.10	404–538	1.5	Wood and bark

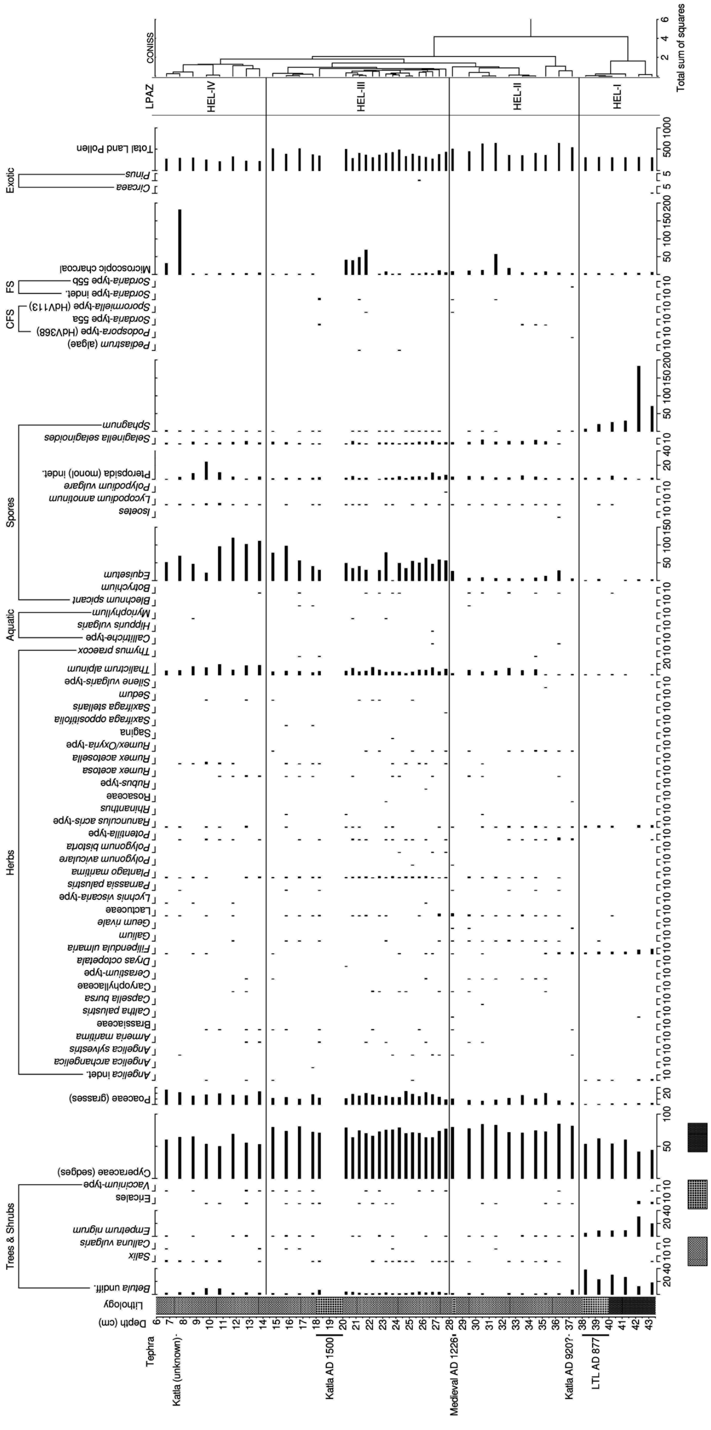


Fig. 3 Pollen percentage diagram for HEL and LPAZ

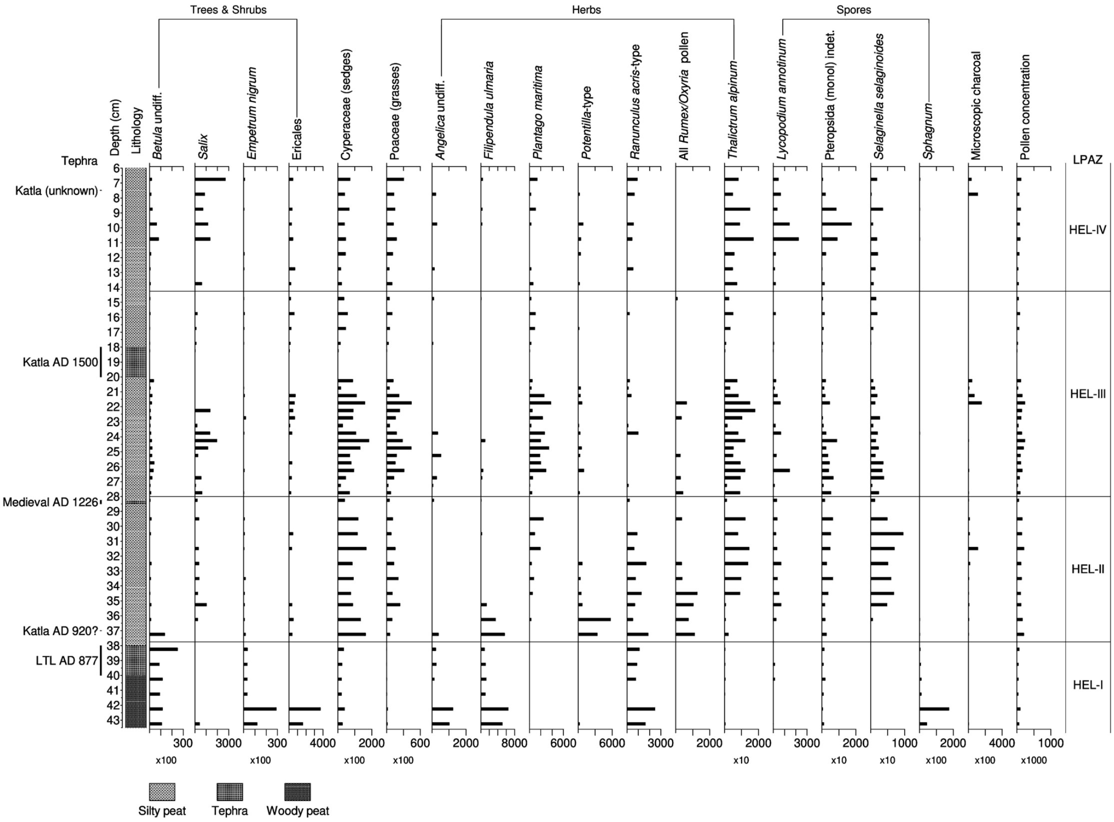


Fig. 4 Pollen concentration diagram for HEL, selected taxa and species ≥ 1% TLP

dominant with values higher than those of HEL I, sustained within a range of 70.8% (33.5 cm) and 84.4% (36.25 cm). Poaceae values rise and fluctuate between 6.1% (36.25) and 19.5% (35.25). Concentration data for HEL II (Fig. 4) suggest that variation between Cyperaceae and Poaceae values correspond. Some pollen and spore taxa occur for the first time e.g. *Plantago maritima*, *Potentilla*-type, *Rumex*/*Oxyria* undiff. and *Selaginella selaginoides,* and are accompanied by CFS (*Podospora*-type and *Sordaria*-type 55a). *Thalictrum alpinum* values increase noticeably (5.6% to 11.6%, 34.5–29.5 cm, AD 1050–1186). Notably, from 37.25 cm (ca. AD 906), values for *Sphagnum* and *Angelica* spp. collapse (≤ 1%), *E. nigrum* values drop to ≤ 1.4%, a pattern also followed by *Betula* (< 1%, 36.25 cm, ca. AD 947). PCA (Fig. 8a) presents a stark contrast to the previous LPAZ (HEL I) with an open landscape dominated by Cyperaceae.

HEL III (Fig. 3, 28–14.25 cm, ca. AD 1235–1614)

The sedimentary context continues to be defined by silty peat with the only disruption to the strata occurring with a tephra deposit at 20 cm (Katla AD 1500). This relative stability is also evident with regard to MS and DBD (Fig. 7a) while, as with HEL II, OM recovers to 60.7% (23.50 cm) between the tephra deposits of AD 1226 and 1500. Following AD 1500, OM rises to 53.5% (15.50 cm). Cyperaceae continues to dominate (range 63.2% to 80.3%) but Poaceae values are now consistently above 10, and can be as high as 23% (24.75, ca. AD 1360). The increasing presence of Poaceae is reflected in the PCA (Fig. 8a) and suggests a strong relationship between Poaceae, *Th. alpinum*, *P. maritima* and *S. selaginoides;* all of which also present persistent and/or high pollen concentration values (Fig. 4). *Angelica sylvestris* (< 1%) and *F. ulmaria* (< 1%) make a tentative reappearance as does *Betula* (≤ 6.1%). There is a spike in microscopic charcoal values (56.1%) at 31.5 cm (ca. AD 1119), although high values (38.2%

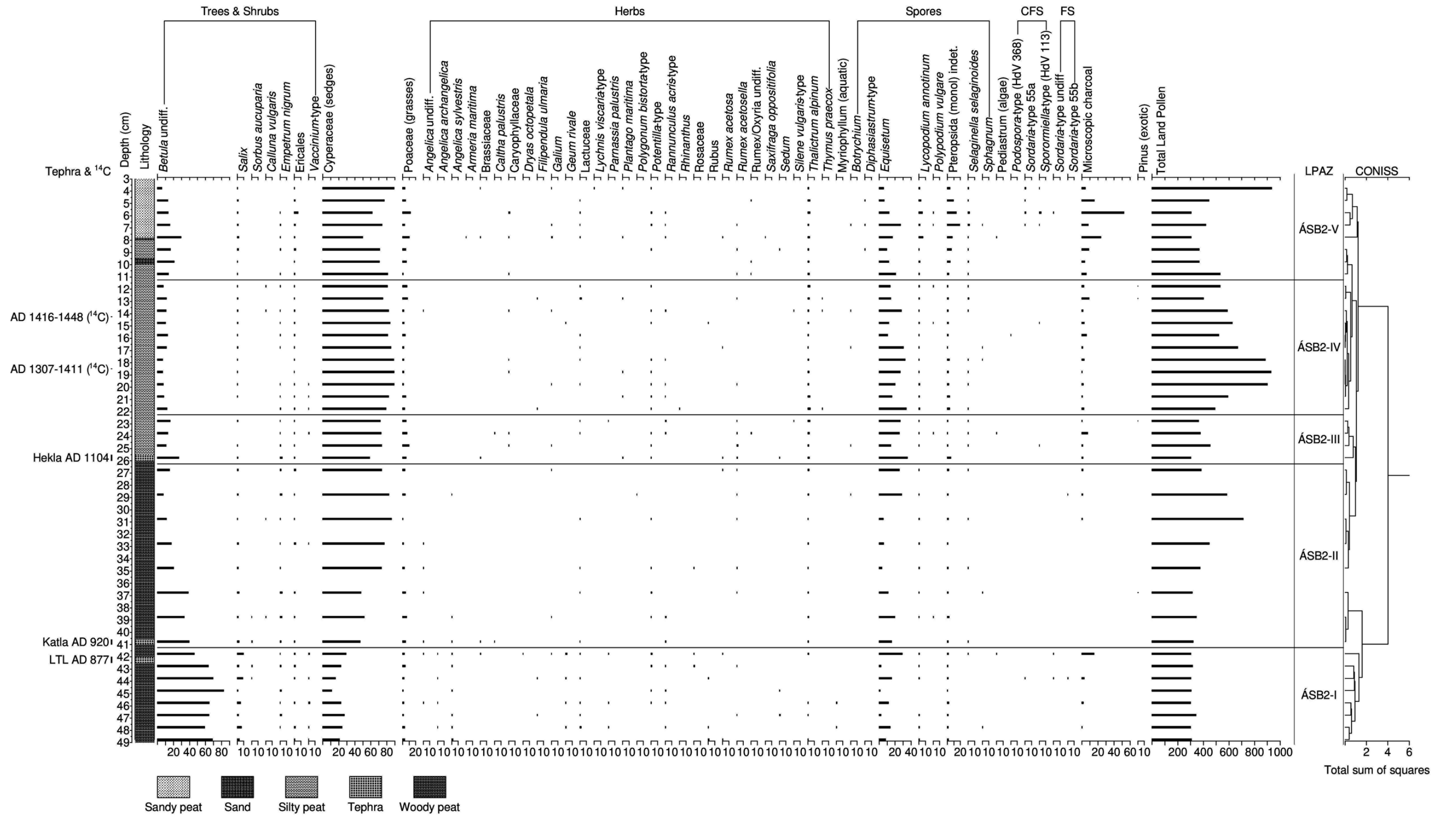


Fig. 5 Pollen percentage diagram for ÁSB2 and LPAZ

to 68.1%) are more consistent between 21.75–20.25 cm (ca. AD 1442–1500).

HEL IV: (Fig. 3, 14.25–6 cm, AD 1614–1850)

Sediments continue to be comprised of silty peats with a declining trend for MS and DBD toward 6 cm (ca. AD 1850) while OM values climb to 57% (Fig. 7a). The cryptic Katla tephra at 7.5 cm (ca. AD 1809) is invisible other than with regard to MS (Fig. 7a). Cyperaceae experiences a range of values sustained between 49.5% and 68.6%, lower compared with the previous range for HEL III, and the overall trend is one of decreasing presence (although it remains dominant). Conversely, Poaceae presents a continuing upward trend, always above 14.6%, and culminating at 25.6% (6.75 cm, ca. AD 1829). Pteropsida (monolete) indet. (≤ 24.3%, 9.75 cm, ca. AD 1745) and *Equisetum* (≤ 110.3%, 13.75 cm, ca. AD 1629) are well represented, the latter particularly visible in the PCA (Fig. 8a). A recovery is observed above 10.75 cm (ca. AD 1717) for both *Betula* (≤ 8.8%) and *Salix* (≤ 1.9%), although it is only the latter that persists in the longer term (this trend also shown in the concentration values for *Betula* and *Salix*, Fig. 4). Microscopic charcoal is of little significance (< 1%) until 7.75 cm with a leap to 180.7% (ca. AD 1802).

LPAZ and sediment properties for ÁSB2 I-V

ÁSB2 I (Fig. 5, 49–41.25 cm, ca. AD 550–913)

Outwith the deposition of the LTL AD 877 (42.5–42 cm) tephra (Fig. 7b), there is no significant change to the peat stratigraphy. OM values are initially relatively high (58%, 48.75 cm) but are situated within a longer-term decline in values with the lowest (ca. 25%, 42.75 cm) associated with the deposition of the LTL. *Betula* is dominant (range 46% to 82.6%), the PCA (Fig. 8b) emphasising this further. Cyperaceae (≤ 28.8%), Poaceae (≤ 3.8%), Salix (≤ 9.3%), Ericales and *E. nigrum* (≤ 1.6% and ≤ 2% respectively), *Vaccinium*-type (≤ 2%), along with *A. archangelica* (≤ 0.3%), *A. sylvestris* (≤ 1%) and *Geum rivale* (≤ 2%), retain a presence throughout ÁSB2; also a feature of pollen concentration (Fig. 6). A peak in microscopic charcoal occurs ca. AD 899 (14.9%, 41.75 cm). CFS (*Sordaria*-type 55a) values are very low.

ÁSB2 II (Fig. 5, 41.25–26.25 cm, AD 913–1101)

There is no significant alteration to the peat strata other than the deposition of the Katla AD 920 tephra (41 cm), its presence conveyed in varying degrees by MS, DBD and OM (Fig. 7b). However, the ongoing gradual decline in OM values is mirrored by increases in MS values (Fig. 7b). DBD values remain relatively stable with only minor fluctuations (Fig. 7b). Between ca. AD 920 and 1101 *Betula* values range between 39.3% (40.75 cm, ca. AD 926) and 7% (28.75 cm, ca. AD 1075) with a declining trend matched also by *Salix* (≤ 3%). *Empetrum nigrum* and Ericales values increase (≤ 3.2% and ≤ 2.3% respectively). *Vaccinium*-type virtually disappears. Cyperaceae values increase considerably (≤ 85.7%). The values of Poaceae vary with an initial increase to 6.1% (38.75 cm, ca. AD 968), a decline to pre-AD 877 levels, before rising again to 4% (26.75 cm, ca. AD 1091). *Th. alpinum* and *S. selaginoides* are more persistent than previously, trends in their values following those of Poaceae. Grazing sensitive taxa such as *Angelica* spp. gradually disappear or are absent e.g. *F. ulmaria*. These trends in percentage values also appear in pollen concentrations (Fig. 6) and a shift toward a more open landscape is indicated in the PCA (Fig. 8b). CFS and microscopic charcoal barely register.

ÁSB2 III (Fig. 5, 26.25–22.25 cm, AD 1101–1205)

Peat sediments become more minerogenic following the deposition of the Hekla AD 1104 tephra (26 cm) with the impact of the eruption most readily observed at 24.5 cm with regard to DBD and OM (Fig. 7b). However, a later peak in MS (23 cm, ca. AD 1183) marks the beginning of a longer term, more persistent, increase in MS values. There is a recovery in *Betula* values (26.4%, 25.75 cm, ca. AD 1111) which persist at levels between 10.8% (24.75 cm, ca. AD 1134) and 15.7% (22.75 cm, ca. AD 1190). Cyperaceae values fall to 58.4% (25.75 cm, ca. AD 1111) and remain lower than those of LPAZ II. Poaceae values rise to 9.7% (24.75 cm, ca. AD 1134) and remain above 5.2% from 22.75 cm (ca. AD 1190), this increase more obvious in the pollen concentration data (Fig. 6). More generally, new apophytic taxa and species appear e.g. Caryophyllaceae, *P. maritima*, while in other instances, values increase, especially for *Rumex acetosella* (≤ 2.2%) and *Th. alpinum* (≤ 3%). CFS (*Sporormiella*-type HdV 113) values are low (< 1%) in contrast to microscopic charcoal which retains a presence and rises to 7.2% (23.75 cm, ca. AD 1161).

ÁSB2 IV (Fig. 5, 22.25–11.25 cm, AD 1205–1541)

There is greater fluctuation in MS, DBD and OM values with an overall increase in minerogenic inputs (Fig. 7b). Cyperaceae is dominant (≤ 89.1%, 18.75 cm, ca. AD 1313), readily observed in the PCA (Fig. 8b). Although Poaceae values increase (7.7%, 12.75 cm, ca. AD 1489), Cyperaceae values never fall below 74.8% (12.75 cm, ca. AD 1489), a pattern echoed in the pollen concentration data (Fig. 6). The decline of *Betula* continues but it remains above 6.2% and

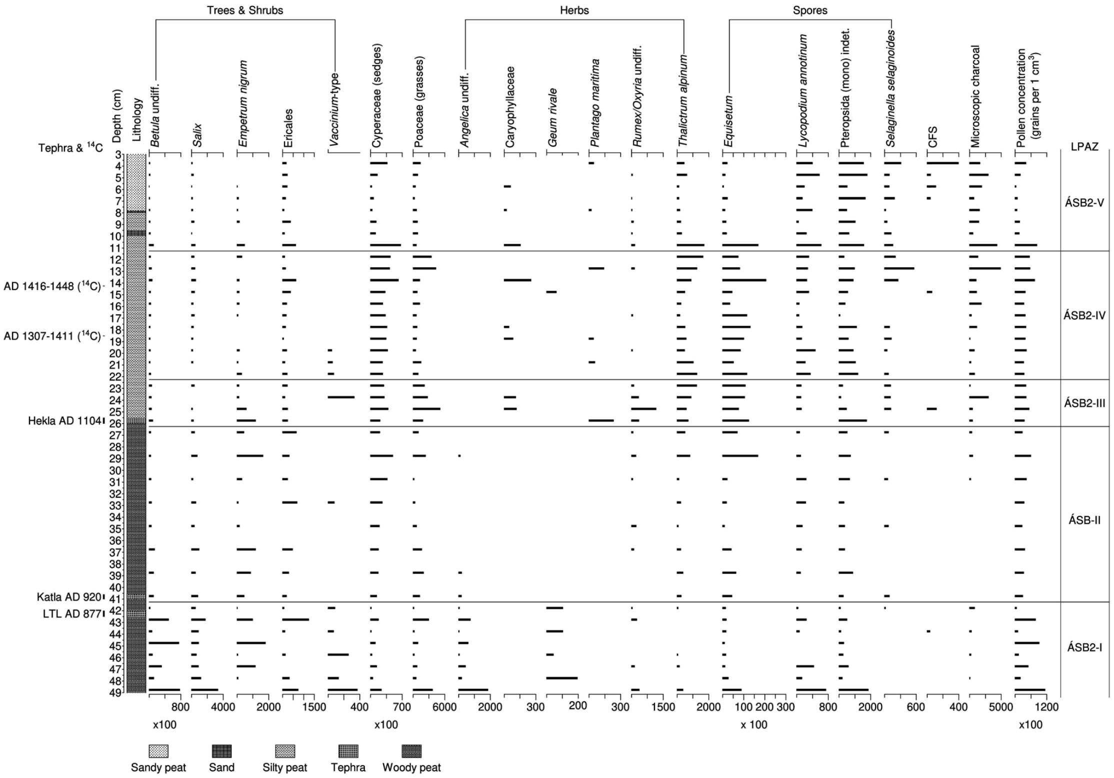


Fig. 6 Pollen concentration diagram for ÁSB2, selected taxa and species ≥ 1% TLP

even recovers to 12.3% (15.75 cm, ca. AD 1398). The signals for *Salix*, Ericales and *E. nigrum* are low (< 1%) but persist. There is a general increase in microscopic charcoal with a peak of 8.7% (12.75 cm, ca. AD 1489). The CFS (*Podospora*- and *Sporormiella*-type HdV 113) signal is relatively mute.

ÁSB2 V (Fig. 5, 11.25–3 cm, AD 1541–1882)

The sedimentary strata are significantly altered with bands of sand truncating the peat sequence at 10 cm (ca. AD 1587) and 8 cm (ca. AD 1666) and with an increased minerogenic input from 7.8 cm (ca. 1676). This disturbance is equally apparent with regard to MS, DBD and OM (Fig. 7b). Trees and shrub values increase, *Betula* (≤ 29.3%), *Salix* (≤ 2.3%), Ericales (≤ 5.9%) and *E. nigrum* (≤ 1%). Conversely, Cyperaceae values fall to 49.7% (7.75 cm, ca. AD 1676), also obvious in the pollen concentration data (Fig. 6), to recover at 3.75 cm (89.1%, ca. AD 1848) with a corresponding drop in *Betula* (5.3%), *Salix* (0.2%) and Ericales (0.4%). Poaceae experiences an initial decline (0.8%, 10.75 cm, ca. AD 1559) but increases to values spanning 3.1% (6.75 cm, ca. AD 1718) to 11.8% (5.75 cm, ca. AD 1760), visible in the PCA (Fig. 8b). *Equisetum* increases to 26.8% (6.75 cm, ca. AD 1718) while *Lycopodium annotinum* (≤ 5.9%, 7.75 cm, ca. AD 1676) and Pteropsida (monolete) indet. (≤ 19.1%, 6.75 cm, ca. AD 1718) reach peak values, and according to the PCA (Fig. 8b), are associated with Poaceae. With regard to CFS, the signal becomes much stronger i.e. a consistent signal for *Sordaria*-type HdV 55a from 7 cm (AD 1707) with *Sporormiella*-type HdV 113 attaining values of 3% (6 cm, ca. AD 1750). Similarly, an ongoing increase in microscopic charcoal becomes more marked, peaking at 52.3% (5.75 cm, ca. AD 1760).

Discussion

Landnám at Helgadalur (ca. AD 723–1235)

The earliest samples from HEL (Fig. 3, from 43.25 cm, ca. AD 723) suggest a Cyperaceae dominated wetland incorporating other species and taxa such as *Betula*, *E. nigrum*, *Angelica* indet., *F. ulmaria* and *Sphagnum*. However, while

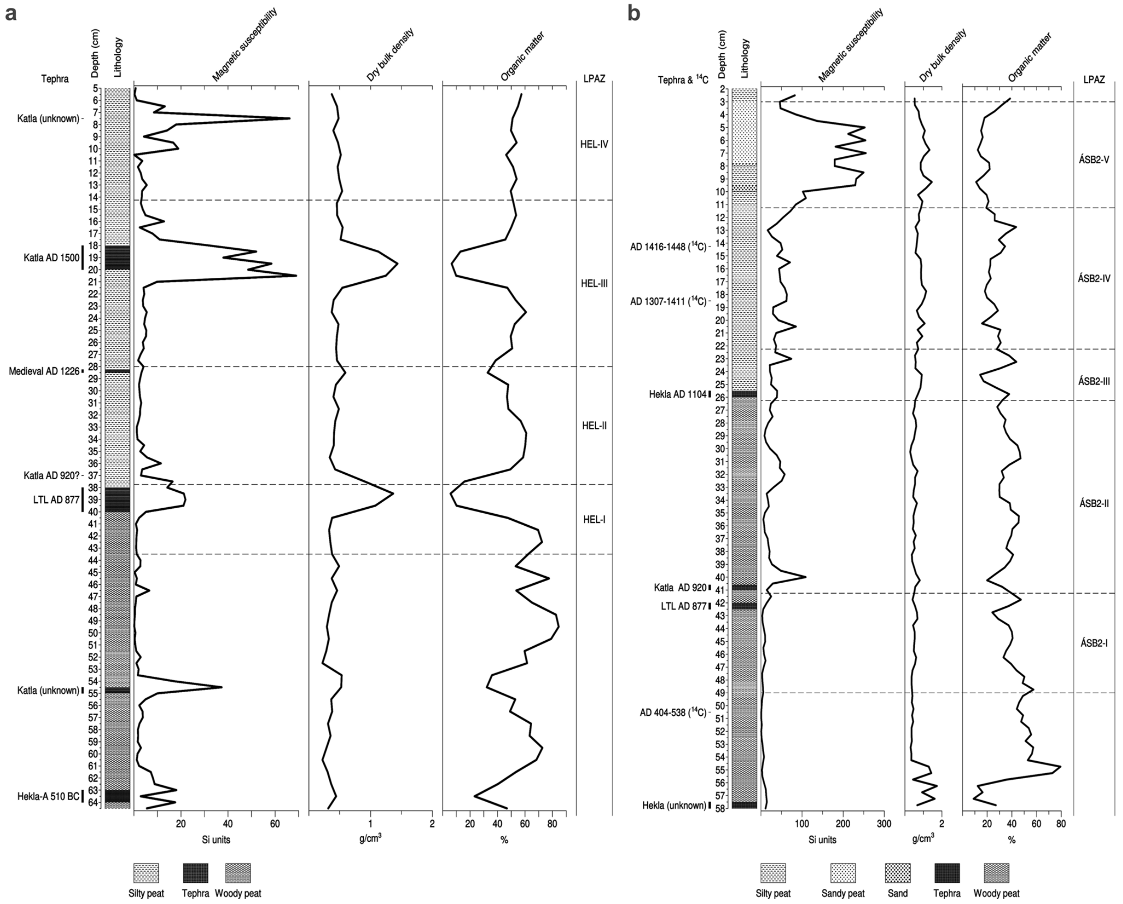


Fig. 7 Sedimentary properties for HEL (**a**) and ÁSB2 (**b**)

Cyperaceae remains dominant, *Betula* displaces *E. nigrum*, *Angelica* indet. and *F. ulmaria* (41.25 cm, ca. AD 819) to become sub-dominant until Landnám (ca. AD 877). This may be linked to climate amelioration, the expansion of *Betula* dominated habitats a recognised feature of south west Iceland at this time (Erlendsson and Edwards 2009). Warmer summer temperatures may have lowered, or given rise to fluctuations in the water table due to lower precipitation and increased evaporation (Charman 2002). Such conditions could have been sufficient to encourage colonisation by *Betula*, which in itself would contribute further (through evapotranspiration) to the drying out of the mire (Berglund 1985). A notable reduction in *Sphagnum* values (Fig. 3, 41.25 cm, ca. AD 819) reinforces the perception of a reduction in moisture in the mire. Nonetheless, the sedimentary context remains stable and organically rich (Fig. 7a, OM 72.5%, 42.50 cm, ca. AD 761). There are traces of microscopic charcoal (≤ 5%) present within the profile prior to the deposition of the LTL ca. AD 877 (Fig. 3). In the absence of other anthropogenic indicators, charcoal may be derived as windblown material from Europe (Duncan and Bey 2004) or, closer to home, residual charcoal arising from vegetation burnt during volcanic eruptions (Buckland et al. 1995).

From ca. AD 877, a Cyperaceae dominated wetland persists. However, species and taxa (Fig. 3) sensitive to grazing by livestock (as represented by *Sordaria*-type 55a CFS) e.g. *Betula*, *Salix*, *Angelica* and *F. ulmaria*, go into decline while values for Poaceae increase and the landscape is occupied by a new suite of plants that favour open terrain e.g. *P. maritima, Potentilla*-type, *Rumex/Oxyria*-type, *S. selaginoides* and Lycopodiaceae (Edwards et al. 2011). In hand with a drop in peak OM (Fig. 7a) values (independent of tephra deposition) between HEL I (72.4%)

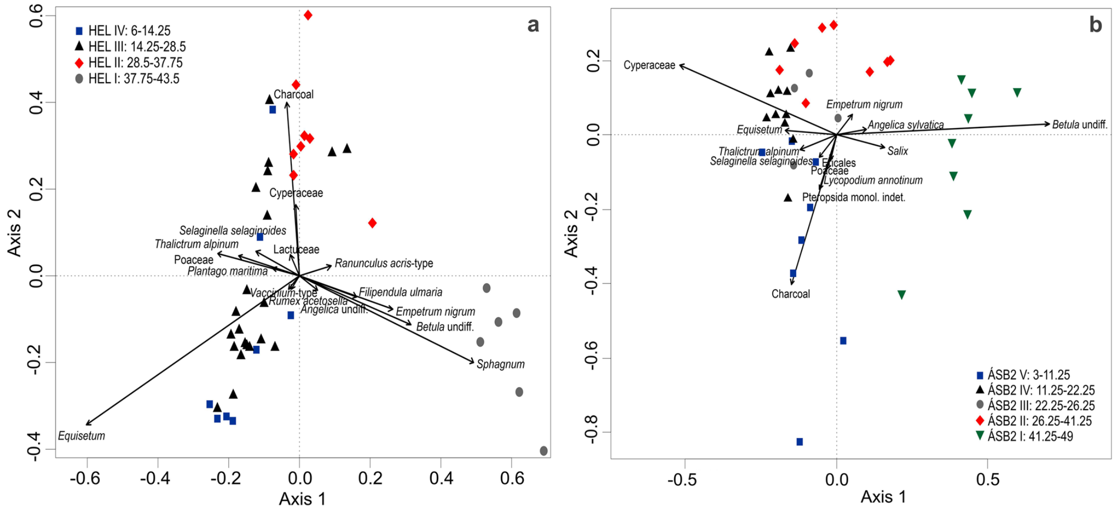


Fig. 8 Principal Component Analysis (PCA) for HEL (**a**) and ÁSB2 (**b**)

and HEL II (60.2%), the changes in the vegetation are indicative of a human presence within the landscape of Helgadalur (Hallsdóttir 1987; Erlendsson 2007; Edwards et al. 2021). In particular, raised values for *Th. alpinum* could indicate that land in the vicinity of HEL was being utilised as a wetland hay meadow (Fjordheim et al. 2018), an important feature of subsistence farming in medieval Iceland (Vésteinsson 1998–2001). The peak in microscopic charcoal ca. AD 1119 (Fig. 3, 56.1%, 31.50 cm) is probably associated with household activity (Buckland et al. 1995), a smokehouse, smithing/smelting (Eyþórsson et al. 2018), household waste dumped or spread as fertiliser (Riddell et al. 2018a), charcoal production (Church et al. 2007), or *sinubruni* (a tradition of burning plant litter in the spring, aimed at returning nutrients to the soil, thought to have begun in Iceland in the 20th century, but which may have arisen earlier).

Transhumance or abandonment at Helgadalur … or just making hay? (ad 1235–1550)

There is now a more persistent signal for grassland (Poaceae) at Helgadalur (Fig. 3, HEL III and HEL IV) with levels remaining above 10% beyond AD 1500 (20–18 cm). This comes at the expense of Cyperaceae although it remains the dominant vegetation. Though not entirely within the scope of this study, the pollen profile would suggest that the ongoing development of grassland is a primary feature of Helgadalur into the modern period (Fig. 3, HEL IV, 14.25–6 cm, AD 1616–1850). This would imply that land use is exclusively directed toward livestock grazing but sensitive species such as *Betula* and *Salix* persist along with phases of recovery in *Angelica* and *F. ulmaria*, while CFS values are low. The latter in particular might suggest periods of abandonment, seasonal grazing, or grazing at low livestock densities (Davies 2019). That microscopic charcoal is present (often at relatively high values) throughout the HEL (Fig. 3) sequence from Landnám runs counter to any interpretation concerning abandonment (Edwards et al. 2011). Therefore, one possibility is that Helgadalur periodically functioned as a *sel* (a shieling), a feature of seasonal transhumance (Lucas 2008; Kupiec et al. 2016). However, the CFS record for Helgadalur is rather poor throughout the sediment stratigraphy even though historical records identify animals there in the early 16th (DI-XII 1857–1986) and early 18th century (Magnússon and Vídalín 1926), while numbers were presumably even higher in the 19th and 20th centuries (Ross et al. 2016; Júlíusson 2020). CFS are extremely localised in terms of their dispersal, abundance bound by factors such as the duration of time livestock occupy an area as well as the size of the livestock population (Davies 2019). Perhaps the intermittent CFS record at Helgadalur is a consequence of the coring site being remote from the farmstead. Even so, it does suggest that the area within the landholding in which the HEL core lies was subject only to low density livestock grazing or periodic utilisation. This therefore reinforces the impression that HEL is situated within a wetland pasture reserved for haymaking, coincident with a persistent, post-Landnám, signal for *Th. alpinum* (Fig. 3, ≤ 13.1%, 27.75–20 cm, ca. AD 1243–1500), and explains the presence of grazing sensitive taxa and species like *Angelica* and *F. ulmaria*. The isolated peak in CFS (Fig. 3, 1.8%, 18.25 cm) associated with the

Katla AD 1500 tephra layer might represent a temporary corralling of animals near HEL in response to the eruption (Edwards et al. 2004).

Landnám at Ásbjarnarnes (ca. AD 877–1370)

Prior to Landnám (42.50–42 cm), vegetation cover at Ásbjarnarnes (Fig. 5) was dominated by *Betula* (between 59 and 82.6%) with Cyperaceae sub-dominant (between 11.2% and 28.8%). Sediments (Fig. 7b) remain unaltered following the deposition of the LTL (except for the AD 920 tephra layer, 41–40.60 cm) and while *Betula* (Fig. 5) values drop, this is gradual, and they remain above 7% through the 10th and into the 11th century. A brief pulse in microscopic charcoal values ca. AD 899 (Fig. 5, 14.9%, 41.75 cm) may represent an initial phase of human occupation but it is striking that microscopic charcoal is absent from the record from the early 10th century until the late 11th century, possibly allied with the albeit declining, but prevailing, presence of *Betula* in this period. The CFS signal is also very weak or non-existent for the medieval period as a whole and, as with Helgadalur, values may be subdued due to variables related to livestock abundance and/or distribution within the landholding (Davies 2019). That said, declines in grazing sensitive species and taxa e.g. *A. archangelica*, *A. sylvestris*, *F. ulmaria*, *Geum rivale*, *Parnassia palustris* and *Vaccinium*-type (Edwards et al. 2011) do occur following AD 920 (Fig. 5). Concurrently, we see an increase in values for Cyperaceae and Poaceae while the *Th. alpinum* signal is more consistent, implying the opening of a scrub/woodland canopy. With specific reference to the MS, DBD and OM data (Fig. 7b), following the deposition of the AD 1104 tephra (26 cm), a minerogenic element is introduced to a hitherto, exclusively (bar tephra deposits), peat dominated sequence. This is coincident with increased pollen values indicative of anthropogenic activity (Fig. 5) i.e. the stronger presence of apophytic taxa (Caryophyllaceae, *P. maritima*, *Rumex acetosa* and *R. acetosella*) microscopic charcoal, and CFS (especially after ca. AD 1370, 16.75 cm). Sedimentary changes occurring in the early 12th century may therefore relate to the inception of erosion on the higher ground of Ásbjarnarnes in the vicinity of ÁSB2, perhaps a consequence of livestock grazing cf. Dugmore et al. (2009) and Gísladóttir et al. (2010); it is too early to attribute this to the onset of the LIA (Ogilvie and Jónsson 2001).

Overall, despite references to Ásbjarnarnes in the quasi-historical texts (Friðriksson and Vésteinsson 2003; Woolf 2007) of Landnámabók (Pálsson and Edwards 1972) and Laxdæla saga (Sveinsson 1934), ostensibly accounts of the Icelandic settlement, it would appear that the arrival of humankind at Ásbjarnarnes in the late 9th century was somewhat muted; a feature comparable with other sites in northern Iceland (Lawson et al. 2007; Riddell et al. 2018b; Roy et al. 2018; Tisdall et al. 2018). It has been mooted that active scrub/woodland clearance was deliberately avoided by early settlers as too labour intensive (Vickers et al. 2011), while it has also been suggested that early settlers utilised coastal sites like Ásbjarnarnes only as a beachhead before moving inland to settle permanently (Smith 1995), which may explain the limited palaeoecological indication of human settlement there. Perhaps, if saga narratives are to be believed, Ásbjarnarnes was inhabited but the initial focus during this period was predicated upon shore rights and access to driftwood, sealing, whale wrecks and fishing as testified to by later 14th (DI-II 1857–1986; DI-III 1857–1986) and 15th (DI-V 1857–1986) century documents. This would not preclude the exploitation of terrestrial resources, but subsistence might not have been entirely dependent upon them. Therefore, based on the close proximity between ÁSB2 and the farmstead (and the premise that ÁSB2 is capturing a local palynomorph signal), from Landnám until the early 12th century, Ásbjarnarnes seems to have been largely uninhabited or utilised only for low-density livestock grazing, perhaps seasonally e.g. winter grazing and shelter (Hejcman et al. 2016). Indeed, it is only from the early 13th century (Fig. 5, 22.25 cm, ca. AD 1205) that the series of anthropogenic proxies intimating tree and shrub clearance become contemporaneous i.e. Cyperaceae has finally become consistently dominant, apophytes persist, and the charcoal signal is increasingly constant and stronger (although the CFS signal remains sparse).

Woodland, coppice and charcoal at Ásbjarnarnes (AD 1361–1600)

In AD 1361, the deed pertaining to the sale of Ásbjarnarnes to Þingeyraklaustur describes an extensive area of "*skog*" (woodland) in the list of resources attached to the farm (DI-III 1857–1986). The description is not entirely clear with regard to area but states that this woodland extended from Hóp westwards across Bjargaás (ca. 2 km; Fig. 1). A later document from AD 1669 identifies the woodland at Ásbjarnarnes as "Nesskógur", the only record of its name, with its exact location and extent unknown (Þorsteinsson 1922–1932). In AD 1705, statements in Jarðabók (Magnússon and Vídalín 1926), clearly distinguishing between woodland, trees and shrubs, also convey that a woodland existed at Ásbjarnarnes down to the mid-17th century. Based upon these historical references to woodland, it may be inferred that a proportion of the *Betula* pollen grains present in the palynological record for ÁSB2 (Fig. 5) is comprised of *B. pubescens*. Woodland in Iceland was seen as an important source of timber (rafters), wood fuel, charcoal (iron smelting and smithing), leaf fodder, winter grazing and shelter for livestock (Magnússon and Vídalín 1926; Vésteinsson and

Simpson 2001; Church et al. 2007; Hejcman et al. 2016); clear incentives to nurture woodlands.

Betula values increase slightly from ca. AD 1370 (Fig. 5, 2%, 16.75 cm) and stabilise (around 10%) in the late 15th century (12.75 cm, ca. AD 1489), the period within which Ásbjarnarnes was subject to Þingeyrarklaustur. This might infer greater rigour imposed by the monastery with regard to managing woodland more sustainably. However, Þingeyrarklaustur did suffer from the depredations of Plague (Riddell et al. 2018b), especially during the earlier outbreak of AD 1402, perhaps allowing scrub there to recover as observed elsewhere in Europe (van Hoof et al. 2006; Yeloff and van Geel 2007; Jónsson 2009). The same may apply at Ásbjarnarnes, although coincident increases in microscopic charcoal values suggest that people remained there. Some Icelandic farms were untouched by plague (Karlsson 1996; Júlíusson 1997) and *Betula* recovery in the 15th century could actually represent altered land management practices in response to plague and human demographics rather than outright abandonment (Streeter et al. 2012).

In a 16th century inventory (DI-XII 1857–1986), Ásbjarnarnes is conspicuous in that it is the only tenant farm of 62 that pays a portion of its rent to Þingeyraklaustur with charcoal (Júlíusson 2014). Charcoal production was also a feature of Ásbjarnarnes in the late 17th century (Magnússon and Vídalín 1926). Given that a charcoal signal at Ásbjarnarnes is consistent from the late 11th century (26.75 cm, ca. AD 1091), in hand with a persistent *Betula* signal, it is possible that charcoal production was an established practice there (bearing in mind that microscopic charcoal as a palynomorph can be derived from other sources in Iceland e.g. volcanism, household smoke, household waste and *sinubruni*). If so, this implies that charcoal production was simply a matter of continuity following the acquisition of Ásbjarnarnes by Þingeyraklaustur although, tentatively, charcoal production may have increased (≤ 8.7%) in terms of output ca. AD 1398–1523 (Fig. 5, 15.75–11.75 cm). Some impact upon *Betula* values would perhaps be expected in relation to the charcoal signal. However, there is none. It has been speculated that some form of coppicing may have been practiced in Iceland in the medieval period (Church et al. 2007); *Betula pubescens* in Iceland is capable of sprouting new shoots from cut stumps which could sustain *Betula* pollen values. It is conjecture, but this may not have necessarily occurred as a conventional coppice rotation (Rackham 1980); coppicing may have been ad hoc at Ásbjarnarnes, with individual trees rather than swathes selected for felling, stool regeneration occurring by default rather than by design, with intervals between harvests longer. This could shroud the removal of trees in terms of *Betula* pollen values and the expected oscillation of said values between the coppice cut and regrowth. That said, the impact of coppicing on *B. pubescens* pollen production in Iceland is unknown, and is poorly understood elsewhere (Bunting et al. 2016). Whatever the case, the fact is that *Betula* persisted at Ásbjarnarnes despite the production of charcoal there, either through limited harvesting, natural regeneration, or coppice stool regrowth. Combined with the limited evidence for the presence of domestic livestock, woodland at Ásbjarnarnes was likely a valued natural resource in the medieval period, as is intimated by the historical archive for AD 1361 (DI-III 1857–1986) and AD 1552 (DI-XII 1857–1986). As an aside, given historical references to it at Ásbjarnarnes (DI-III 1857–1986), driftwood was rarely used as a source of fuel in medieval Iceland and was valued more as a source of timber (Mooney 2018). Beyond the period and context under scrutiny, the survival of woodland at Ásbjarnarnes (Fig. 5, ÁSB2 V, 11.25–3 cm, AD 1541–1882) into the modern period is notable, as is the later disturbance (minerogenic input) manifest in the sediments (Fig. 7b).

Pollen sources for HEL and ÁSB2

It is possible to be reasonably confident that the pre-Landnám pollen assemblages of HEL (Fig. 3) and ÁSB2 (Fig. 5) reflect the local vegetation within (and surrounding) the wetlands sampled. Pollen dispersal over large distances at this time would have been inhibited by greater woodland cover (Berglund 1985; Caseldine 2001; Edwards et al. 2021) and source areas for reworked pollen grains were likely restricted to the active volcanic zone (Möckel et al. 2017) and glacial outwash plains (both some distance from HEL and ÁSB2). Following Landnám, the development of a more open landscape enhances the capacity for pollen to arrive at HEL and ÁSB2 from farther afield (Berglund 1985); not least with regard to *Betula* (Rymer 1973; Eddudóttir et al. 2016). Furthermore, high values for *Betula* pollen grains and Pteropsida (monolete) indet. spores in pollen stratigraphies in Iceland have been associated with the aeolian reworking of sediments (Gathorne-Hardy et al. 2009) disturbed by anthropogenic activity. This may apply to both HEL and ÁSB2. However, there is nothing in the sedimentary record to suggest any significant influx of eroded materials at HEL (Fig. 7a) outwith volcanic ash deposits, while at ÁSB2 (with regard to *Betula*), woodland is a persistent feature of the historical archive (DI-III 1857–1986; Magnússon and Vídalín 1926; Þorsteinsson 1922–1932) between the 14th and 17th century. While it is feasible that pollen originating from overseas can arrive in Iceland (Duncan and Bey 2004; Varga et al. 2021), this is not thought to be significant with regard to interpreting Icelandic pollen profiles (Hättestrand et al. 2008), borne out here by the very limited presence of exotic taxa at HEL and ÁSB2 (Figs. 3 and 5).

Conclusions

The early phases of both HEL and ÁSB2 provide insights into what is effectively a prehistoric period in Iceland (Friðriksson and Vésteinsson 2003). Landnám is visible palaeoecologically at both locations but there is variation in the magnitude of anthropogenic impact, consistent with palynological findings from elsewhere in Iceland as shown by e.g. Riddell et al. (2018a) and Streeter et al. (2015). At HEL, we see a pre-Landnám transition from wetland to woodland to post-Landnám pasture. This hysteresis (Hallsdóttir 1987) is apparent in the sediment stratigraphy (OM), the decline in grazing sensitive plant species, the increase in apophytic plant species, and the presence of CFS. Overall, the medieval period for HEL was focussed upon the development of a hayfield, although some of the palynological attributes attached to the latter could be a consequence of low density and/or seasonal grazing. Significantly, there is no evidence that Viðeyjarklaustur was exerting any direct influence over land management practices at Helgadalur.

The pre-Landnám context at ÁSB2 is of a *Betula* dominated scrub/woodland. The arrival of people at Ásbjarnarnes ca. AD 877 is quite muted in comparison with HEL with no change in sediments and only a gradual decline in *Betula* cover. In fact, it is not until ca. AD 920 that we start to see any real decline in grazing sensitive species and taxa, and although apophytes are present, there is no increase in their range or values until ca. AD 1104 (also in association with sedimentary changes). Overall, human occupation and exploitation of resources at Ásbjarnarnes is gradual; while the environmental proxies for human activity are always present, it is only in the early 13th century that they represent a coherent signal. Analysis of palaeoecological data, in hand with historical documents, suggests that a *B. pubescens* woodland survived at Ábjarnarnes more or less throughout the medieval period and that this may have been linked to charcoal production. There is a very slight possibility that woodland was conserved at Ásbjarnarnes, (with a concomitant increase in charcoal production) once it fell under the aegis of Þingeyraklaustur, but this is inconclusive.

The simplest interpretation of the palaeoecological datasets presented here is that medieval tenancies in Iceland were largely unaffected ecologically by absorption into a manorial system overseen by monasticism. There is neither conclusive evidence of alteration and/or intensification of resource exploitation or grazing, nor is there any evidence of new plant species being introduced at the behest of a monastery (e.g. no Poaceae pollen grains characteristic of cereal-type were identified at either site). These findings might suggest that the respective monastic houses oversaw their tenants' activities with a minimum of investment beyond ensuring rents and tithes were met and that the agricultural innovations of European monasticism were perhaps only restricted to the immediate vicinity of the cloister. However, it is important to bear in mind that opportunities for diversification or alternative agricultural strategies at Helgadalur were limited by daily and seasonal daylight hours. At Ásbjarnarnes the resource focus may have been directed more toward the ocean. Perhaps neither Helgadalur nor Ásbjarnarnes are necessarily representative of monastic tenancies, they are but two properties of the ca. 120 tenancies shared between the monasteries of Viðeyjarklaustur and Þingeyraklaustur. It is however important to bear in mind that nuance concerning phyto-social contexts may be obscured due to the low values for non-Cyperaceae pollen types (Caseldine and Hatton 1994) in the pollen samples. Furthermore, with regard to Helgadalur in particular, the coring site is relatively distant from the farmstead, the centre of human activity within that landholding. Therefore, further palaeoecological evaluation of tenant farms may be required in order to consider more conclusively the influence of both ecclesiastical (and secular) manorial systems on land ownership and land use in medieval Iceland.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00334-021-00861-y.

Acknowledgements The authors would like to thank Susanne Möckel for advice and support with regard to the processing of statistical data, Benjamin D. Hennig for the production of maps, and Glóey Helgudóttir-Finnsdóttir for assistance with translating Icelandic historical texts.

Funding The authors are grateful to the Icelandic Research Fund (RANNIS Grant No. 140983-053, 141842-051, 163290-051, 163290-052, 163290-053) and the Landsvirkjun Energy Fund (Grant No. NÝR-05-2019 and NÝR-07-2020).

References

Aaby B, Berglund BE (1986) Characterization of peat and lake deposits. In: Berglund BE (ed) Handbook of holocene palaeoecology and palaeohydrology. Wiley, Chichester, pp 231–246

Andersen ST (1979) Identification of wild grass and cereal pollen. Danmarks Geologiske Undersøgelse Årbog 1978:69–92

Arnalds Ó, Þorarinsdóttir EF, Metúsalemsson S, Jónsson Á, Grétarsson E, Árnason Á (2001) Soil erosion in Iceland. Soil Conservation Service and the Agricultural Research Institute, Iceland

Aston M (2000) Monasteries in the landscape. Tempus, Stroud

Berglund BE (1985) Early agriculture in scandinavia: research problems related to pollen-analytical studies. Nor Archaeol Rev 18:77–90

Birks HJB, Birks HH (1980) Quaternary palaeoecology. Edward Arnold, London

Björck S, Persson T, Kristersson I (1978) Comparison of two concentration methods for pollen in minerogenic sediments. Geologiska Föreningen i Stockholm Förhandlingar 100:107–111

Blaauw M (2010) Methods and code for 'classical' age-modelling of radiocarbon sequences. Quat Geochronol 5:512–518

Bolender D, Johnson E, Bello G (2020) Tenancy, finance, and access to commercial goods: Interpreting impoverished assemblages in Skagafjörður, Iceland, CE 1300–1900. J Anthropol Archaeol 60:101,227

Bond J (2004) Monastic landscapes. Tempus, Stroud

Bonny AP (1972) A method for determing absolute pollen frequencies in lake sediments. New Phytol 71:393–405

Brady NC, Weil RR (1996) Elements of the nature and properties of soils. Pearson Prentice-Hall, Upper Saddle River

Breitenlechner E, Hilber M, Lutz J, Kathrein Y, Unterkircher A, Oeggl K (2010) The impact of mining activities on the environment reflected by pollen, charcoal and geochemical analyses. J Archaeol Sci 37:1,458–1,467

Buckland PC, Edwards KJ, Blackford J, Dugmore AJ, Sadler JP, Sveinbjarnardóttir G (1995) A question of Landnám: pollen, charcoal and insect studies on Papey, eastern Iceland. In: Butlin R, Roberts N (eds) Ecological relations in historical times: human impact and adaption. Blackwell, Oxford, pp 245–264

Bunting MJ, Grant MJ, Waller M (2016) Approaches to quantitative reconstruction of woody vegetation in managed woodlands from pollen records. Rev Palaeobot Palynol 225:53–66

Caseldine C (2001) Changes in *Betula* in the Holocene record from Iceland—a palaeoclimatic record or evidence for early Holocene hybridisation? Rev Palaeobot Palynol 117:139–152

Caseldine C, Hatton J (1994) Interpretation of Holocene climatic change for the Eyjaförður area of northern Iceland from pollen-analytical data: Comments and preliminary results. Environmental Change in Iceland. Münchener Geographische Abhandlungen, Reihe B 12:41–62

Charman D (2002) Peatlands and environmental change. Wiley, Chichester

Church MJ, Dugmore AJ, Mairs KA et al (2007) Charcoal production during the Norse and early medieval periods in Eyjafjallahreppur, southern Iceland. Radiocarbon 49:659–672

Cugny C, Mazier F, Galop D (2010) Modern and fossil non-pollen palynomorphs from the Basque mountains (western Pyrenees, France): the use of coprophilous fungi to reconstruct pastoral activity. Veget Hist Archaeobot 19:391–408

Davies AL (2019) Dung fungi as an indicator of large herbivore dynamics in peatlands. Rev Palaeobot Palynol 271:104,108

Dearing JA (1994) Environmental magnetic susceptibility. Using the Bartington MS2 system. Chi Publishing, Kenilworth

DI-I-XVI (1857–1986) Diplomatarium Íslandicum: Íslenzkt fornbréfasafn, Vol I-XVI. Íslenzka bókmenntafélagið, Kaupmannahöfn

Dugmore AJ, Gísladóttir G, Simpson IA, Newton A (2009) Conceptual models of 1200 years of Icelandic soil erosion reconstructed using tephrochronology. J North Atl 2:1–18

Duncan BN, Bey I (2004) A modeling study of the export pathways of pollution from Europe: seasonal and interannual variations (1987–1997). J Geophys Res: Atmos 109:D08301

Eddudóttir SD, Erlendsson E, Gísladóttir G (2015) Life on the periphery is tough: vegetation in Northwest Iceland and its responses to early-Holocene warmth and later climate fluctuations. Holocene 25:1,437–1,453

Eddudóttir SD, Erlendsson E, Tinganelli L, Gísladóttir G (2016) Climate change and human impact in a sensitive ecosystem: the Holocene environment of the Northwest Icelandic highland margin. Boreas 45:715–728

Eddudóttir SD, Erlendsson E, Gísladóttir G (2017) Effects of the Hekla 4 tephra on vegetation in Northwest Iceland. Veget Hist Archaeobot 26:389–402

Eddudóttir SD, Erlendsson E, Gisladottir G (2020) Landscape change in the Icelandic highland: a long-term record of the impacts of land use, climate and volcanism. Quat Sci Rev 240:106,363

Edwards KJ, Dugmore AJ, Blackford JJ (2004) Vegetational response to tephra deposition and land-use change in Iceland: a modern analogue and multiple working hypothesis approach to tephropalynology. Polar Rec 40:113–120

Edwards KJ, Erlendsson E, Schofield JE (2011) Is there a Norse 'footprint' in North Atlantic pollen records? In: Sigmundsson S (ed) Viking settlements and Viking society: papers from the proceedings of the sixteenth viking congress, Reykjavík and Reykholt, 16th-23rd August 2009. Hið íslenzka fornleifafélag & University of Island Press, Reykjavík, pp 65–82

Edwards KJ, Bennett KD, Davies AL (2019) Palaeoecological perspectives on Holocene environmental change in Scotland. Earth Environ Sci Trans R Soc Edinb 110:199–217

Edwards KJ, Erlendsson E, Schofield JE (2021) Landnám and the North Atlantic flora. In: Panagiotakopulu E, Sadler JP (eds) Biogeography in the sub-arctic: the past and future of North Atlantic biota. Wiley, Chichester, pp 185–214

Eiríksson J, Knudsen KL, Haflidason H, Heinemeier J (2000) Chronology of late Holocene climatic events in the northern North Atlantic based on AMS ^{14}C dates and tephra markers from the volcano Hekla, Iceland. J Quat Sci 15:573–580

Erlendsson E (2007) Environmental change around the time of the Norse settlement of Iceland. University of Aberdeen, Aberdeen

Erlendsson E, Edwards KJ (2009) The timing and causes of the final pre-settlement expansion of *Betula pubescens* in Iceland. Holocene 19:1,083–1,091

Erlendsson E, Edwards KJ, Lawson I, Vésteinsson O (2006) Can there be a correspondence between Icelandic palynological and settlement evidence. In: Arneborg J, Grønnov B (eds) The dynamics of northern societies. Proceedings of the SILA/NABO conference on Arctic and North Atlantic archaeology, Copenhagen, May 10th-14th, 2004. Studies in archaeology and history 10. National Museum of Denmark, Copenhagen, pp 345–351

Erlendsson E, Edwards KJ, Gísladóttir G (2014) Landscape change, land use, and occupation patterns inferred from two palaeoenvironmental datasets from the Mosfell Valley, SW Iceland. In: Zori D, Byock J (eds) Viking archaeology in Iceland: Mosfell archaeological project. Brepols, Turnhout, pp 181–192

Eyþórsson B, Erlendsson E, Gísladóttir G, Sveinbjarnardóttir G (2018) Natural resources—access and exploitation. In: Sveinbjarnardóttir G, Þorláksson H (eds) Snorri Sturluson and Reykholt; the author and magnate, his life, works and environment at Reykholt in Iceland. Museum Tusculanum Press, Copenhagen, pp 205–234

Fjordheim K, Moen A, Hjelle KL, Bjune AE, Birks HH (2018) Modern pollen–vegetation relationships in traditionally mown and unmanaged boreal rich-fen communities in central Norway. Rev Palaeobot Palynol 251:14–27

Friðriksson A, Vésteinsson O (2003) Creating a past: a historiography of the settlement of Iceland. In: Bennett JH (ed) Contact, continuity, and collapse: the Norse colonization of the North Atlantic. Brepols, Belgium, pp 139–161

Gathorne-Hardy FJ, Erlendsson E, Langdon PG, Edwards KJ (2009) Lake sediment evidence for late Holocene climate change and landscape erosion in western Iceland. J Paleolimnol 42:413–426

Gilchrist R (2014) Monastic and church archaeology. Annu Rev Anthropol 43:235–250

Gísladóttir G, Erlendsson E, Lal R, Bigham J (2010) Erosional effects on terrestrial resources over the last millennium in Reykjanes, southwest Iceland. Quat Res 73:20–32

Grimm EC (2011) Tilia 1.7.16. Illinois State Museum, Springfield

Hafliðason H, Larsen G, Ólafsson G (1992) The recent sedimentation history of Thingvallavatn, Iceland. Oikos 65:80–95

Haldon J, Mordechai L, Newfield TP, Chase AF, Izdebski A, Guzowski P, Labuhn I, Roberts N (2018) History meets palaeoscience: consilience and collaboration in studying past societal responses to environmental change. Proc Natl Acad Sci USA 115:3,210–3,218

Hallsdóttir M (1987) Pollen analytical studies of human influence on vegetation in relation to the Landnám tephra layer in southwest Iceland. University of Lund, Lund

Hallsdóttir M (1993) Frjórannsókn á mósniðum úr Viðey. Raunvísindastofnun Háskólans, Reykjavík

Harrison R (2014) Connecting the land to the sea at Gásir: international exchange and long-term Eyjafjörður ecodynamics in Medieval Iceland. In: Harrison R, Maher R (eds) Human ecodynamics in the North Atlantic: a collaborative model of humans and nature through space and time. Lexington Publishers, Lanham, pp 117–136

Hättestrand M, Jensen C, Hallsdóttir M, Vorren K-D (2008) Modern pollen accumulation rates at the north-western fringe of the European boreal forest. Rev Palaeobot Palynol 151:90–109

Heiri O, Lotter AF, Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. J Paleolimnol 25:101–110

Hejcman M, Hejcmanová P, Pavlů V, Thorhallsdottir AG (2016) Forage quality of leaf fodder from the main woody species in Iceland and its potential use for livestock in the past and present. Grass Forage Sci 71:649–658

Hjelle KL, Halvorsen LS, Overland A (2010) Heathland development and relationship between humans and environment along the coast of western Norway through time. Quat Int 220:133–146

Icelandic Meteorological Office (Veðurstofa Íslands) (2007) Monthly averages (Mánaðameðaltöl) Reykjavik. https://www.vedur.is/vedur/vedurfar/medaltalstoflur/. Accessed 29 Sept 2021

Jakobsson S (2013) From reciprocity to manorialism: on the peasant mode of production in Medieval Iceland. Scand J Hist 38:273–295

Jóhannesson H, Einarsson S (1988) Krísuvíkureldar I. Aldur Ögmundarhrauns Og Miðaldalagsins Jökull 38:71–87

Jóhannesson H, Sæmundsson K (1998) Geological map of Iceland, 1:500,000. Natturufraedistofnun Islands, Reykjavik

Jónsson SA (2009) Vegetation history of Fljótsdalshérað during the last 2000 years: a palynological study. University of Iceland, Reykjavik

Júlíusson ÁD (1997) Bønder i prestens tid: landbrugg, godsdrift og social konflikt i semiddelalderens Islandske bondesamfund. University of Copenhagen, Copenhagen

Júlíusson ÁD (2007) Peasants, aristocracy and state power in Iceland 1400–1650. The CAHD Papers 2. Center for Agrarian Historical Dynamics. Reykjavík

Júlíusson ÁD (2010) Signs of power: manorial demesnes in Medieval Iceland. Viking Mediev Scand 6:1–29

Júlíusson ÁD (2014) Jarðeignir kirkjunnar og tekjur af þeim 1000–1550. Center for Agrarian Historical Dynamics, Reykjavík

Júlíusson ÁD (2020) Agricultural growth in a cold climate: the case of Iceland in 1800–1850. Scand Econ Hist Rev. https://doi.org/10.1080/03585522.2020.1788985

Júlíusson ÁD, Lárusdottir B, Lucas G, Pálsson G (2020) Episcopal economics: property and power in post-reformation Iceland. Scand J Hist 45:95–120

Karlsson G (1996) Plague without rats: the case of fifteenth-century Iceland. J Mediev Hist 22:263–284

Karlsson G (2000) Iceland's 1100 years: the history of a marginal society. Hurst & Company Publishers, London

Kristinsson H (1986) A guide to flowering plants and ferns of Iceland. Mál og Menning, Reykjavík

Kristjánsdóttir S (2010) Icelandic evidence for a late-medieval hospital: excavations at Skriduklaustur. Mediev Archaeol 54:371–381

Kristjánsdóttir S (2017) Leitin að klaustrunum – klausturhald á Íslandi í fimm aldir. Forlagið, Reykjavík

Kupiec P, Milek K, Gisladottir GA, Woollett J (2016) Elusive sel sites: the geoarchaeological quest for Icelandic shielings and the case for Þorvaldsstaðasel, in northeast Iceland. In: Collis J, Pearce M, Nicolis F (eds) Summer farms: seasonal exploitation of the uplands from prehistory to the present. JR Collis Publications, Sheffield, pp 221–2,365

Laine A, Gauthier E, Garcia J-P, Petit C, Cruz F, Richard H (2010) A three-thousand-year history of vegetation and human impact in Burgundy (France) reconstructed from pollen and non-pollen palynomophs analysis. C R Biol 333:850–857

Larsen DJ, Miller GH, Geirsdóttir Á, Ólafsdóttir S (2012) Non-linear Holocene climate evolution in the North Atlantic: a high-resolution, multi-proxy record of glacier activity and environmental change from Hvítárvatn, central Iceland. Quat Sci Rev 39:14–25

Larsen G, Róbertsdóttir BG, Óladóttir BA, Eiríksson J (2020) A shift in eruption mode of Hekla volcano, Iceland, 3000 years ago: two-coloured Hekla tephra series, characteristics, dispersal and age. J Quat Sci 35:143–154

Lawson IT, Gathorne-Hardy FJ, Church MJ, Newton AJ, Edwards KJ, Dugmore AJ, Einarsson A (2007) Environmental impacts of the Norse settlement: palaeoenvironmental data from Myvatnssveit, northern Iceland. Boreas 36:1–19

Lomas-Clarke SH, Barber KE (2004) Palaeoecology of human impact during the historic period: palynology and geochemistry of a peat deposit at Abbeyknockmoy, Co., Galway, Ireland. Holocene 14:721–731

Lucas G (2008) Pálstóftir: a Viking age shieling in Iceland. Nor Archaeol Rev 41:85–100

Lucas G (2012) Later historical archaeology in Iceland: a review. Int J Hist Archaeol 16:437–454

Magnússon Á, Vídalín P (1926) Jarðabók, Vol 8. Hin íslensk fræðafelagið í Kaupmannahöfn & Möller, S.L., Kaupmannahöfn

Mann ME (2002a) Medieval climatic optimum. In: MacCracken MC, Perry JS (eds) Encyclopedia of global environmental change, vol 1: the earth system: physical and chemical dimensions of global environmental change. Wiley, Chichester, pp 514–516

Mann ME (2002b) Little ice age. In: MacCracken MC, Perry JS (eds) Encyclopedia of global environmental change, vol 1: the earth system: physical and chemical dimensions of global environmental change. Wiley, Chichester, pp 504–509

McGovern T, Smairowski K, Hambrecht G, Brewington S, Harrison R, Hicks M, Feeley FJ, Prehal B, Woollett J (2017) Zooarchaeology of the Scandinavian settlements in Iceland and Greenland: diverging pathways. City University of New York (CUNY) Academic Works. https://academicworks.cuny.edu/hc_pubs/638/

Möckel SC, Erlendsson E, Gísladóttir G (2017) Holocene environmental change and development of the nutrient budget of histosols in North Iceland. Plant Soil 418:437–457

Mooney DE (2018) Does the 'Marine Signature' of driftwood persist in the archaeological record? An experimental case study from Iceland. Environ Archaeol 23:217–227

Moore PD, Webb JA, Collison ME (1991) Pollen analysis. Blackwell Scientific Publications, Oxford

Moriwaki H (1990) Late-and postglacial shoreline displacement and glaciation in and around the Skagi peninsula, Northern Iceland. Geogr Rep Tokyo Metrop Univ 25:81–97

Munsell Soil-Color Charts (2009) Xrite, Grand Rapids

Nakagawa T, Brugiapaglia E, Digerfeldt G, Reille M, de Beaulieu J-L, Yasuda Y (1998) Dense-media separation as a more efficient pollen extraction method for use with organic sediment/deposit samples: comparison with the conventional method. Boreas 27:15–24

Noël H, Garbolino E, Brauer A, Lallier-Vergès E, de Beaulieu J-L, Disnar J-R (2001) Human impact and soil erosion during the last 5000 yrs as recorded in lacustrine sedimentary organic matter at Lac d'Annecy, the French Alps. J Paleolimnol 25:229–244

Ogilvie AEJ, Jónsson T (2001) "Little Ice Age" research: a perspective from Iceland. Clim Change 48:9–52

Oksanen J, Blanchet FG, Friendly M, Kindt R, Legendre P, McGlinn D, Minchin PR, O'Hara RB, Simpson GL, Solymos P (2016) vegan: Community Ecology Package. R package version 2.4-3. https://CRAN.R-project.org/package=vegan

Ottósson JG, Sveinsdóttir A, Harðardóttir M (2016) Vistgerðir á Íslandi. Fjölrit Náttúrufræðistofnunar 54. Náttúrufræðistofnun Íslands, Garðabær. Oddi ehf. http://vistgerdakort.ni.is/

Pálsson G (2018) Storied lines: network perspectives on land use in early modern Iceland. Nor Archaeol Rev 51:112–141

Pálsson H, Edwards P (1972) The Book of settlements: Landnámabók. University of Manitoba Press, Winnipeg

Patterson WA III, Edwards KJ, Maguire DJ (1987) Microscopic charcoal as a fossil indicator of fire. Quat Sci Rev 6:3–23

Pétursdóttir LB (2014) Post-settlement landscape change in the Mosfell Valley, SW Iceland: a multiple profile approach. University of Iceland, Reykjavik

Rackham O (1980) Ancient woodland, its history, vegetation and uses in England. Edward Arnold, London

Reimer PJ, Austin WE, Bard E et al (2020) The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP) Radiocarbon 62:725–757

Riddell S, Erlendsson E, Gísladóttir G, Edwards KJ, Byock J, Zori D (2018a) Cereal cultivation as a correlate of high social status in medieval Iceland. Veget Hist Archaeobot 27:679–696

Riddell SJ, Erlendsson E, Eddudóttir SD, Gísladóttir G, Kristjánsdóttir S (2018b) Pollen, plague & protestants: the Medieval Monastery of Þingeyrar (Þingeyraklaustur) in Northern Iceland. Environ Archaeol 1:1–18. https://doi.org/10.1080/14614103.2018.1531191

Ross LC, Austrheim G, Asheim L-J et al (2016) Sheep grazing in the North Atlantic region: a long-term perspective on environmental sustainability. Ambio 45:551–566

Roy N, Woollett J, Bhiry N, Haemmerli G, Forbes V, Pienitz R (2018) Perspective of landscape change following early settlement (landnám) in Svalbarðstunga, northeastern Iceland. Boreas 47:671–686

Rymer L (1973) Modern pollen rain studies in Iceland. New Phytol 72:1,367–1,373

Schmid MM, Zori D, Erlendsson E, Batt C, Damiata BN, Byock J (2017) A Bayesian approach to linking archaeological, paleoenvironmental and documentary datasets relating to the settlement of Iceland (Landnám). Holocene 28:19–33

Sigurmundsson FS, Gísladóttir G, Óskarsson H (2014) Decline of birch woodland cover in Þjórsárdalur Iceland from 1587 to 1938. Hum Ecol 42:577–590

Smith KP (1995) Landnám: the settlement of Iceland in archaeological and historical perspective. World Archaeol 26:319–347

Stockmarr J (1971) Tablets with spores used in absolute pollen analysis. Pollen Spores 13:614–621

Stolz C, Grunert J (2010) Late Pleistocene and Holocene landscape history of the central Palatinate forest (Pfälzerwald, south-western Germany). Quat Int 222:129–142

Streeter R, Dugmore AJ, Vésteinsson O (2012) Plague and landscape resilience in premodern Iceland. Proc Natl Acad Sci USA 109:3,664–3,669

Streeter R, Dugmore AJ, Lawson IT, Erlendsson E, Edwards KJ (2015) The onset of the palaeoanthropocene in Iceland: changes in complex natural systems. Holocene 25:1,662–1,675

Sveinsson E (1934) Laxdœla Saga. Íslenzk Fornrit V. Hið íslenzka fornritafélag, Reykjavík

Thorarinsson S (1967) The eruption of Hekla 1947–1948, vol 1: the eruptions of Hekla in historical times: a tephrochronological study. Societas Scientiarum Islandica, Reykjavík

Thordarson T, Hoskuldsson A (2002) Iceland. Classic Geology in Europe 3. Terra, Harpenden

Þorsteinsson H (1922–1932) Annales Islandici Posterioum Sæculorum (Annálar 1400–1800), vol I. Hinu Íslenzka Bókmenntafélag, Reykjavík

Tinganelli L, Erlendsson E, Eddudóttir SD, Gísladóttir G (2018) Impacts of climate, tephra and land use upon Holocene landscape stability in Northwest Iceland. Geomorphology 322:117–131

Tipping R (1997) Medieval woodland history from the Scottish Southern Uplands: fine spatial-scale pollen data from a small woodland hollow. In: Smout TC (ed) Scottish woodland history. Scottish Cultural Press, Edinburgh, pp 52–75

Tipping R (2010) Bowmont: an environmental history of the Bowmont Valley and the northern Cheviot Hills, 10 000 BC - AD 2000. Society of Antiquaries of Scotland, Edinburgh

Tisdall E, Barclay R, Nichol A, McCulloch R, Simpson I, Smith H, Vésteinsson O (2018) Palaeoenvironmental evidence for woodland conservation in Northern Iceland from settlement to the twentieth century. Environ Archaeol 23:205–216

Troels-Smith J (1955) Karakterisering af løse jordarter (Characterization of unconsolidated sediments). Danmarks Geologiske Undersøgelse, 4 række, Bd 3, Nr. 10. Reitzels Forlag, Copenhagen

Van Geel B, Buurman J, Brinkkemper O, Schelvis J, Aptroot A, van Reenen G, Hakbijl T (2003) Environmental reconstruction of a Roman Period settlement site in Uitgeest (The Netherlands), with special reference to coprophilous fungi. J Archaeol Sci 30:873–883

Van Hoof TB, Bunnik FPM, Waucomont JGM, Kürschner WM, Visscher H (2006) Forest re-growth on medieval farmland after the Black Death pandemic—implications for atmospheric CO_2 levels. Palaeogeogr Palaeoclimatol Palaeoecol 237:396–409

Varga G, Dagsson-Walhauserová P, Gresina F, Helgadottir A (2021) Saharan dust and giant quartz particle transport towards Iceland. Sci Rep 11:11,891

Vésteinsson O (1998–2001) Patterns of settlement in Iceland: a study in prehistory. Saga-Book Viking Society for Northern Research 25:1–29

Vésteinsson O (2007) A divided society: Peasants and the aristocracy in medieval Iceland. Viking Mediev Scand 3:117–139

Vésteinsson O, Simpson IA (2001) Fuel utilisation in pre-industrial Iceland. A micro-morphological and historical analysis. In: Guðmundsson G (ed) Current Issues in Nordic Archaeology. Proceedings of the 21st conference of Nordic Archaeologists, 6–9 September 2001, Akureyri, Iceland. Society of Icelandic Archaeologists, Reykjavik, pp 181–187

Vickers K, Erlendsson E, Church MJ, Edwards KJ, Bending J (2011) 1000 years of environmental change and human impact at Stóra-Mörk, southern Iceland: a multiproxy study of a dynamic and vulnerable landscape. Holocene 21:979–995

Wimble G, Wells CE, Hodgkinson D (2000) Human impact on mid- and late Holocene vegetation in south Cumbria, UK. Veget Hist Archaeobot 9:17–30

Woolf A (2007) From Pictland to Alba, 789–1070. Edinburgh University Press, Edinburgh

Yeloff D, van Geel B (2007) Abandonment of farmland and vegetation succession following the Eurasian plague pandemic of AD 1347–52. J Biogeogr 34:575–582

Zori D, Byock JL (2014) Viking archaeology in Iceland: Mosfell archaeological project. Brepols, Turnhout

ESM1: Major elements (wt%) of basaltic glass shards in tephra layers for the Helgadalur (HEL) sedimentary sequence.

Depth (cm)	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
7-8	47.91	4.53	13.02	15.04	0.2199	4.95	9.37	3.25	0.7858	0.8	99.8757
7-8	47.22	4.47	12.77	14.68	0.2169	4.91	9.54	3.2	0.7846	0.7202	98.5117
7-8	47.56	4.48	12.95	14.83	0.2278	4.98	9.44	3.34	0.7672	0.7432	99.3182
7-8	47.41	4.48	12.87	14.79	0.2138	4.93	9.55	3.27	0.7591	0.7473	99.0202
7-8	48.9	1.6577	14.51	12.34	0.2029	7.26	12.28	2.34	0.2185	0.14	99.8491
7-8	47.02	4.48	12.71	14.97	0.2597	4.93	9.46	3.19	0.7769	0.8034	98.6
7-8	47.22	4.44	12.77	14.68	0.2336	4.95	9.51	3.07	0.7502	0.7875	98.4113
7-8	47.31	4.46	12.83	14.46	0.2658	4.87	9.42	3.17	0.7533	0.7639	98.303
7-8	47.24	4.41	12.75	14.63	0.2119	5.07	9.43	3.31	0.7526	0.7669	98.5714
7-8	47.49	4.48	12.77	14.95	0.2547	4.95	9.51	3.16	0.7386	0.7398	99.0431
7-8	47.42	4.5	12.82	14.96	0.2519	4.93	9.43	3.29	0.7771	0.7084	99.0874
7-8	47.28	4.44	12.97	14.77	0.2031	4.83	9.49	3.17	0.7819	0.7559	98.6909
18-20	46.61	4.67	12.85	14.85	0.2374	5.09	9.82	3.1	0.6674	0.5967	98.4915
18-20	46.88	4.77	12.82	15.36	0.2439	5.14	9.72	3.02	0.6927	0.578	99.2246
18-20	46.76	4.66	12.8	15.33	0.2246	5.16	9.89	3.07	0.702	0.5991	99.1957
18-20	46.64	4.77	12.67	15.36	0.2275	5.26	9.88	2.95	0.684	0.5743	99.0158
18-20	46.57	4.76	12.72	15.24	0.2135	5.12	9.9	3.14	0.6895	0.6322	98.9852
18-20	46.5	4.69	12.64	15.08	0.2494	5.22	9.87	3.09	0.6676	0.5815	98.5885
18-20	46.89	4.71	12.78	15.13	0.2455	5.21	9.82	3.06	0.7092	0.572	99.1267
18-20	46.73	4.74	12.67	15.13	0.2459	5.25	9.82	3.05	0.6884	0.5908	98.9151
28-28.5	49.87	1.74	13.55	13.49	0.2186	6.62	10.84	2.39	0.174	0.1545	99.0471
28-28.5	50.25	1.75	13.45	13.32	0.2481	6.54	10.91	2.39	0.1866	0.177	99.2217
28-28.5	49.91	1.76	13.69	13.71	0.2344	6.7	10.84	2.39	0.1874	0.1549	99.5767
28-28.5	49.75	1.74	13.48	13.6	0.2125	6.73	10.81	2.44	0.1757	0.1629	99.1011
28-28.5	49.86	1.76	13.6	13.73	0.2465	6.6	10.86	2.47	0.175	0.1687	99.4702
28-28.5	49.91	1.78	13.52	12.8	0.2197	6.5	10.96	2.24	0.1692	0.1849	98.2838
28-28.5	50	1.78	13.41	13.66	0.2217	6.55	10.92	2.31	0.1744	0.1621	99.1882
28-28.5	50.2	1.76	13.5	13.75	0.2307	6.56	10.94	2.38	0.1943	0.1674	99.6824
28-28.5	50.24	1.76	13.56	13.71	0.2254	6.63	10.9	2.34	0.1838	0.1596	99.7088
28-28.5	50.02	1.73	13.58	13.43	0.2246	6.54	10.87	2.36	0.1859	0.1456	99.0861
37	47.55	4.52	13.01	14.85	0.2204	4.87	9.4	3.25	0.7985	0.544	99.0129
37	47.18	4.42	12.87	14.68	0.2314	4.8	9.28	3.26	0.7878	0.5694	98.0786
37	47.26	4.54	12.81	14.8	0.2214	4.88	9.37	3.13	0.7944	0.6047	98.4105
37	49.66	1.86	13.74	12.9	0.2161	6.41	11.41	2.36	0.2293	0.1509	98.9363
37	49.67	1.85	13.78	13.06	0.213	6.55	11.33	2.5	0.2396	0.2203	99.4129
37	49.44	1.75	13.76	12.63	0.2053	6.71	11.5	2.37	0.1957	0.1904	98.7514
37	49.69	1.87	13.68	13.17	0.2426	6.52	11.15	2.56	0.2305	0.1727	99.2858
37	49.66	1.88	13.79	13.06	0.2047	6.28	11.23	2.56	0.2368	0.1689	99.0704
37	51.29	1.92	13.86	12.31	0.219	5.53	9.85	3.05	0.5764	0.2703	98.8757
37	49.47	2.03	13.95	12.88	0.2819	6.42	10.8	2.78	0.399	0.2354	99.2463
37	49.83	1.83	13.87	13.13	0.2154	6.55	11.29	2.44	0.2268	0.1635	99.5457
37	47.3	4.46	12.84	14.86	0.2168	4.85	9.4	3.21	0.777	0.5449	98.4587
37	47.56	4.51	12.98	14.64	0.2589	4.89	9.38	3.39	0.7886	0.5433	98.9408
37	49.8	1.8	13.61	12.94	0.2256	6.49	11.31	2.43	0.2368	0.199	99.0414
37	49.78	1.84	13.7	12.73	0.2261	6.55	11.26	2.56	0.2219	0.2114	99.0794
38-40	50.05	1.83	13.73	13.25	0.222	6.58	11.27	2.49	0.2145	0.1731	99.8096
38-40	49.86	1.86	13.77	13.08	0.2303	6.51	11.39	2.42	0.2277	0.1251	99.4731
38-40	49.98	1.87	13.85	13.18	0.2413	6.66	11.33	2.42	0.2244	0.1615	99.9172
38-40	49.58	1.8	14.04	12.56	0.2137	6.68	11.53	2.39	0.2052	0.1755	99.1744
38-40	49.75	1.83	13.83	13.13	0.2347	6.29	11.17	2.52	0.2211	0.1922	99.168
38-40	49.96	1.88	13.6	13.14	0.2484	6.43	11.18	2.39	0.2292	0.1609	99.2185
38-40	49.77	1.84	13.69	12.75	0.2189	6.47	11.37	2.42	0.229	0.1524	98.9103
38-40	49.85	1.82	13.93	12.88	0.2329	6.53	11.23	2.39	0.2209	0.1527	99.2365
38-40	46.98	3.83	13.35	14.32	0.228	5.67	11.01	2.94	0.5813	0.3783	99.2876
38-40	49.96	1.78	14.05	12.17	0.2386	6.7	11.64	2.46	0.2196	0.1322	99.3504
38-40	50.15	1.77	13.89	13.03	0.2136	6.6	11.32	2.51	0.2263	0.1976	99.9075
38-40	49.78	1.84	13.67	13.09	0.2096	6.49	11.19	2.41	0.2127	0.1498	99.0421
38-40	49.51	1.81	13.72	13.07	0.2062	6.62	11.44	2.45	0.2209	0.1783	99.2254
38-40	49.84	1.86	13.81	12.88	0.201	6.5	11.3	2.41	0.2152	0.1935	99.2097
38-40	49.9	1.94	13.67	13.49	0.234	6.24	10.86	2.58	0.2452	0.1743	99.3335
54.5-55	48.14	4.44	12.98	14.67	0.2175	4.71	9.32	3.14	0.7891	0.5472	98.9538
54.5-55	48.02	4.39	13.22	14.51	0.2383	4.64	9.28	3.19	0.8456	0.5003	98.8342
54.5-55	48.33	4.46	13.16	14.59	0.2353	4.72	9.27	3.07	0.8408	0.5018	99.1779

54.5-55	49.07	4.45	13.33	15.14	0.2259	4.79	9.48	2.94	0.824	0.4889	100.7388
54.5-55	48.02	4.36	13.29	14.45	0.225	4.7	9.22	3.16	0.8142	0.5232	98.7624
54.5-55	48.1	4.34	13.2	14.66	0.2277	4.74	9.34	3.23	0.8046	0.5662	99.2085
54.5-55	48	4.47	13.13	14.76	0.2074	4.71	9.21	3.16	0.832	0.5552	99.0346
54.5-55	48.1	4.4	13.21	14.66	0.2592	4.77	9.26	3.16	0.8125	0.6014	99.2331
54.5-55	48.12	4.39	13.32	14.71	0.2336	4.73	9.29	3.14	0.8371	0.517	99.2877
54.5-55	47.84	4.32	13.11	14.7	0.2364	4.75	9.29	3.31	0.82	0.6024	98.9788
54.5-55	48.19	4.4	13.11	14.58	0.2258	4.73	9.3	3.18	0.8326	0.5946	99.143
54.5-55	48.07	4.4	13.12	14.52	0.232	4.72	9.22	3.21	0.8184	0.5144	98.8248
54.5-55	47.86	4.34	13.13	14.49	0.2289	4.76	9.21	3.2	0.8523	0.5782	98.6494
54.5-55	47.94	4.42	13.22	14.41	0.2442	4.62	9.23	3.21	0.7935	0.5021	98.5898
54.5-55	47.86	4.35	13.21	14.55	0.2069	4.79	9.27	3.32	0.8102	0.5453	98.9124
77-78	47.25	4.37	13.19	14.86	0.2358	4.98	9.7	3.02	0.7404	0.4879	98.8341
77-78	47.44	4.34	13.17	15.12	0.205	5.06	9.74	2.97	0.7288	0.4613	99.2351
77-78	47.31	4.38	13.13	14.96	0.2305	5.07	9.77	2.91	0.7164	0.5451	99.022
77-78	47.37	4.4	13	14.83	0.2301	5.03	9.79	3.18	0.7406	0.5343	99.105
77-78	47.47	4.34	13.06	14.92	0.2059	5.12	9.74	3.09	0.7313	0.5284	99.2056
77-78	46.99	4.41	13.14	14.71	0.1911	5.11	9.82	3.07	0.7209	0.5582	98.7202
77-78	47.03	4.42	13.13	15.01	0.197	5.14	9.79	3.04	0.7465	0.4567	98.9602
77-78	47.31	4.39	13.16	14.86	0.1862	4.95	9.71	3.04	0.7125	0.5199	98.8386
77-78	47.02	4.34	13.11	15.01	0.1957	5	9.78	3.07	0.7534	0.4811	98.7602
77-78	47.22	4.48	12.93	14.92	0.2221	5.07	9.83	2.69	0.7495	0.5074	98.619
77-78	47.62	4.35	13.15	14.88	0.2292	4.9	9.68	2.98	0.7791	0.5059	99.0742
77-78	47.48	4.35	13.12	14.91	0.2389	5.1	9.86	3.06	0.7284	0.5005	99.3478
77-78	47.2	4.37	13.08	14.71	0.2024	5.07	9.74	3.15	0.7254	0.4692	98.717
77-78	47.28	4.32	13.18	14.55	0.2446	5.11	9.75	3.1	0.7091	0.5232	98.7669
92-97	47.46	4.29	13.11	15.29	0.2349	5.19	10.07	2.86	0.704	0.5323	99.7412
92-97	47.27	4.25	13.18	15.19	0.2226	5.16	10.05	2.91	0.6875	0.4583	99.3784
92-97	47.08	4.29	13.03	15.19	0.1936	5.3	9.99	2.92	0.7067	0.5055	99.2058
92-97	47.02	4.22	12.91	14.73	0.213	5.2	10.12	2.94	0.6951	0.4731	98.5212
92-97	47.1	4.31	12.95	14.66	0.2091	5.28	10.15	3.05	0.7238	0.4853	98.9182
92-97	47.23	4.33	12.99	15.08	0.2037	5.21	10.1	2.91	0.6818	0.4307	99.1662
92-97	46.93	4.32	12.98	15.28	0.2401	5.29	10.1	3.02	0.7083	0.4576	99.326
92-97	46.99	4.31	12.98	15.13	0.2305	5.21	10.07	2.96	0.688	0.4971	99.0656
92-97	47.2	4.27	13.15	15.22	0.2221	5.21	10.11	2.96	0.6885	0.4432	99.4738
92-97	46.98	4.3	13.22	15.23	0.2262	5.43	9.99	3.06	0.6646	0.4932	99.594
92-97	47.42	4.26	13.15	14.8	0.2284	5.22	10	3.01	0.6822	0.4814	99.252
92-97	47.19	4.34	13.03	15.14	0.2016	5.34	10.11	2.73	0.6689	0.4133	99.1638
92-97	47.21	4.27	13.18	15.05	0.1884	5.22	9.99	2.89	0.6862	0.4555	99.1401
92-97	46.81	4.31	12.9	14.94	0.2376	5.11	10.09	2.91	0.7147	0.465	98.4873
92-97	47.04	4.21	12.9	14.73	0.1735	5.06	9.99	2.9	0.6842	0.4897	98.1774

ESM1: Major elements (wt%) of silicic and intermediate glass shards in tephra layers for the Helgadalur (HEL) sedimentary sequence.

Depth (cm)	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
38-40	71.33	0.27	14.70	2.40	0.09	0.22	0.86	5.33	4.57	0.01	99.79
38-40	71.17	0.25	14.92	2.52	0.08	0.20	0.92	5.31	4.58	0.00	99.95
38-40	72.09	0.25	14.74	2.33	0.03	0.26	0.86	5.22	4.59	0.06	100.43
38-40	71.40	0.24	14.71	2.40	0.08	0.20	0.90	4.78	4.68	0.06	99.45
38-40	71.33	0.26	14.58	2.35	0.06	0.24	0.86	5.19	4.57	0.02	99.45
38-40	70.95	0.23	14.77	2.33	0.03	0.23	0.84	5.22	4.59	0.00	99.20
38-40	71.12	0.26	14.99	2.39	0.07	0.21	0.85	5.18	4.52	0.01	99.61
38-40	72.01	0.27	14.80	2.39	0.05	0.23	0.84	5.16	4.57	0.01	100.33
38-40	70.97	0.26	14.51	2.35	0.08	0.24	0.86	4.95	4.61	0.00	98.84
38-40	71.18	0.23	14.82	2.32	0.10	0.24	0.85	5.25	4.67	0.04	99.69
63-64	64.56	0.81	15.30	6.47	0.21	1.14	4.06	4.61	1.78	0.30	99.24
63-65	65.87	0.92	14.42	7.18	0.19	1.29	3.69	4.28	1.86	0.30	100.00
63-66	65.15	0.80	15.76	6.90	0.17	1.20	4.47	4.35	1.67	0.21	100.69

63-67	64.83	0.84	15.25	6.99	0.23	1.31	4.35	4.27	1.77	0.37	100.20
63-68	61.39	1.18	15.80	8.51	0.23	1.81	5.07	4.14	1.55	0.50	100.18
63-69	63.08	0.92	15.57	7.48	0.20	1.45	4.89	4.19	1.67	0.33	99.78
63-70	62.95	0.87	15.33	6.86	0.16	1.35	4.46	4.69	1.75	0.30	98.72
63-71	64.42	0.80	15.59	7.04	0.21	1.23	4.62	4.41	1.68	0.31	100.30
63-72	65.02	0.80	15.70	6.52	0.17	1.10	4.15	4.53	1.77	0.33	100.10
63-73	64.65	0.79	15.70	6.51	0.18	1.16	4.18	4.58	1.69	0.30	99.74
63-74	64.88	0.79	15.66	6.39	0.18	1.15	4.25	4.40	1.72	0.24	99.66
63-75	64.55	0.86	15.91	6.81	0.18	1.27	4.41	4.34	1.68	0.33	100.34
63-76	64.88	0.86	15.66	6.07	0.15	1.29	4.45	4.41	1.72	0.33	99.82
63-77	65.13	0.80	15.82	6.56	0.18	1.20	4.28	4.33	1.70	0.26	100.25
63-78	65.70	0.79	15.81	6.83	0.15	1.22	4.31	4.48	1.67	0.27	101.23
63-79	64.27	0.77	15.86	6.55	0.18	1.19	4.43	4.62	1.71	0.30	99.88
63-80	65.16	0.80	15.78	6.43	0.21	1.17	4.14	4.35	1.74	0.26	100.04

ESM1: Major elements (wt%) of basaltic glass shards in tephra layers for the Ásbjarnarnes (ÁSB2) sedimentary sequence.

Depth (cm)	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
25.5-26	71.65	0.1902	14.24	3.19	0.0706	0.1065	1.95	4.81	2.44	0.0067	98.654
25.5-26	72.58	0.1797	14.18	3.21	0.1017	0.1219	1.91	4.67	2.68	0.0042	99.6375
25.5-26	71.99	0.212	14.23	3.14	0.0754	0.0995	1.88	4.68	2.77	0.0117	99.0886
25.5-26	73.33	0.2347	11.98	2.7	0.0695	0.0795	1.3096	3.81	2.69	0.0067	96.21
25.5-26	72.65	0.2404	14.11	3.13	0.1483	0.1176	1.74	4.54	2.75	0.0016	99.4279
25.5-26	71.93	0.171	14.15	3.16	0.122	0.099	1.96	4.53	2.79	0.0167	98.9287
25.5-26	71.87	0.2042	14.46	3.14	0.1101	0.1217	2	4.36	2.62	0.0343	98.9203
25.5-26	72.13	0.2209	14.38	3.18	0.1532	0.1054	1.99	4.71	2.65	0	99.5195
25.5-26	72.22	0.2141	14.38	3.26	0.1113	0.1053	1.92	4.62	2.68	0.0318	99.5425
25.5-26	72.7	0.1992	14.4	3.02	0.1197	0.1344	1.79	4.56	2.75	0	99.6733
25.5-26	72.07	0.1745	14.22	3.21	0.1065	0.1	1.9	4.56	2.65	0.0284	99.0194
25.5-26	72.2	0.2133	14.31	3.05	0.1137	0.0964	1.85	4.54	2.67	0.0577	99.1011
25.5-26	72.21	0.1793	14.34	3.22	0.1459	0.1005	1.9	4.66	2.67	0.0484	99.4741
25.5-26	71.73	0.2311	14.03	3.19	0.1376	0.1105	1.92	4.64	2.68	0.056	98.7252
25.5-26	72.22	0.1845	14.51	3.2	0.1148	0.1023	1.81	4.61	2.67	0.0209	99.4425
25.5-26	72.18	0.2321	14.23	3.14	0.1567	0.1235	1.92	4.48	2.81	0.0409	99.3132
25.5-26	72.05	0.2355	14.36	3.16	0.1315	0.0863	1.93	4.93	2.68	0.0284	99.5917
25.5-26	71.39	0.1709	15.22	2.81	0.0658	0.1084	2.26	5.22	2.43	0.0209	99.696
40.5-41	46.99	4.4	12.82	14.69	0.2384	4.95	9.42	2.92	0.7725	0.4615	97.6624
40.5-41	46.92	4.37	13	14.64	0.2533	4.99	9.41	3.09	0.7761	0.5524	98.0018
40.5-41	46.94	4.45	12.89	14.92	0.2551	5.1	9.58	3.12	0.7653	0.5458	98.5662
40.5-41	46.76	4.49	12.85	14.74	0.2394	4.84	9.58	3.12	0.7736	0.581	97.974
40.5-41	46.87	4.52	12.99	14.64	0.2343	4.94	9.61	3.05	0.7673	0.553	98.1746
40.5-41	47.08	4.38	12.99	14.73	0.2436	4.9	9.83	2.99	0.7514	0.529	98.424
40.5-41	46.95	4.49	12.92	14.84	0.2184	4.87	9.67	3	0.7751	0.6058	98.3393
40.5-41	47.08	4.52	12.95	14.81	0.2339	4.99	9.61	3.23	0.8224	0.5158	98.7621
40.5-41	46.92	4.62	12.89	14.86	0.2131	4.88	9.73	2.98	0.7559	0.5291	98.3781
40.5-41	47.04	4.62	12.93	14.73	0.2358	4.97	9.34	3.08	0.74	0.5362	98.222
40.5-41	47.04	4.62	12.82	14.87	0.2782	4.91	9.64	3.14	0.8197	0.5382	98.6761
40.5-41	47.19	4.48	12.96	14.75	0.2367	4.96	9.65	3.05	0.815	0.573	98.6647
40.5-41	47.43	4.43	13.1	14.81	0.2417	4.9	9.59	2.95	0.778	0.5199	98.7496
42-42.5	50.13	1.97	13.62	13.09	0.2221	6.35	10.97	2.63	0.2571	0.1348	99.374
42-42.5	50	1.99	13.74	12.81	0.2099	6.54	10.88	2.61	0.2838	0.1452	99.2089
42-42.5	49.53	1.9	13.73	12.34	0.2469	6.82	11.15	2.45	0.2168	0.1312	98.5149
42-42.5	49.7	2.02	13.78	12.52	0.231	6.24	11.03	2.66	0.259	0.1958	98.6358
42-42.5	49.48	1.96	13.81	12.93	0.2308	6.22	10.7	2.56	0.2668	0.205	98.3626
42-42.5	50.42	1.77	13.51	12.78	0.2225	6.23	10.84	2.65	0.3086	0.1676	98.8987
42-42.5	49.66	2.04	13.64	13.19	0.2312	6.32	10.81	2.61	0.2704	0.1809	98.9525
42-42.5	49.7	1.94	13.85	12.9	0.1972	6.28	11	2.55	0.2543	0.1676	98.8391
42-42.5	49.92	1.81	13.97	12.28	0.2231	6.46	11.34	2.52	0.2397	0.1658	98.9286
42-42.5	49.81	1.87	13.93	12.6	0.2284	6.48	11.29	2.52	0.228	0.1916	99.148
42-42.5	49.23	1.8	13.92	12.32	0.1884	7.12	11.91	2.36	0.2002	0.1556	99.2042
42-42.5	49.68	2.03	13.61	13.08	0.2366	6.35	10.95	2.62	0.2551	0.2006	99.0123
42-42.5	49.35	1.95	13.75	13.05	0.2326	6.39	10.83	2.6	0.267	0.2052	98.6248
57.5-58	62.38	0.7793	15.38	8.78	0.2635	1.0518	4.72	4.51	1.66	0.2325	99.7571
57.5-58	65.11	0.6335	15.42	7.48	0.251	0.7293	4	4.07	2.04	0.1955	99.9293
57.5-58	67.03	0.4193	15.12	6.06	0.1407	0.4184	3.36	4.54	2.03	0.0987	99.2171
57.5-58	67.26	0.396	15.09	5.51	0.1646	0.4068	3.38	4.49	2.1	0.0614	98.8588
57.5-58	67.18	0.3993	15.24	5.63	0.1395	0.3894	3.31	4.63	2.07	0.1053	99.0935
57.5-58	64.46	0.6465	15.57	7.11	0.2058	0.7683	4.15	4.46	1.8	0.2153	99.3859
57.5-58	63.91	0.6056	15.49	7.49	0.2176	0.8064	3.9	4.63	1.83	0.1922	99.0718
57.5-58	64.11	0.6659	15.42	7.49	0.207	0.7589	4.18	4.45	1.76	0.2095	99.2513
57.5-58	63.52	0.7616	15.29	8.1	0.2579	0.9105	4.27	4.47	1.7	0.229	99.509
57.5-58	62.52	0.7994	15.32	8.56	0.2337	0.9706	4.51	4.09	1.92	0.2628	99.1865
57.5-58	65.4	0.5587	15.43	6.61	0.2023	0.583	3.65	4.49	1.87	0.1091	98.9031
57.5-58	66.63	0.567	15.33	6.23	0.1989	0.4894	3.34	4.78	2.01	0.1309	99.7062
57.5-58	65.47	0.5354	15.19	6.86	0.1703	0.6337	3.75	3.3	1.9	0.2689	98.0783
57.5-58	66.71	0.4502	15.15	5.79	0.1669	0.4111	3.19	4.65	2.06	0.0928	98.671
66.5-67	65.95	0.4769	15.41	6.45	0.2024	0.5164	3.64	4.63	1.81	0.1274	99.2131
66.5-67	63.19	0.6951	15.15	7.89	0.1924	0.8169	4.21	4.25	1.78	0.196	98.3704
66.5-67	68.08	0.3637	15.22	5.26	0.1395	0.3719	3.23	4.47	2.02	0.0548	99.2099
66.5-67	72.18	0.1469	14.5	3.14	0.1053	0.1169	1.96	5.08	2.49	0	99.7191
66.5-67	65.19	0.5381	15.26	6.53	0.213	0.5197	3.62	4.26	1.84	0.0844	98.0552

66.5-67	66.39	0.4214	15.34	5.54	0.1407	0.4879	3.24	4.35	2.01	0.1418	98.0618
66.5-67	67.01	0.4783	15.37	6.02	0.1799	0.4447	3.48	4.89	2.04	0.101	100.0139
66.5-67	68.07	0.4243	15.13	5.24	0.1741	0.3281	3.12	4.53	2.08	0.1485	99.245
66.5-67	66.17	0.5238	15.43	6.65	0.2402	0.5898	3.81	4.32	1.94	0.1231	99.7969
66.5-67	67.19	0.4669	15.32	6.22	0.1714	0.5154	3.36	4.44	1.93	0.1027	99.7164
66.5-67	64.88	0.6612	15.48	7.35	0.2379	0.7139	3.99	4.86	1.79	0.2294	100.1924
66.5-67	66.7	0.4247	15.41	6	0.2037	0.4431	3.39	4.62	1.88	0.1525	99.224
66.5-67	65.34	0.5558	15.39	6.92	0.2236	0.6534	4.04	4.41	1.83	0.1733	99.5361
66.5-67	66.53	0.4817	15.33	6.16	0.1977	0.5034	3.7	4.55	1.94	0.1365	99.5293
71.5-73	63.85	0.7395	15.65	8.56	0.2407	0.9726	4.53	4.44	1.71	0.2574	100.9502
71.5-73	67.09	0.4313	15.39	5.85	0.1682	0.3889	3.44	4.45	2.05	0.1544	99.4128
71.5-73	65.35	0.5994	15.43	7.37	0.2518	0.6883	3.99	4.7	1.85	0.2299	100.4594
71.5-73	65.44	0.5566	15.62	7.51	0.2222	0.7245	4.06	4.39	1.82	0.2404	100.5837
71.5-73	66.23	0.396	15.39	6.23	0.1894	0.4331	3.55	4.58	2.03	0.0929	99.1214
71.5-73	68.33	0.3997	15.33	5.67	0.1837	0.3772	3.27	4.39	2.08	0.0383	100.0689
71.5-73	65.68	0.5687	15.49	6.89	0.1527	0.6687	3.78	4.75	1.89	0.1234	99.9935
71.5-73	67.22	0.4211	15.36	6.1	0.1801	0.4648	3.45	4.61	2.02	0.069	99.895
71.5-73	65.63	0.5612	15.8	7.44	0.233	0.7196	3.88	4.72	1.79	0.1562	100.93
71.5-73	65.82	0.5772	15.52	7.36	0.2129	0.6363	3.86	4.46	1.88	0.2122	100.5386
71.5-73	66.51	0.4575	15.4	6.26	0.1563	0.4547	3.59	4.43	1.99	0.1476	99.3961

ESM1: Major elements (wt%) of silicic and intermediate glass shards in tephra layers for the Ásbjarnarnes (ÁSB2) sedimentary sequence.

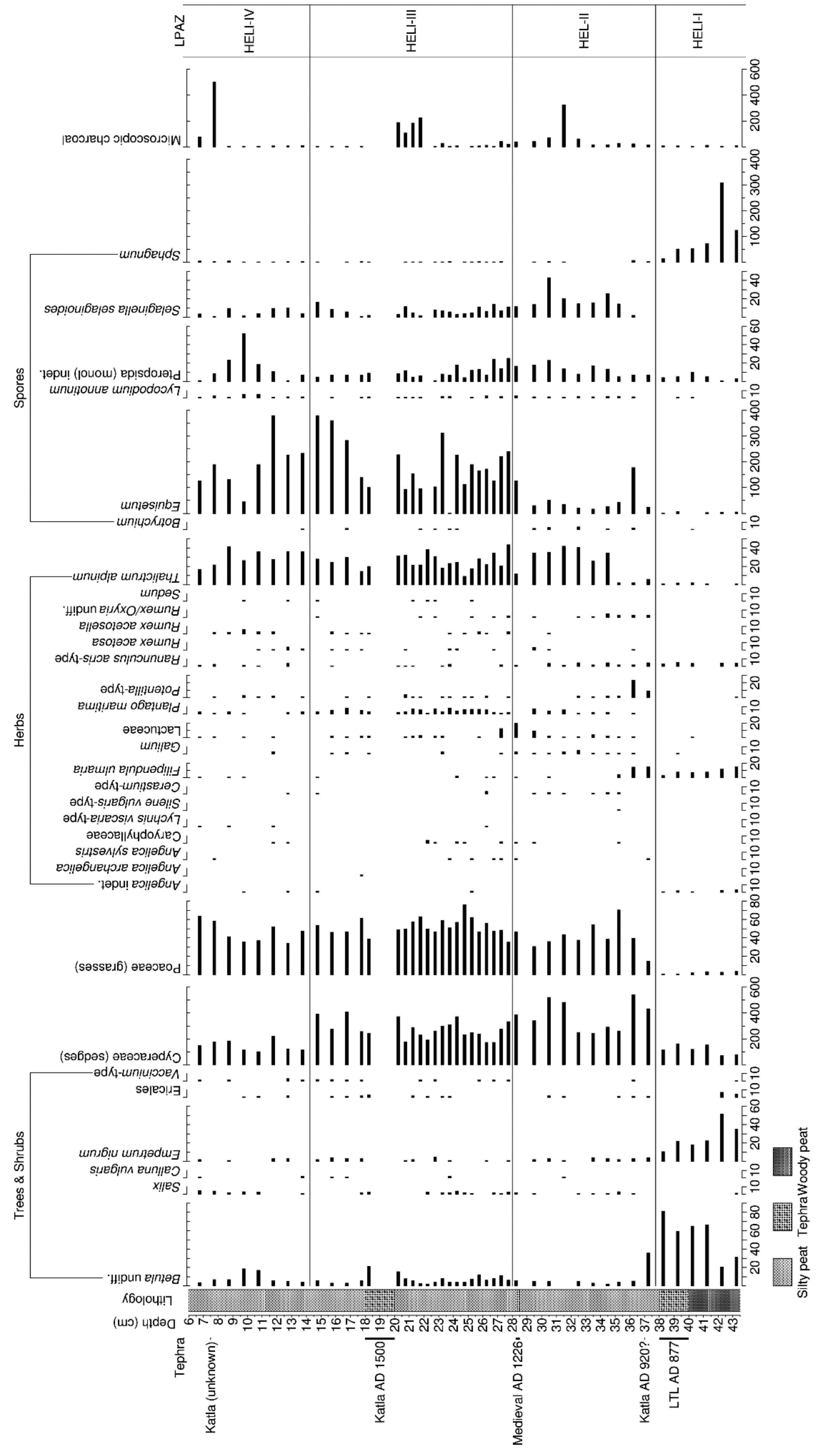
Depth (cm)	**SiO_2**	**TiO_2**	**Al_2O_3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**	**Total**
25.5-26	71.65	0.19	14.24	3.19	0.07	0.11	1.95	4.81	2.44	0.01	98.65
25.5-26	72.58	0.18	14.18	3.21	0.10	0.12	1.91	4.67	2.68	0.00	99.64
25.5-26	71.99	0.21	14.23	3.14	0.08	0.10	1.88	4.68	2.77	0.01	99.09
25.5-26	73.33	0.23	11.98	2.70	0.07	0.08	1.31	3.81	2.69	0.01	96.21
25.5-26	72.65	0.24	14.11	3.13	0.15	0.12	1.74	4.54	2.75	0.00	99.43
25.5-26	71.93	0.17	14.15	3.16	0.12	0.10	1.96	4.53	2.79	0.02	98.93
25.5-26	71.87	0.20	14.46	3.14	0.11	0.12	2.00	4.36	2.62	0.03	98.92
25.5-26	72.13	0.22	14.38	3.18	0.15	0.11	1.99	4.71	2.65	0.00	99.52
25.5-26	72.22	0.21	14.38	3.26	0.11	0.11	1.92	4.62	2.68	0.03	99.54
25.5-26	72.70	0.20	14.40	3.02	0.12	0.13	1.79	4.56	2.75	0.00	99.67
25.5-26	72.07	0.17	14.22	3.21	0.11	0.10	1.90	4.56	2.65	0.03	99.02
25.5-26	72.20	0.21	14.31	3.05	0.11	0.10	1.85	4.54	2.67	0.06	99.10
25.5-26	72.21	0.18	14.34	3.22	0.15	0.10	1.90	4.66	2.67	0.05	99.47
25.5-26	71.73	0.23	14.03	3.19	0.14	0.11	1.92	4.64	2.68	0.06	98.73
25.5-26	72.22	0.18	14.51	3.20	0.11	0.10	1.81	4.61	2.67	0.02	99.44
25.5-26	72.18	0.23	14.23	3.14	0.16	0.12	1.92	4.48	2.81	0.04	99.31
25.5-26	72.05	0.24	14.36	3.16	0.13	0.09	1.93	4.93	2.68	0.03	99.59
25.5-26	71.39	0.17	15.22	2.81	0.07	0.11	2.26	5.22	2.43	0.02	99.70
57-58	62.38	0.78	15.38	8.78	0.26	1.05	4.72	4.51	1.66	0.23	99.76
57-58	65.11	0.63	15.42	7.48	0.25	0.73	4.00	4.07	2.04	0.20	99.93
57-58	67.03	0.42	15.12	6.06	0.14	0.42	3.36	4.54	2.03	0.10	99.22
57-58	67.26	0.40	15.09	5.51	0.16	0.41	3.38	4.49	2.10	0.06	98.86
57-58	67.18	0.40	15.24	5.63	0.14	0.39	3.31	4.63	2.07	0.11	99.09
57-58	64.46	0.65	15.57	7.11	0.21	0.77	4.15	4.46	1.80	0.22	99.39
57-58	63.91	0.61	15.49	7.49	0.22	0.81	3.90	4.63	1.83	0.19	99.07
57-58	64.11	0.67	15.42	7.49	0.21	0.76	4.18	4.45	1.76	0.21	99.25
57-58	63.52	0.76	15.29	8.10	0.26	0.91	4.27	4.47	1.70	0.23	99.51
57-58	62.52	0.80	15.32	8.56	0.23	0.97	4.51	4.09	1.92	0.26	99.19

57-58	65.40	0.56	15.43	6.61	0.20	0.58	3.65	4.49	1.87	0.11	98.90
57-58	66.63	0.57	15.33	6.23	0.20	0.49	3.34	4.78	2.01	0.13	99.71
57-58	65.47	0.54	15.19	6.86	0.17	0.63	3.75	3.30	1.90	0.27	98.08
57-58	66.71	0.45	15.15	5.79	0.17	0.41	3.19	4.65	2.06	0.09	98.67
66.5-67	65.95	0.48	15.41	6.45	0.20	0.52	3.64	4.63	1.81	0.13	99.21
66.5-67	63.19	0.70	15.15	7.89	0.19	0.82	4.21	4.25	1.78	0.20	98.37
66.5-67	68.08	0.36	15.22	5.26	0.14	0.37	3.23	4.47	2.02	0.05	99.21
66.5-67	72.18	0.15	14.50	3.14	0.11	0.12	1.96	5.08	2.49	0.00	99.72
66.5-67	65.19	0.54	15.26	6.53	0.21	0.52	3.62	4.26	1.84	0.08	98.06
66.5-67	66.39	0.42	15.34	5.54	0.14	0.49	3.24	4.35	2.01	0.14	98.06
66.5-67	67.01	0.48	15.37	6.02	0.18	0.44	3.48	4.89	2.04	0.10	100.01
66.5-67	68.07	0.42	15.13	5.24	0.17	0.33	3.12	4.53	2.08	0.15	99.25
66.5-67	66.17	0.52	15.43	6.65	0.24	0.59	3.81	4.32	1.94	0.12	99.80
66.5-67	67.19	0.47	15.32	6.22	0.17	0.52	3.36	4.44	1.93	0.10	99.72
66.5-67	64.88	0.66	15.48	7.35	0.24	0.71	3.99	4.86	1.79	0.23	100.19
66.5-67	66.70	0.42	15.41	6.00	0.20	0.44	3.39	4.62	1.88	0.15	99.22
66.5-67	65.34	0.56	15.39	6.92	0.22	0.65	4.04	4.41	1.83	0.17	99.54
66.5-67	66.53	0.48	15.33	6.16	0.20	0.50	3.70	4.55	1.94	0.14	99.53

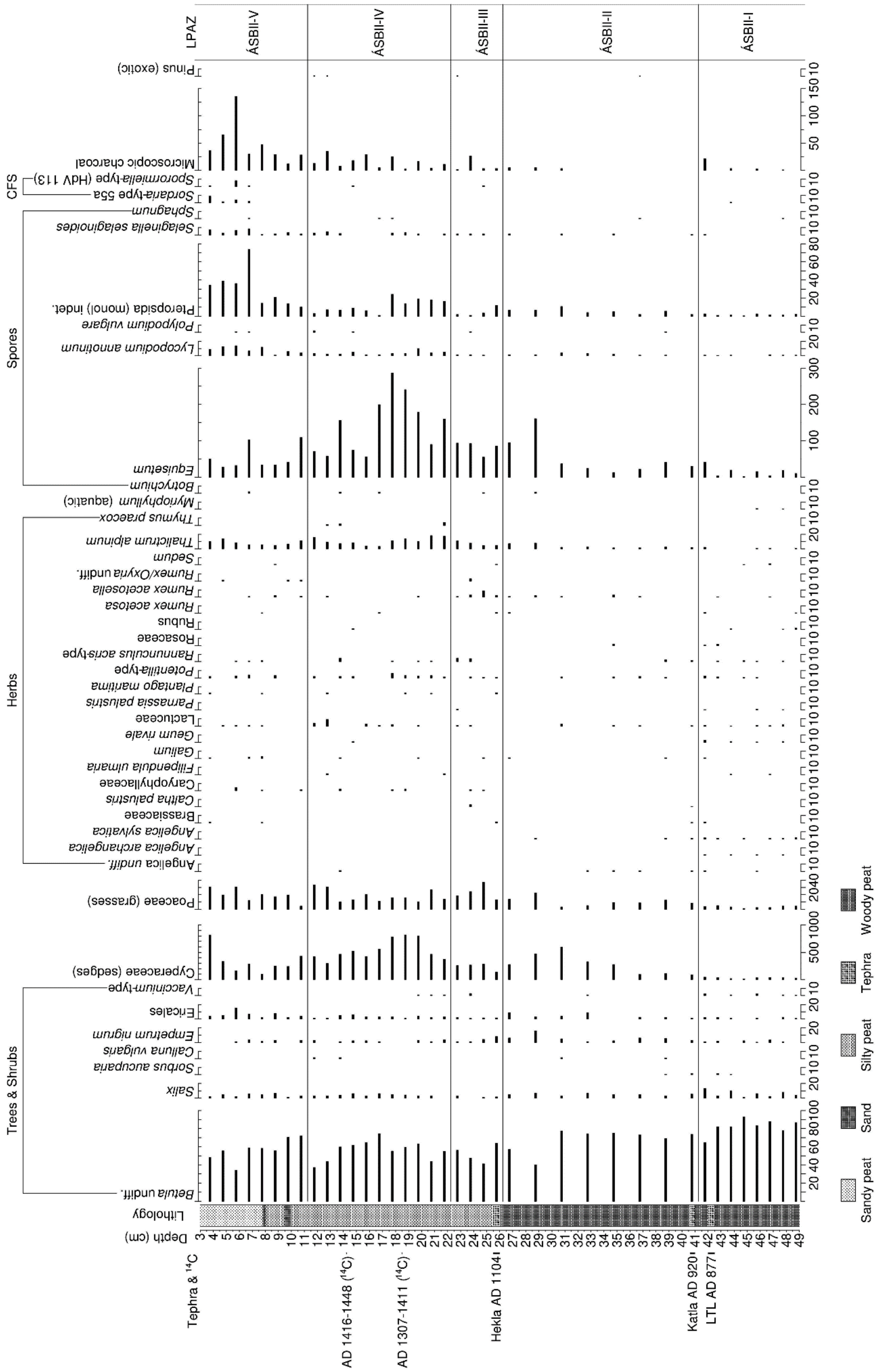
ESM2 Table 3 Sediment descriptions for HEL and ÁSB2

Core	Depth (cm)	Munsell (code & colour)	Tröels-Smith (composition)	Note
HEL	5-18	7.5YR 3-4 dark brown	Ag2-Sh2	
	18-20	10YR 2-1 black	Ga	Katla 1500
	20-28.25	7.5yr 3-4 dark brown	Ag2-Sh2	
	28.25-28.5	7.5YR 3-4 dark brown	Ga	Medieval 1226
	28.5-38	7.5YR 3-4 dark brown	Ag2-Sh2	
	38-40	10YR 4-1 dark grey	Ga	Landnám Tephra Layer AD 877
	40-64.5	7.5YR 2.5-2 very dark brown	Th3-Tl1	
ÁSB2	0-3	10YR 2-1 black	Th1 Tb1 Sh2	
	3-7.8	10YR 2-2 very dark brown	Ga2 Sh2	
	7.8-8	5YR 2.5-1 black	Ga4	
	8-9.5	5YR 5-8 yellowish red	Ag2 Sh2	Fe (oxidised)
	9.5-10	5YR 2.5-1 black	Ga4	
	10-12	10YR 4-4 Dark yellowish brown	Ag1 Th1 Sh2	
	12-25.5	10YR 4-3 brown	Ag1 Th1 Sh2	
	25.5-26	10YR 6-3 pale brown	Ag4	Hekla AD 1104
	26-40.6	10YR 2-2 very dark brown	Tb1 Sh3	
	40.6-41	5YR 2.5-1 black	Ga4	Katla AD 920
	41-42	10YR 2-2 very dark brown	Tb1 Sh3	
	42-42.5	7YR 2.5-1 black	Ga4	Landnám Tephra Layer AD 877
	42.5-57.5	10YR 2-2 very dark brown	Tb1 Sh3	
	57.5-58	10YR 6-1 grey	Ga4	Hekla tephra (unknown)

ESM2 Fig. 1 Pollen Percentage HEL (excluding Cyperaceae)



ESM2 Fig. 2 Pollen Percentage ASB2 (excluding Cyperaceae)



Appendix I: List of plant taxa mentioned in the text.

Abies (fir)
Alnus (alder)
Allium (garlic)
Angelica (angelica)
Angelica archangelica (garden angelica)
Angelica sylvestris (wild angelica)
Anthemis-type (yarrow, sneezewort etc.)
Artemisia-type (mugwort/wormwood)
Artemisia vulgaris (mugwort)
Asperugo procumbens (madwort)
Betula (birch)
Betula pubescens (downy birch)
Betula nana (dwarf birch)
Borago officinalis (borage)
Caltha palustris (marsh marigold)
Carum carvi (caraway)
Caryophyllaceae (chickweeds, stitchworts, mouse-ears etc.)
Chelidonium majus (greater celandine)
Cyperaceae (sedges)
Empetrum nigrum (crawberry)
Equisetum (horsetail)
Equisetum fluviatile (water horsetail)
Ericales (Ericaceae & Empetraceae)
Filipendula ulmaria (meadowsweet)
Galium (bedstraw)
Gentianella-type (Gentian)
Geum rivale (water avens)
Hippuris vulgaris (common mare’s tail)
Hordeum-type (barley)
Humulus lupulus (hops)
Isoëtes (quillwort)
Isoëtes echinospora (spring quillwort)
Juniperus communis (juniper)
Lactuceae (Chicoraceae; dandelions, hawkweeds etc)
Leymus arenaria (lyme grass)
Linum (flax)
Lupinus nootkatensis (Alaskan lupin)
Lycopodium annotinum (interrupted clubmoss)
Lynchis visacria (sticky catchfly)
Lynchis alpine (alpine catchfly)
Menyanthes trifoliata (bogbean)
Montia fontana (water blinks)
Myrica gale (bog myrtle)
Myriophyllum alterniflorum (alternate water-milfoil)
Myriophyllum spicatum (spiked water-milfoil)
Oxyria digyna (mountain sorrel)
Parnassia palustris (grass of Parnassus)
Pinus (pine)
Plantago lanceolata (ribwort plantain)
Plantago major (greater plantain)
Plantago maritima (sea plantain)
Poaceae (grasses)
Polygonum aviculare (knotgrass)
Potentilla-type (e.g. cinquefoil)
Ranunculus acris (meadow buttercup)
Rhinanthus-type (e.g. yellow rattle)
Rumex (sorrel)
Rumex acetosa (common sorrel)
Rumex acetosella (sheep’s sorrel)
Salix (willow)
Sanguisorba officinalis (great burnet)
Selaginella selaginoides (lesser clubmoss)
Sinapis-type (mustard)
Sphagnum (sphagnum moss)
Thalictrum alpinum (Alpine meadow rue)
Tsuga (hemlock)
Ulmus (elm)
Urtica (nettle)
Vaccinium (blaeberry)
Valeriana officinalis (valerian)